CANADA-NUNAVUT
GEOSCIENCE OFFICE

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BUREAU GÉOSCIENTIFIQUE
CANADA-NUNAVUT

KANATAMI-NUNAVUMI
GEOSCIENCE TITIGAKVIIT

SUMMARY OF ACTIVITIES 2012

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Front cover photo: Jaco Ishulutak, well-known carver from Pangnirtung, examining carving stone from a new discovery on southern Hall Peninsula. Photo by David Mate, Canada-Nunavut Geoscience Office.

Back cover photo: Folded Archean tonalitic gneiss in eastern Hall Peninsula. Photo by Gabe Creason, Dalhousie University.

Foreword

The Canada-Nunavut Geoscience Office (CNGO) was established in 1999 to help foster the development of Nunavut's mineral and energy resources and infrastructure. It is a partnership between Natural Resources Canada (NRCan), Aboriginal Affairs and Northern Development Canada (AANDC) and the Government of Nunavut's Department of Economic Development and Transportation. Nunavut Tunngavik Incorporated (NTI) is an ex-officio member of the office. Fully staffed, the office consists of seven employees with expertise in Precambrian, Paleozoic and Quaternary geology; GIS; and online data dissemination. In February 2013, the CNGO will be moving into the new Inuksugait Phase IV building in downtown Iqaluit.

The mandate of the CNGO is to provide geoscience information and expertise that supports 1) responsible resource exploration and development, 2) responsible infrastructure development, 3) education and training, and 4) geoscience awareness and outreach. The CNGO concentrates on new geoscience mapping and research, supporting geoscience-capacity building, disseminating geoscience information and developing collaborative partnerships of strategic importance to Nunavut.

The CNGO is pleased to be presenting results from its numerous collaborative geoscience projects in its inaugural *Canada-Nunavut Geoscience Office Summary of Activities* volume. This is an exciting undertaking for the office, with the intent being to publish a similar volume on a yearly basis. This volume is divided into four sections and consists of 18 papers. The four sections are Mineral Deposit Studies, Regional Geoscience, Geoscience for Infrastructure, and Carving Stone. All papers will be available for download online at www.cngo.ca.

The focus of the Mineral Deposit Studies section is a synthesis of multiyear research in the Borden Basin that encompasses a suite of investigations aimed at understanding the geological evolution and economic potential of Mesoproterozoic basins of eastern Nunavut. This work is being led by Laurentian University with support provided by the CNGO and Polar Continental Shelf Project. This article summarizes observations and interpretations from a range of thematic studies and recent fieldwork focused on mapping the deep-water carbonate mounds of the Ikpiarjuk Formation.

The focus of the papers in the Regional Geoscience section is on the Hall Peninsula Integrated Geoscience Project and research in the Hudson Bay and Foxe basins supported by Geo-mapping for Energy and Minerals (GEM). The Hall Peninsula Integrated Geoscience Program (HPIGP) is being led by the Canada-Nunavut Geoscience Office in collaboration with Dalhousie University, University of Alberta, Université Laval, University of Manitoba, University of Ottawa, University of Saskatchewan, Arctic College and the Geological Survey of Canada. The focus is on bedrock and surficial mapping and a range of thematic studies that includes Archean and Paleoproterozoic tectonics, geochronology, landscape uplift and exhumation, detailed mapping in mineralized areas, microdiamonds, sedimentary rock xenoliths and permafrost.

During the past five years, the CNGO has collaborated with NRCan's Geo-mapping for Energy and Minerals program to evaluate the petroleum potential of the Hudson Bay and Foxe basins in eastern Nunavut. The goals of CNGO research have been to better understand the Paleozoic stratigraphy in the basins, provide a stratigraphic correlation between the two basins and to assess the petroleum potential in the region. A synthesis of the interpretations and observations from this five-year project can be found in this volume.

The Geoscience for Infrastructure section highlights collaborative research conducted by the Canada-Nunavut Geoscience Office, Natural Resources Canada and Université Laval. Papers in this volume address permafrost studies in Iqaluit and coastal climate-change research. Permafrost and terrain-stability research on key strategic infrastructure continues in the City of Iqaluit, with an emphasis on the Iqaluit International Airport, the gateway to the eastern Canadian Arctic. The city and airport infrastructure is underlain by continuous permafrost that is now warming and thawing, which results in terrain instability. Recent results have demonstrated a clear link between original terrain units, permafrost features and the problems currently affecting infrastructure.

Coastal climate-change issues across Nunavut are being addressed by scientists from the Climate Change Geoscience Program (CCGP) of the Earth Sciences Sector of NRCan with support from the CNGO. The focus of activities has been on regions, localities and communities where the resource industry utilizes existing coastal infrastructure or where industry activity may lead to development of coastal infrastructure. A focus this year has been on Coronation Gulf and surrounding regions, although activities have also occurred in other parts of Nunavut.

The Carving Stone section consists of two papers. The first provides a summary of results from the Nunavut Carving Stone Deposit Evaluation Program, a collaborative project between the Government of Nunavut's Department of Economic Development and Transportation and the CNGO. Its primary goal is to verify the quality and size of hand-mined carving-stone deposits and identify new deposits throughout Nunavut. To date, a total of 75 sites in proximity to 19 communities have been evaluated and two previously unknown 'major' deposits have been confirmed. The second paper describes new ultramafic carving-stone occurrences discovered as part of the Hall Peninsula Integrated Geoscience Project.

Acknowledgments

The CNGO would like to thank all authors of papers in this first *Summary of Activities*. Your dedication has been greatly appreciated and is critical in helping the CNGO deliver such a product. RnD Technical is also thanked for their technical editing and assembling of the volume. In addition, special thanks are extended to reviewers of papers:

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Préface

Le Bureau géoscientifique Canada-Nunavut a été créé en 1999 en vue de promouvoir le développement des ressources ainsi que de l'infrastructure minières et énergétiques du Nunavut. Il s'agit d'un partenariat entre Ressources naturelles Canada (RNCan), Affaires autochtones et Développement du Nord Canada et le ministère du Développement économique et des Transports du Nunavut. La société Nunavut Tunngavik Incorporated (NTI) est membre d'office du Bureau. Lorsque tous les postes y sont occupés, celui-ci regroupe sept employés spécialisés dans la géologie du Précambrien, du Paléozoïque et du Quaternaire, le système d'information géographique et la diffusion de données en ligne. En février 2013, le Bureau déménagera dans le nouvel immeuble Inuksugait, Phase IV, au centre-ville d'Iqaluit.

Le mandat du Bureau géoscientifique Canada-Nunavut est de fournir des données et un savoir-faire géoscientifiques en appui 1) à l'exploration et à l'exploitation responsables des ressources, 2) à l'aménagement responsable de l'infrastructure, 3) à l'enseignement et à la formation, et 4) à la sensibilisation et à l'information du public sur les enjeux géoscientifiques. Le Bureau concentre ses efforts sur la cartographie des enjeux géoscientifiques émergents et les recherches connexes, sur le soutien du renforcement des capacités géoscientifiques, sur la diffusion de données géoscientifiques et sur la mise en place de partenariats efficaces d'importance stratégique pour le Nunavut.

Le Bureau est fier de faire connaître les résultats obtenus grâce à ses nombreux projets de collaboration géoscientifique dans ce premier numéro du *Sommaire des activités du Bureau géoscientifique Canada-Nunavut*. Il s'agit d'un projet stimulant pour le Bureau, qui entend publier un nouveau numéro du Sommaire tous les ans. Celui-ci comprend quatre sections et un total de 18 articles. Les quatre sections sont les suivantes : Études sur les gisements minéraux, Études géoscientifiques régionales, Études géoscientifiques liées à l'infrastructure et Pierre à sculpter. Tous les articles seront publiés (en anglais seulement, accompagnés de résumés en français) sur Internet et pourront être téléchargés depuis le www.cngo.ca.

La section Études sur les gisements minéraux fait la synthèse d'une recherche pluriannuelle sur le bassin de Borden qui englobe une série d'études visant à comprendre l'évolution géologique et le potentiel économique des bassins mésoprotérozoïques de l'est du Nunavut. Ces travaux sont menés par l'Université Laurentienne, avec l'appui du Bureau et de l'Étude du plateau continental polaire. Le volume résume les observations et les interprétations tirées de toute une gamme d'études thématiques, ainsi que de travaux sur le terrain menés récemment, qui mettent l'accent sur la cartographie des monticules carbonatés en eau profonde de la formation d'Ikpiarjuk.

Les articles réunis dans la section Études géoscientifiques régionales portent sur le Projet géoscientifique intégré de la péninsule Hall et sur la recherche effectuée dans le bassin de la baie d'Hudson et dans le bassin de Foxe, appuyée par le Programme de géocartographie de l'énergie et des minéraux (GEM). Le Programme géoscientifique intégré de la péninsule Hall est dirigé par le Bureau géoscientifique Canada-Nunavut en collaboration avec l'Université Dalhousie, l'Université de l'Alberta, l'Université Laval, l'Université du Manitoba, l'Université d'Ottawa, l'Université de la Saskatchewan, le Collège de l'Arctique et la Commission géologique du Canada. Il met l'accent sur la cartographie du substratum rocheux et de la géologie de surface, et comprend une gamme d'études thématiques : tectonique de l'Archéen et du Paléoprotérozoïque, géochronologie, soulèvement et exhumation du paysage, cartographie détaillée des zones minéralisées, microdiamants, xénolites des roches sédimentaires et pergélisol.

Au cours des cinq dernières années, le Bureau a collaboré avec le Programme de géocartographie de l'énergie et des minéraux de RNCan afin d'évaluer le potentiel pétrolier du bassin de la baie d'Hudson et du bassin Foxe, dans l'est du Nunavut. La recherche menée par le Bureau visait à mieux comprendre la stratigraphie du Paléozoïque dans ces bassins, d'établir une corrélation stratigraphique entre les deux bassins et d'évaluer le potentiel pétrolier de la région. Le présent volume comporte une synthèse des interprétations et des observations tirées de ce projet de cinq ans.

La section Études géoscientifiques liées à l'infrastructure traite des recherches menées en collaboration par le Bureau géoscientifique Canada-Nunavut, Ressources naturelles Canada et l'Université Laval. Les articles de cette section résument les études sur le pergélisol effectuées à Iqaluit et la recherche sur les changements climatiques dans les zones côtières. Les recherches sur le pergélisol et sur la stabilité du terrain entreprises en rapport avec les infrastructures stratégiques se poursuivent dans la ville d'Iqaluit, principalement à l'aéroport international, porte d'entrée de l'Est de l'Arctique canadien. L'infrastructure de la ville et de l'aéroport repose sur un pergélisol continu qui commence à se réchauffer et à dégeler, phénomènes qui rendent le terrain instable. Les résultats obtenus récemment ont révélé un lien clair entre les unités de terrain originales, les caractéristiques du pergélisol et les problèmes que connaît actuellement l'infrastructure.

Les enjeux liés aux changements climatiques dans les zones côtières de tout le Nunavut font l'objet d'études par des chercheurs du programme Géosciences des changements climatiques du Secteur des sciences de la Terre de RNCan, avec l'appui du Bureau. Leurs activités sont axées sur les régions, les municipalités et les communautés où les infrastructures côtières existantes sont utilisées par l'industrie des ressources naturelles et celles où l'activité industrielle pourrait entraîner l'aménagement d'une infrastructure côtière. Cette année, le programme a mis l'accent sur le golfe Coronation et sur les régions environnantes, bien que les chercheurs aient également mené des activités dans d'autres secteurs du Nunavut.

La section Pierre à sculpter comporte deux articles. Le premier résume les résultats obtenus par le Programme d'évaluation des gisements de pierre à sculpter du Nunavut, projet conjoint dirigé par le ministère du Développement économique et des Transports du Nunavut et le Bureau. Le Programme a pour principal objectif de vérifier la qualité et la taille des gisements de pierre à sculpter exploités manuellement et de trouver de nouveaux gisements dans tout le Nunavut. À ce jour, le Programme a permis d'évaluer 75 emplacements situés près de 19 communautés et de confirmer la présence de deux nouveaux gisements « importants ». Le deuxième article décrit les nouvelles occurrences de pierre à sculpter ultramafique découvertes grâce au Programme géoscientifique intégré de la péninsule Hall.

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Le Bureau tient à remercier les auteurs des articles publiés dans ce premier *Sommaire des activités*. Votre dévouement est extrêmement apprécié et c'est grâce à vous que nous pouvons publier un tel document. Merci à RnD Technical d'avoir vu à l'édition technique et à l'assemblage de ce numéro. Nos remerciements vont également aux personnes suivantes, lecteurs critiques des articles :

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Nicolas Pinet, Commission géologique du Canada
Eric Prosh, gouvernement du Nunavut
Martin Ross, Université de Waterloo
Mary Sanborn-Barrie, Commission géologique du Canada
David Schneider, Université d'Ottawa
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Rod Smith, Commission géologique du Canada
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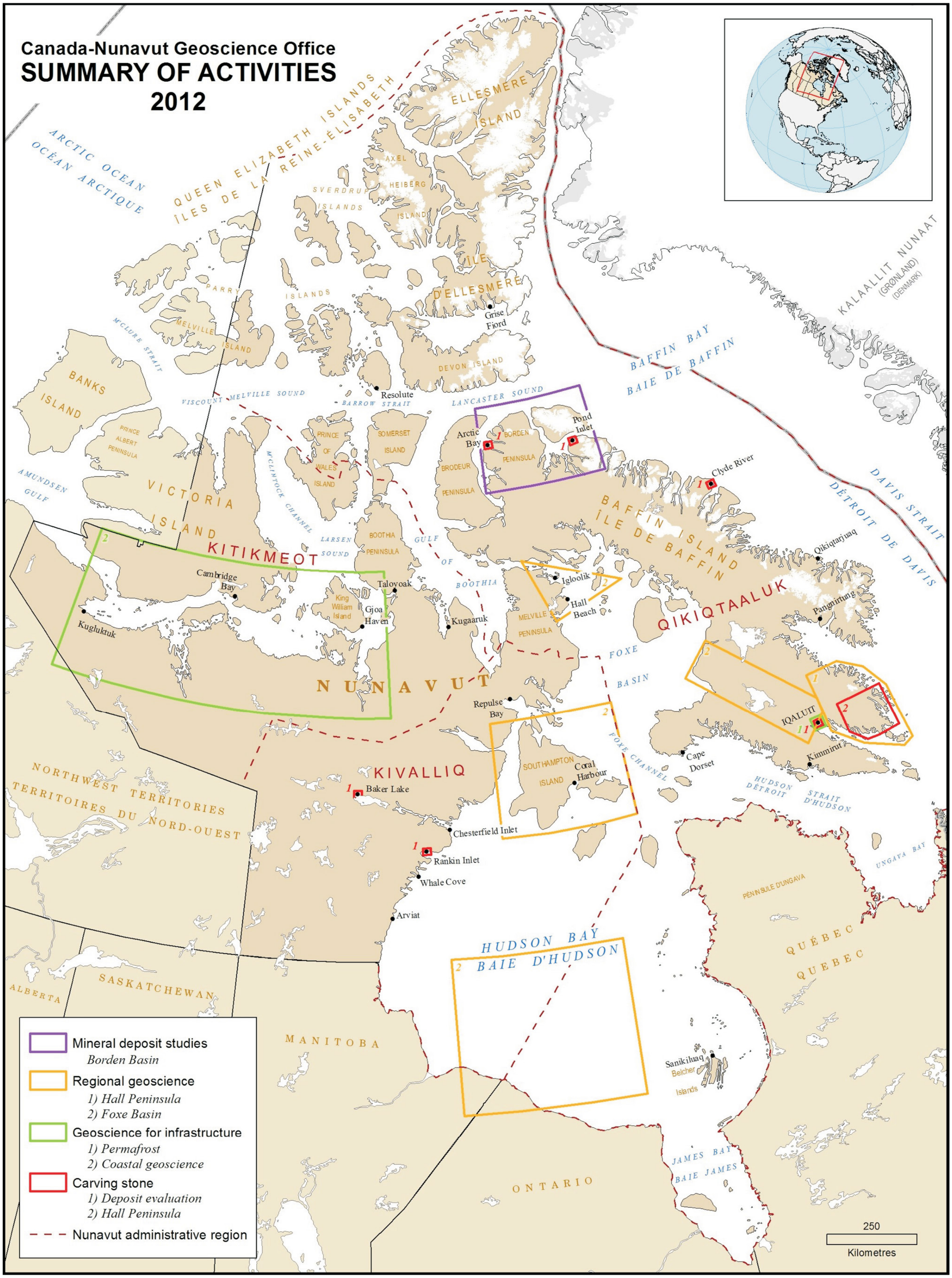
Canada-Nunavut Geoscience Office
SUMMARY OF ACTIVITIES
2012
ARCTIC OCEAN
OCÉAN ARCTIQUE
QUEEN ELIZABETH ISLANDS
ILES DE LA REINE-ÉLISABETH
ELLESMERE ISLAND
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AXEL HEIBERG ISLAND
SVERDRUP ISLANDS
PARRY ISLANDS
MELVILLE ISLAND
M'CLURE STRAIT
BANKS ISLAND
PRINCE ALBERT PENINSULA
VICTORIA ISLAND
AMUNDSEN GULF
VISCOUNT MELVILLE SOUND
BARROW STRAIT
LANCASTER SOUND
DEVON ISLAND
Grise Fiord
Resolute
PRINCE OF WALES ISLAND
SOMERSET ISLAND
M'CLINTOCK CHANNEL
LARSEN SOUND
BOOTHIA PENINSULA
GULF OF BOOTHIA
BRODEUR PENINSULA
BORDEN PENINSULA
Arctic Bay
Pond Inlet
Clyde River
BAFFIN BAY
BAIE DE BAFFIN
KALAALLIT NUNAAT
(GRØNLAND)
(DENMARK)
DAVIS STRAIT
DÉTROIT DE DAVIS
BAFFIN ISLAND
ÎLE DE BAFFIN
Qikiqtarjuaq
Pangnirtung
QIKIQTAALUK
KITIKMEOT
Cambridge Bay
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King William Island
Gjoa Haven
Taloyoak
Kugaaruk
Igloolik
Hall Beach
MELVILLE PENINSULA
FOXE BASIN
NUNAVUT
Repulse Bay
IQALUIT
Kimmirut
Cape Dorset
SOUTHAMPTON ISLAND
Coral Harbour
FOXE CHANNEL
HUDSON STRAIT
DÉTROIT D'HUDSON
KIVALLIQ
Baker Lake
Chesterfield Inlet
Rankin Inlet
Whale Cove
Arviat
NORTHWEST TERRITORIES
TERRITOIRES DU NORD-OUEST
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
HUDSON BAY
BAIE D'HUDSON
UNGAVA BAY
PÉNINSULE D'UNGAVA
QUÉBEC
QUEBEC
Sanikiluaq
Belcher Islands
JAMES BAY
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Mineral deposit studies
Borden Basin
Regional geoscience
1) Hall Peninsula
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Geoscience for infrastructure
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Carving stone
1) Deposit evaluation
2) Hall Peninsula
Nunavut administrative region
250
Kilometres

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Economic potential of the Mesoproterozoic Borden Basin zinc district, northern Baffin Island, Nunavut: update 2011–2012

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Abstract

The Borden Basin Project is a multiyear endeavour that encompasses a suite of investigations aimed at understanding the geological evolution and economic potential of Mesoproterozoic basins of eastern Nunavut. Part of the Borden Basin is a proven but poorly understood Zn district that includes the Nanisivik mine (in operation from 1976 to 2002). Since the end of the 2011 field season, field and analytical advances have resulted in publication of results from five thematic studies focused on the basin's economic potential:

1) A field-based study mapped and characterized the many known carbonate-hosted Zn-Pb±Cu showings in the 250 by 100 km Milne Inlet graben (main zone of known mineralization), identified the structural and stratigraphic controls on the spatial distribution of three showing types, and highlighted two geographic zones of elevated economic potential.
2) A field-based and analytical study of a thick (>100 m) and unexplored black shale unit showed that geochemical and geological conditions in the basin during shale accumulation would have been appropriate for the deposition of sedimentary exhalative (SEDEX)-type sulphides, if local vent sources of dissolved metals had been present (currently unknown). This work also provided a first direct date of 1092±59 Ma (U-Th-Pb whole-rock geochemistry on black shale) for the deposition of part of the Bylot Supergroup, which is considerably younger than the previous, assumed depositional age, and coincides with the Grenvillian orogeny and assembly of Rodinia.
3) A fluid inclusion study of the Nanisivik orebody showed that ore-forming fluids were Na-rich and comparatively low-temperature (<100 °C), in striking contrast to results of earlier studies (200–250 °C). The fluid inclusion homogenization temperatures increase toward the 'mine dike', a Franklin-aged (ca. 720 Ma) intrusion that crosscut the orebody and locally modified the fluid inclusions (i.e., to higher homogenization-temperatures).
4) Rhenium-osmium dating of pyrite from the Nanisivik orebody and the Hawker Creek group of showings provided for the first time a direct date of ca. 1100 Ma for the mineralizing event. This date refutes recent work that indicated a Phanerozoic age for the mineralizing event, and refocuses the economic potential of the event onto Proterozoic hostrocks only. The results also suggest that fluid movement was roughly coeval with sediment deposition, and may have been driven by tectonic events associated with the amalgamation of Rodinia.

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5) Study of the siliciclastic basal strata of the Mesoproterozoic succession showed that early phases of the basin's depositional history were not aulacogenic, as previously assumed, and that the potential for unconformity-type U deposits in this basin is low.

Fieldwork in 2012 focused on understanding vent-related deep-water carbonate mounds that were deposited during the accumulation of a black shale succession, and on outlining the tectonic evolution of the basin using sediment provenance.

Résumé

Le Projet du bassin de Borden est une entreprise pluriannuelle qui englobe une série d'études visant à comprendre l'évolution géologique et le potentiel économique des bassins mésoprotérozoïques de l'est du Nunavut. Une partie du bassin de Borden est un district de Zn confirmé, mais mal compris, qui comprend la mine de Nanisivik (exploitée de 1976 à 2002). Depuis la fin de la campagne d'exploration de 2011, les progrès des travaux sur le terrain et des analyses ont abouti à la publication des résultats de cinq études thématiques sur le potentiel économique du bassin :

1) Une étude sur le terrain a permis de cartographier et de caractériser les nombreux indices connus de Zn-Pb±Cu encaissés dans des roches carbonatées du graben de Milne Inlet, d'une étendue de 250 km sur 100 km (principale zone de la minéralisation connue); d'identifier les contrôles structuraux et stratigraphiques de la répartition spatiale de trois types d'indices; et de mettre en évidence deux zones géographiques à potentiel économique élevé.
2) Une étude sur le terrain et l'analyse d'une épaisse (> 100 m) unité d'ampélite inexplorée ont révélé que les conditions géochimiques et géologiques dans le bassin pendant l'accumulation des schistes aurait été propices à la mise en place de sulfures de type sédimentaire exhalatif (SEDEX), si des cheminées, sources de métaux dissous, avaient été présentes localement (ce qu'on n'a pu établir pour le moment). Ces travaux ont également fourni une première datation directe de 1 092 ± 59 Ma (géochimie U-Th-Pb en roche totale sur ampélite) pour la mise en place d'une partie du Supergroupe de Bylot, soit un âge beaucoup plus jeune que celui présumé auparavant et qui, d'ailleurs, coïncide avec l'orogenèse grenvillienne et l'assemblage du Rodinia.
3) Une étude des inclusions fluides du corps minéralisé de Nanisivik a révélé que les fluides minéralisateurs étaient riches en Na et de température relativement basse (< 100 °C), ce qui contraste fortement avec les résultats d'études antérieures (200 à 250 °C). Les températures d'homogénéisation des inclusions fluides augmentent vers le « dyke de la mine », une intrusion datant du Franklin (vers 720 Ma) qui a recoupé le corps minéralisé et modifié les inclusions fluides par endroits (c.-à-d. à des températures d'homogénéisation plus élevées).
4) La datation au rhénium-osmium de la pyrite provenant du corps minéralisé de Nanisivik et du groupe d'indices de Hawker Creek a fourni pour la première fois une date directe d'environ 1 100 Ma pour l'événement de minéralisation. Cette datation réfute de récents travaux qui indiquaient un âge phanérozoïque pour la minéralisation, et remet l'accent, en termes du potentiel économique de l'événement, uniquement sur les roches encaissantes du Protérozoïque. Les résultats semblent indiquer également que le mouvement des fluides était à peu près contemporain de la sédimentation, et peut avoir été suscité par des événements tectoniques liés à l'amalgamation du Rodinia.
5) Une étude des strates basales silicoclastiques de la succession du Mésoprotérozoïque a révélé que les premières phases de l'histoire sédimentaire du bassin ne sont pas aulacogènes, comme on le supposait précédemment, et qu'il est peu probable de trouver des gisements d'uranium de type discordant dans ce bassin.

Le travail sur le terrain en 2012 a porté sur la compréhension des monticules carbonatés d'eau profonde liés aux bouches hydrothermales, qui ont été mis en place au cours de l'accumulation d'une succession de schistes ampélitiques, et sur la description de l'évolution tectonique du bassin en fonction de la provenance des sédiments.

Introduction

The Borden Basin is one of the Mesoproterozoic Bylot basins (Figure 1; Fahrig et al., 1981), a group of four putatively aulacogenic basins in northeastern Nunavut and northwestern Greenland, which had initially been interpreted as collectively opening onto a global ocean (Jackson and Iannelli, 1981). Other than an inferred age of 1270 Ma for basal volcanic rocks (corresponding to the Mackenzie igneous event; Galley et al., 1983; LeCheminant and Heaman, 1989), no depositional age has been available. The basin's depositional age was assumed to be close to that inferred for the basalt, and considerably older than the age of crosscutting dikes inferred to be related to the Franklin igneous event (Heaman et al., 1992; Denyszyn et al., 2009) ca. 720 Ma. The Borden Basin contains three depositional zones or 'troughs' (Figure 1), of which the Milne Inlet graben (~250 by 100 km) is both the largest and the only

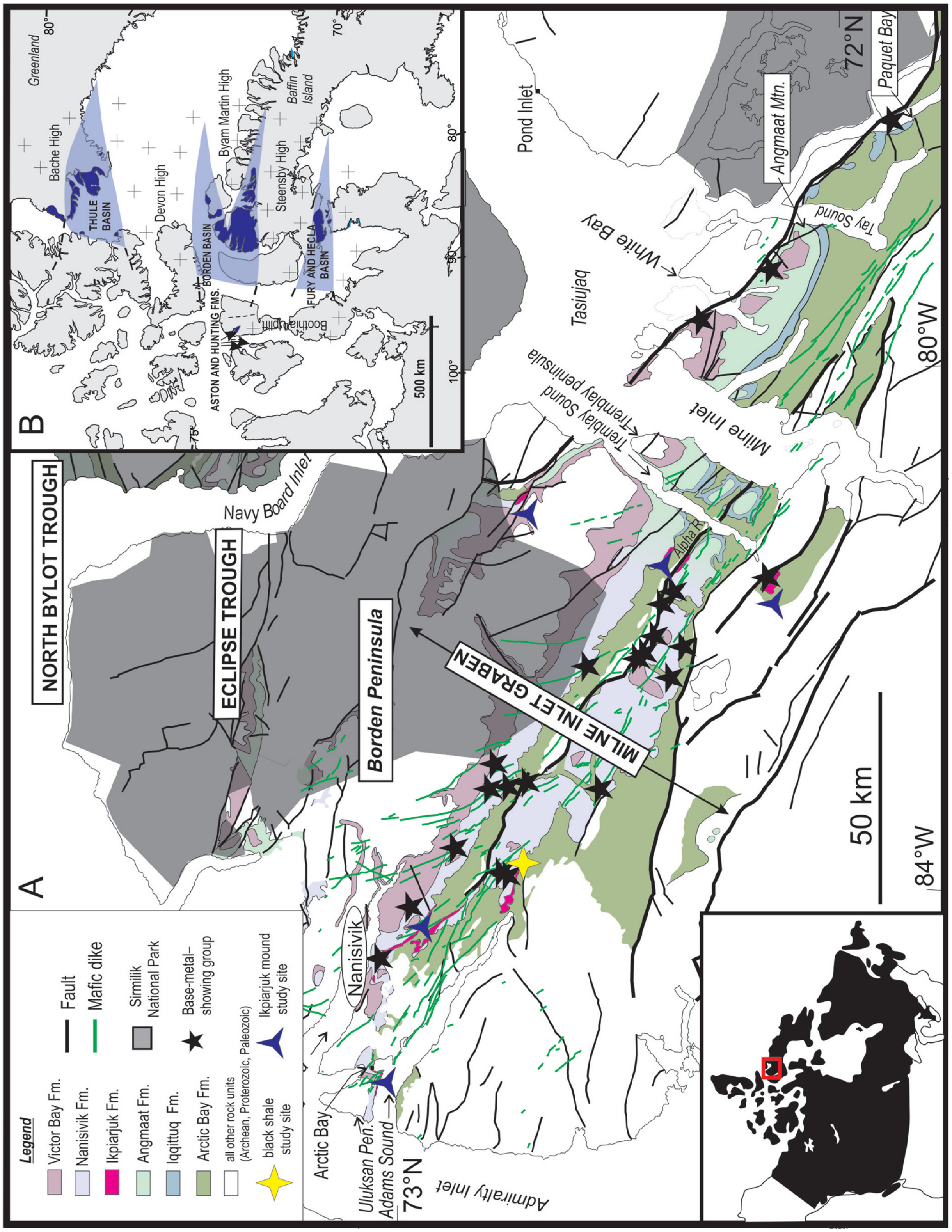

Figure 1. Geological maps of the Borden Basin, northern Baffin Island, Nunavut, showing **a)** the distribution of stratigraphic units that are relevant to known and potential base-metal mineralization and the distribution of the main Zn-Pb±Cu showings (after Scott and deKemp 1998 and Turner, 2009, 2011); **b)** the inferred regional geology of the Bylot basins; exposure areas are shown in dark blue and the inferred former extent of the basins is in pale blue (after Jackson and Iannelli, 1981).

one known to contain base-metal showings. Establishment of the basin's stratigraphy (Figure 2) began with Lemon and Blackadar (1963), and regional mapping and stratigraphy were undertaken in the 1970s (Jackson and Iannelli, 1981). Recent work has yielded a detailed and modern understanding of the basin's carbonate rocks (Sherman et al., 2002; Turner, 2009, 2011), which are the hostrocks of the Borden Basin Zn district. The district contains numerous Zn-Pb-Cu showings (Figure 1), of which the Nanisivik deposit is the best known (produced 19 Mt at ~10% Zn+Pb between 1976 and 2002).

The Borden Basin Project, a multiyear academic study supported by the Canada-Nunavut Geoscience Office, is based at Laurentian University's Mineral Exploration Research Centre (Sudbury, Ontario). A series of intense, early field seasons focused on deciphering the regional stratigraphy of carbonate host units of the Borden Basin Zn district (Figure 1; Turner, 2009, 2012a, b). The upgraded stratigraphic understanding facilitated the mapping of most of the basin's numerous showings (Turner 2011). As the project matured, further studies focused on understanding the controls on the spatial distribution of Zn mineralization at Nanisivik and throughout the Borden Basin, determining the economic potential of other major stratigraphic units in the basin, characterizing the evolution and economic potential of related Mesoproterozoic basins in the eastern Arctic islands of Canada, and resolving the cause and timing of the mineralizing event at Nanisivik. The results of these studies, a group of which have been published since the 2011 field season, will help to focus exploration in this poorly understood, large, and surprisingly underexplored basin.

Field activity in 2012 included two project components:

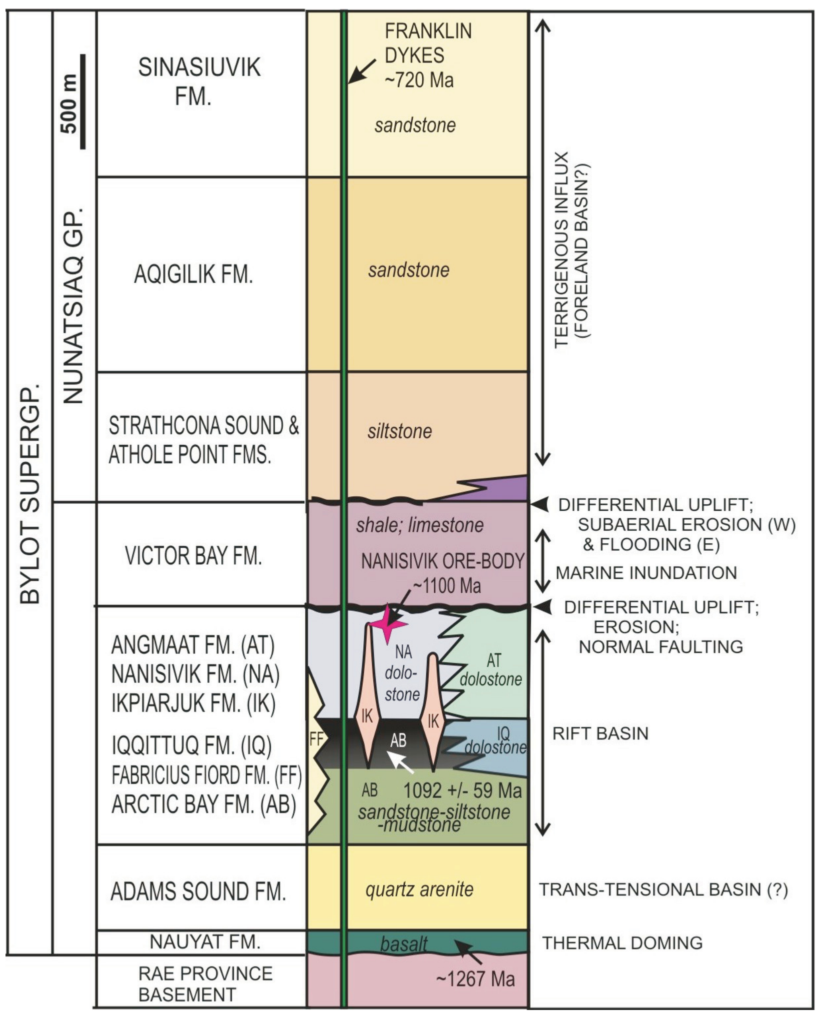

Figure 2. Revised stratigraphy of the Borden Basin, northern Baffin Island, Nunavut (after Turner, 2009, 2011), with updated tectonostratigraphic history (Turner, 2009; Turner, 2011; Long and Turner, 2012; Turner and Kamber, 2012), depositional age for the Arctic Bay Formation (Turner and Kamber, 2012) and mineralization age for the Nanisivik orebody (Hnatyshin et al., 2011). Black fill indicates the black shale unit of the Arctic Bay Formation. Abbreviations: E, east; W, west.

- the second and final field season of a graduate student project that addresses the characteristics and origin of enigmatic, very large, deep-water carbonate mounds that accumulated at seafloor-vent sites along syndepositionally active faults under an anoxic water column at the same time as the accumulation of a thick black shale succession
- the field component of a sediment-provenance study that will help to constrain the types of depositional systems and tectonic events that prevailed throughout the interval of tectonic instability represented by the Bylot Supergroup

Results of 2011–2012

Structural and stratigraphic controls on carbonate-hosted base-metal sulphide mineral distribution

Controls on the distribution of Zn and other sulphides in the Milne Inlet graben of the Borden Basin were addressed by field mapping based on existing stratigraphy and the recently clarified stratigraphy of diverse carbonate-rock units in the basin (Turner, 2009). The results of the regional mapping of showings (Turner, 2011) identified the combinations of structural and stratigraphic controls that constrain the spatial distribution of sulphide concentrations in the Milne Inlet graben, which is the only part of the Borden Basin that is known to contain Zn-Pb±Cu showings; three main settings were identified. Previous work (Arne et al., 1991) showed that the Nanisivik deposit accumulated under a reducing gas-cap: sulphides that ascended in solution through fractures associated with basin-scale faults and then precipitated upon contact with a horizontal gas-water interface. The constraints on the gas-trap were not identified. The recent mapping project identified the spatial controls on the gas-caps and, hence, on the Nanisivik orebody (Figure 3). At a regional scale, a newly identified unconformity, which separates the district's main carbonate hostrock (Nanisivik Formation) from overlying shale (Victor Bay Formation), represents an erosionally undulatory land surface with local normal-fault scarps; hills and valleys (both erosional and downfaulted) of the post-Nanisivik Formation land surface were eventually progressively inundated by seawater and buried by terrigenous mud of the lower Victor Bay Formation (Figure 3; Turner, 2011). The paleo-highs in this buried unconformity surface acted as traps for evading gas, which was presumably generated from underlying organic-rich shale. Metalliferous fluid rose along regional fracture systems and precipitated sulphide minerals (Figure 4) at the interface between gas and pore water, as outlined in Arne et al. (1991). This new understanding of the controls on the most impressive showings in the Borden Basin identifies the potential for unexplored, unconformity-related areas to contain blind sulphide bodies similar to that at Nanisivik. One of the two other types of showings contains replacement Zn mineralization very close to basin-bounding faults. Unexplored areas of potential interest for this type of showing are present both outside and inside the borders of Sirmilik National Park.

SEDEX and polymetallic black shale potential of the Arctic Bay Formation

The Arctic Bay Formation, which is over 1 km thick, contains an impressive thickness of black shale in the northwestern part of the Milne Inlet graben (Figure 5a). The regional stratigraphy and sedimentology of this unit have never been thoroughly addressed, and the black shale has

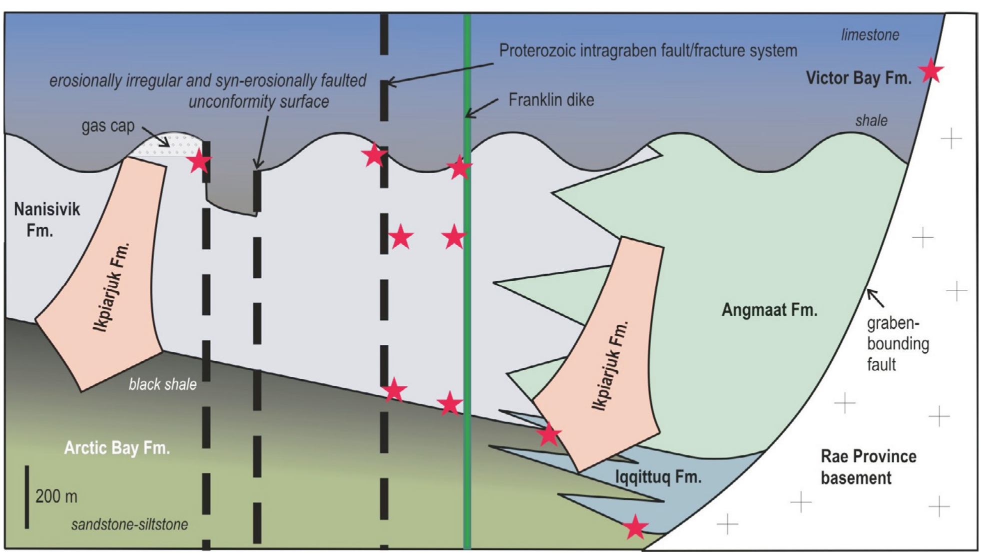

Figure 3. Economic potential of stratigraphic units in the middle of the Bylot Supergroup in the Milne Inlet graben, northern Baffin Island, Nunavut: diagram of the revised stratigraphy of carbonate strata, showing the main geological conditions that controlled distribution of carbonate-hosted base-metal sulphide bodies (red stars; after Turner, 2011).

not been the subject of significant exploration interest since the area was first mapped by the Geological Survey of Canada (GSC) in the 1970s (Jackson and Iannelli, 1981). A field-based project begun in 2009 came to fruition in 2012 with publication of field and analytical results (Turner and Kamber, 2012) that addressed the regional stratigraphy and basin configuration of the Arctic Bay Formation and the potential of its black shale to host economic concentrations of metals. Fieldwork focused on one location where black shale is well exposed (Figures 1, 5a). Stratigraphic sections were measured through as much of the Arctic Bay Formation as was exposed, and siltstone-shale intervals were analyzed on-site using a hand-held X-ray fluorescence (XRF) analyzer to identify intervals with elevated concentrations of redox-sensitive elements; equivalent samples were collected for laboratory-based analysis at Laurentian University. Comparison of the two datasets showed that the XRF data accurately reflect the trace-element concentrations of most of the elements of interest. In the northwestern, deep-water part of the basin, redox-sensitive elements in the black shale interval (>100 m thick) show a consistent pattern, with particularly high concentrations occurring at a level two-thirds of the way through the black shale interval (Figure 5b). The presence of elevated redox-sensitive elements reflects a capacity to reduce and precipitate any dissolved base metals that may have been supplied, which is a fundamental requirement for the development of a SEDEX-favourable environment. This basin water would have been capable of precipitating Zn, Pb, Cu and Ni, had they been supplied at local vent sites. The study did not find any direct evidence of nearby venting of metalliferous fluids into seawater, possibly because only one section was studied. The structure and stratigraphy of the succession record extension throughout deposition of the black shale interval in the form of syndepositional extensional faulting, deep anoxic water, paleobathymetric subdivision into local sub-basins, minimal terrigenous input, and vent-related carbonate precipitates. This group of attributes is known to be strongly favourable for the development of SEDEX deposits. The apparent global nadir in the number of known SEDEX deposits at the time of this basin's existence may be an artifact of either preservation or preferential exploration activity, or may be explained by some as yet unknown aspect of the Earth-surface oxidation state of the late Mesoproterozoic, which is the current object of widespread research activity. The SEDEX potential of this unexplored succession remains unknown, and warrants further investigation because most of the essential preconditions were present.

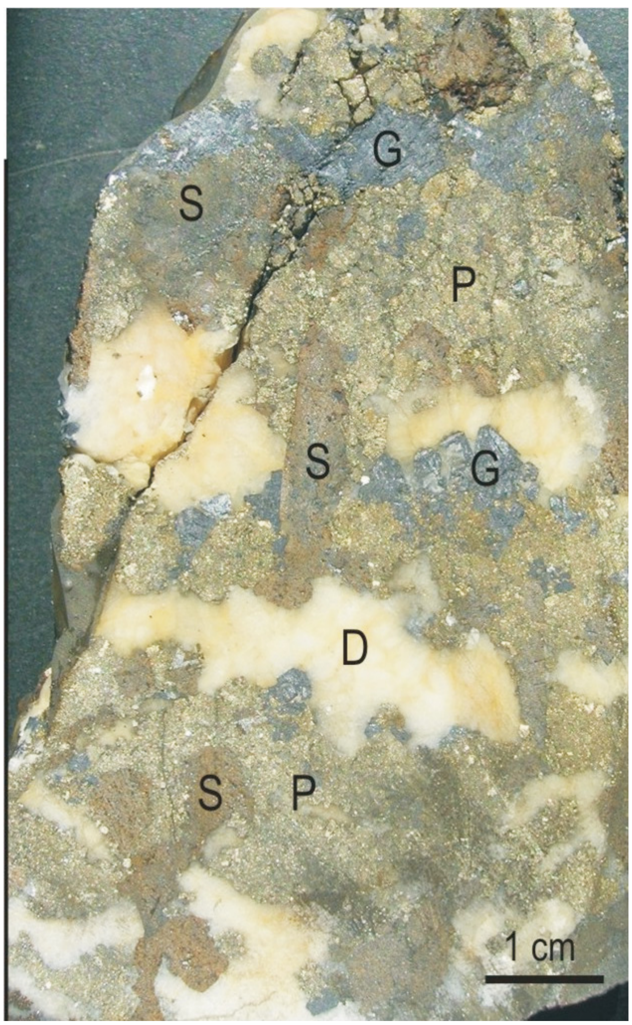

Figure 4. Typical banded ore from the Nanisivik deposit of Baffin Island, Nunavut, consisting of sphalerite (S), galena (G), pyrite (P) and dolomite (D).

Nature of mineralizing fluids in the Nanisivik deposit

Previous fluid-inclusion studies of the Nanisivik deposit (McNaughton and Smith, 1986; Arne et al., 1991) yielded homogenization temperatures (Th) in the range of 200–250 ºC, which is considerably hotter than is typical for carbonate-hosted Zn-Pb deposits, and led to the conclusion that the Nanisivik ore deposit was unusual among carbonate-hosted Zn-Pb deposits. These previous studies were undertaken prior to the development of the concept of 'fluid-inclusion assemblages' (FIA). The FIA 'protocol' is a method of obtaining and understanding fluid-inclusion data that ensures that only fluid inclusions that are petrographically related to the time of entrapment of a homogeneous fluid (i.e., a group of inclusions with the same density and chemistry) are analyzed and that inclusions that have been modified since entrapment are excluded. This protocol excludes populations of inclusions with widely varying homogenization temperatures (i.e., variable density), such as those that have been modified since their entrapment. Using this approach, a fluid-inclusion study (Morden, 2011) using the same samples as those used in one of the previous studies (Arne et al., 1991) demonstrated conclusively that the mineralizing event occurred at approximately 80 to 100 ºC, which is within the range that is considered normal for carbonate-hosted Zn-Pb deposits

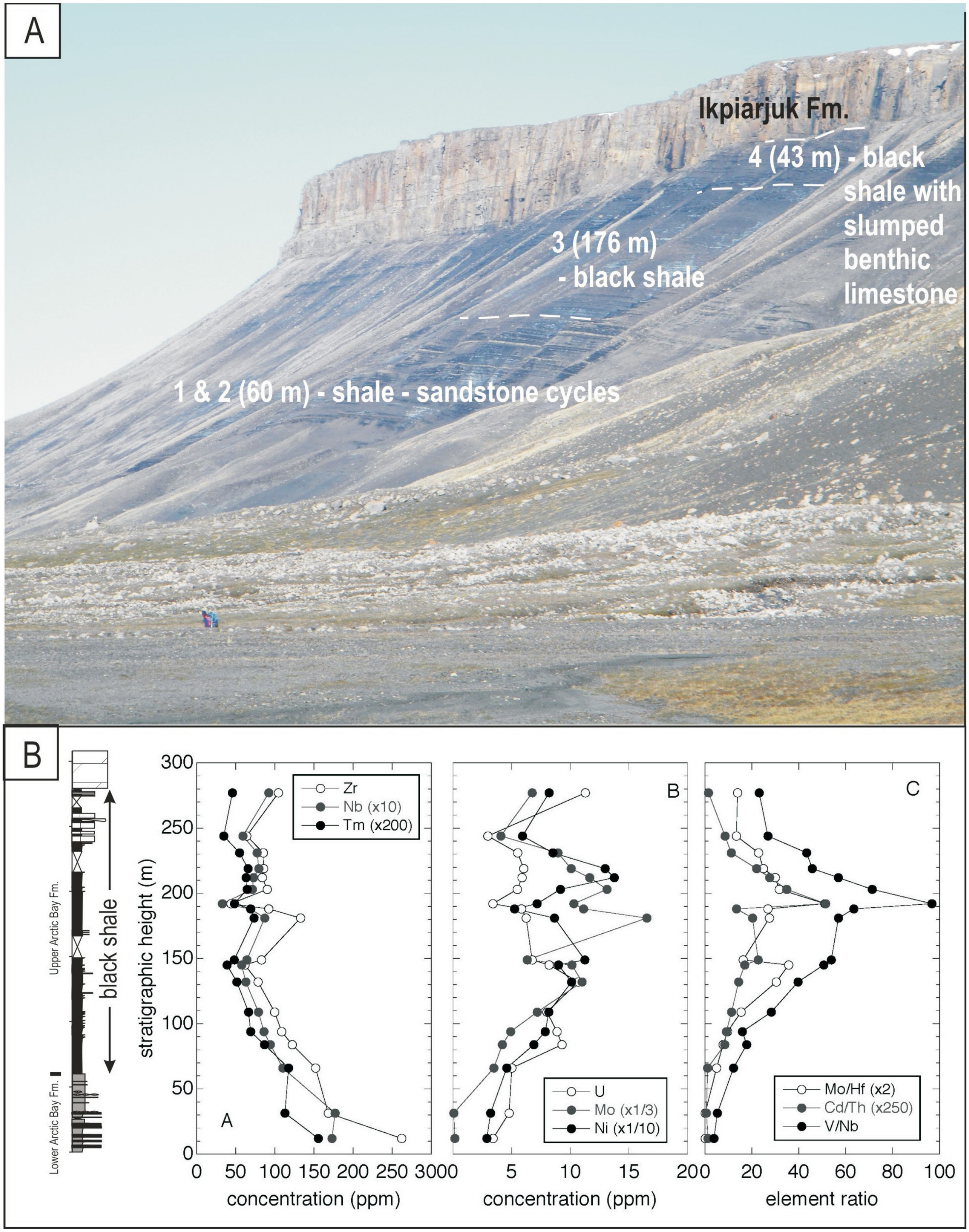

Figure 5. Unexplored black shale unit of the upper Arctic Bay Formation, northern Baffin Island, Nunavut: **a)** exposure in the northwestern part of the Milne Inlet graben (after Turner and Kamber, 2012); **b**) distribution of conservative trace elements, redox-sensitive metals and ratios of redox-sensitive elements to conservative elements, showing strong anoxia in the middle part of the black shale succession; this condition is highly favourable for the development of sedimentary-exhalative–type base-metal mineralization.

(Figure 6). More critically, the results for some FIAs also demonstrated that, in some cases, fluid-inclusion Th had been reset (i.e., their Th increased) in the vicinity of the crosscutting 'mine dike' (Heaman et al., 1992; Pehrsson and Buchan 1999; Denyszyn et al., 2009); previous studies had identified this trend (McNaughton and Smith, 1986; Arne et al., 1991), but later evidence (Sherlock et al., 2004) seemed to refute that conclusion. In addition, study of fluid-inclusion–solute composition, using a novel method of decrepitation followed by scanning electron microscope–energy dispersive spectrometry, showed that the mineralizing fluid was Na-rich and had a variable Ca-Mg content (the latter related to interaction of the fluid with the host-rock). Significantly, a population of K-rich fluids was found, which may explain the occurrence of 'white-rock' adularia that was dated at 461 Ma (Sherlock et al., 2004). The results show conclusively that the orebody predated intrusion of the 'mine dike' at ca. 720 Ma, which supports the exclusion of all younger rocks from involvement in the mineralizing event and refocuses exploration in the district onto Proterozoic strata only.

Re-Os dating of Nanisivik ore

Carbonate-hosted base-metal deposits are notoriously difficult to date and a range of techniques has yielded an array of generally conflicting dates (Mesoproterozoic to lower Paleozoic) for the mineralizing event at Nanisivik (Olsen, 1984; Christensen et al., 1993; Symons et al., 2000; Sherlock et al., 2004); the most recent of these studies provided an indirect date of ca. 461 Ma for the Nanisivik orebody (Sherlock et al., 2004). Rhenium-osmium dating of pyrite from the Nanisivik orebody as part of the Borden Basin project now provides the first direct date for the ore-forming event at Nanisivik: ca. 1100 Ma (Hnatyshin et al., 2011; Hnatyshin et al., work in progress). This Mesoproterozoic date indicates that the mineralizing event could not have affected Paleozoic rocks, as had been previously implied by a much younger, indirect date (Sherlock et al., 2004). Furthermore, the new date implies that the fluid-flow event that was responsible for the Nanisivik orebody coincided with assembly of the supercontinent Rodinia and the Grenvillian orogeny. Further sedimentological and stratigraphic studies currently underway will shed light on the regional tectonic events that triggered the movement of the mineralizing fluid.

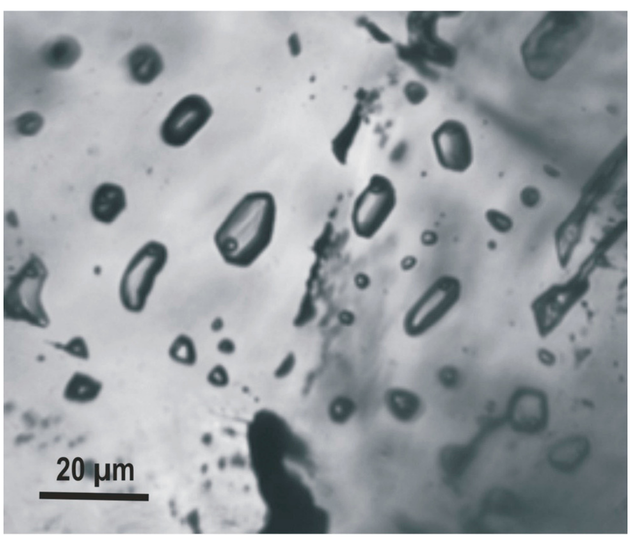

Figure 6. Infrared (1100 nm) image of a fluid-inclusion assemblage (FIA) of aqueous, saline fluid inclusions (~20 wt. % NaCl equivalent) in sphalerite from Nanisivik ore of the Borden Basin, northern Baffin Island, Nunavut. The low vapour-to-liquid ratio indicates a comparatively low homogenization temperature (<100 °C), as confirmed by microthermometry.

Sedimentology and uranium potential of basal siliciclastic units in the Bylot basins

Fieldwork undertaken during the earliest stages of investigation of the Bylot basins in the 1970s (Jackson and Iannelli, 1981) concluded that a significant proportion of the basal siliciclastic-dominated succession in the Borden Basin had been deposited in subaerial (flood basalt) and fluvial (quartz arenite) environments, and that the Bylot basins preserved a stratigraphic succession that had been deposited in a succession of extensional and tectonically quiescent settings, which represented aulacogens that opened onto a paleo-ocean located to the north-northwest in present-day co-ordinates (Jackson and Iannelli, 1981). New field data indicate instead that basalt of the Nauyat Formation was predominantly of marine origin and architectural analysis of siliciclastic units near the base of the successions in three of the Bylot basins (Long and Turner, 2012) showed that these strata were deposited almost exclusively in marine environments. The lowest strata in the basins have regionally consistent characteristics and exhibit no thickness, paleocurrent or compositional features that would indicate deposition in aulacogenic rifts (Figure 7). Instead, these strata were deposited in a regional basin, which may have been of transtensional origin and which evolved into a rift-like setting that predominated throughout deposition of the middle part of the succession (Turner, 2009; 2011; Turner and Kamber, 2012), ending with pronounced uplift after deposition of the Nanisivik Formation and laterally equivalent Angmaat Formation (Turner, 2011).

The quartzose strata that form the basal parts of the stratigraphic successions in the Bylot basins are generally compositionally mature (lack significant feldspar) and are quartz cemented. These attributes indicate that the rocks would have had little potential to develop significant porosity during their diagenetic histories and, therefore, that their potential to contain unconformity-type U deposits is low.

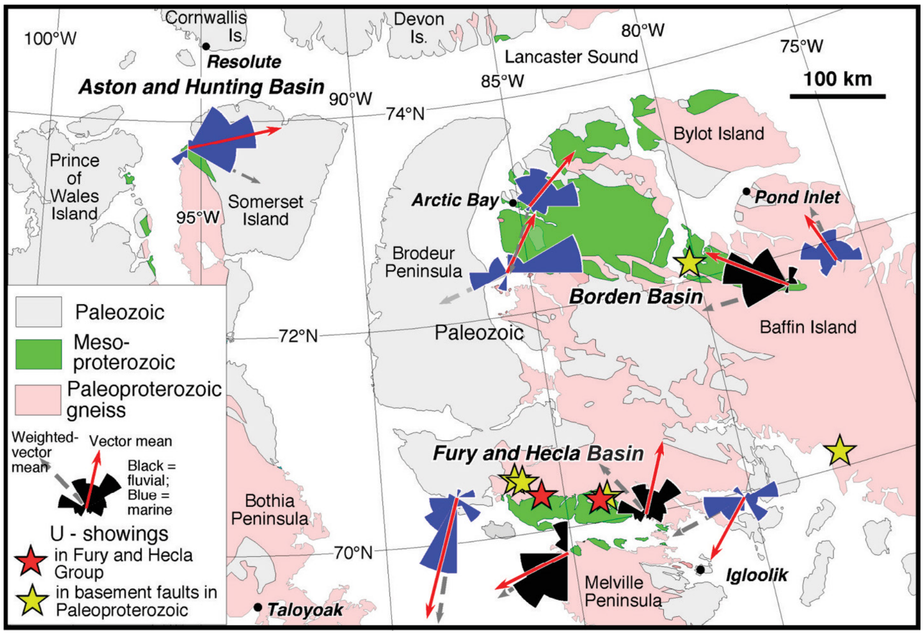

Figure 7. Map of the Bylot basins, northern Baffin Island, Nunavut, with paleocurrent rose diagrams representing the terrigenous clastic units in the lowermost parts of their respective stratigraphic successions (after Long and Turner, 2012). The paleocurrent data do not show evidence of rift-like basin configurations for the early history of the basins.

Field season 2012

Ikpiarjuk Formation vent mounds

This Ph.D. research project addresses the origin of peculiar, extremely large (hundreds of metres thick and kilometres long) deep-water carbonate mounds that developed along intragraben faults during deposition of the Arctic Bay Formation's black shale interval (Figures 1, 3, 5a; Turner, 2004; Hahn and Turner, 2012a, b, in press). The black shale shows geochemical evidence of an anoxic deep-water environment that would have favoured SEDEX mineralization had vent sources of dissolved metals been present (Figure 5b; Turner and Kamber 2012). Study of vent-related carbonate strata may help to illuminate the geochemical evolution of the basin's water during the interval of black shale deposition.

Two field seasons have been completed for this study (total of 11 weeks of fieldwork; 5 sites covered in 2011 and 2012). Fieldwork consisted of the measurement of stratigraphic sections, detailed descriptions of mound lithofacies and their relationships with enclosing strata, and collection of samples for later geochemical analysis. All significant field exposures of the mounds have now been sampled and described, and the three-dimensional relationship of mound facies with enclosing strata established. Samples from the 2011 season were slabbed and 80 thin sections were prepared. All thin sections have been described and a subset selected for geochemical analyses (rare earth elements [REEs] and stable C and O isotopes). Laser-ablation inductively coupled plasma–mass spectrometry (LA-ICP-MS) has been used on specific phases in 20 thin sections to analyze REEs and major elements, and is ongoing. Samples from the 2012 field season have been slabbed and submitted for thin-section preparation. Analyses of REEs and major elements will be completed on this sample set in 2013. The results of the 2011 field season were presented at a poster session (Carbonates in Rifts) at the April 2012 American Association of Petroleum Geologists conference held in Long Beach, California (Hahn and Turner, 2012a), and mound lithofacies are the subject of a forthcoming GSC Current Research paper (Hahn and Turner, in press).

Geochronology of the Bylot Supergroup

The tectonostratigraphic history of the Borden Basin, as once construed, included initial aulacogenic rifting, quiescence and passive margin, and eventually renewed rifting (Jackson and Iannelli, 1981). This interpretation has now been replaced with a considerably more complex history (Figure 2). Initial development of a possibly transtensional basin (Nauyat and Adams Sound formations; Long and Turner, 2012) was followed by a markedly extensional phase associated with waning siliciclastic sedimentation, development of deep, asymmetric grabens and eventual development of thick, structurally controlled carbonate deposits (Arctic Bay–Iqqittuq–Ikpiarjuk, Nanisivik–Angmaat and Fabricius Fiord formations). Pronounced, differential, regional uplift, erosional denudation, and local block faulting, recorded in an unconformity that developed after deposition of the Nanisivik and Angmaat formations

(Turner, 2009, 2011), were followed by differential marine inundation and carbonate-ramp development, and eventually uplift and karst formation in one part of the basin associated with coeval drowning in another (Sherman et al., 2002). The final phase of basin evolution is recorded by >2 km of predominantly siliciclastic rocks, which are characterized by variable paleocurrent orientations (Knight and Jackson, 1994) and marine paleoenvironments that evolved from flysch-like deep-water siltstone to shallow-marine quartzose sandstone.

The new Re-Os pyrite date for the mineralizing event at Nanisivik (Hnaytshin et al., 2011, work in progress) indicates that the development of the Nanisivik orebody, and possibly the Borden Basin Zn district as a whole, was coeval with the assembly of Rodinia. Understanding the event that drove late Mesoproterozoic mineralizing fluids in the Borden Basin is critical to determining the economic potential of both the Borden Basin and the other basins in the Bylot-basin group. Characterizing the basin's evolution will also shed light on this area's position in Rodinia: the relative disposition of continental masses within Rodinia remains contentious, and the position and tectonic status of northern Laurentia during this time are especially enigmatic. The related issues of basin evolution and metallogeny may be investigated through the evolving sediment provenance of the basin, which records the regional dynamics of the evolving interior of the supercontinent under assembly.

The succession of stratigraphic events and depositional environments recorded by the Bylot Supergroup in the Milne Inlet graben of the Borden Basin is now reasonably well understood, and so a component of fieldwork in 2012 focused on the collection of material for a detailed detrital zircon analysis of the entire Bylot Supergroup in the Borden Basin. The detrital zircon sample suite is currently being prepared and will be analyzed at Laurentian University's chemical fingerprinting LA-ICP-MS lab.

In the course of fieldwork, it became evident that the Mesoproterozoic geology of the area now occupied by Sirmilik National Park is not accurately depicted by the existing compilation map (Scott and deKemp, 1998); the establishment of the park clearly predated an adequate understanding of the distribution of bedrock units that underlie much of the area now encompassed by the park boundaries.

Future work

Subprojects of the Borden Basin endeavour have recently produced results that characterize the mineralizing fluid at Nanisivik and highlight the area's high economic potential for carbonate-hosted Zn mineralization; a fluid-inclusion and trace-element study to characterize the regional metallogeny will be an appropriate addition to the research program in the near future. The tectonostratigraphic history and economic potential of the other Bylot basins (Fury and Hecla, Aston and Hunting, and Thule) remains poorly known and should be addressed with field mapping, sediment provenance, and stratigraphic and geochemical studies.

Economic considerations

All stratigraphic units in the Borden Basin remain underexplored. Work to date indicates strong potential for carbonate-hosted Zn in two specific tectonostratigraphic settings (Turner, 2011): near the top of Nanisivik Formation dolostone in the Milne Inlet graben, beneath both buried and erosionally removed paleo-highs in the unconformity surface, and low in the Iqqittuq Formation, near graben-bounding faults. Geophysical and geochemical methods may be required to search for blind deposits in the prospective areas. The geographic extent of the relevant zones spans areas both within and outside Sirmilik National Park.

The potential for SEDEX-type mineralization in black shale of the Arctic Bay Formation remains unknown, but most of the preconditions known to be necessary for synsedimentary exhalative–type sulphide deposition were present (Turner and Kamber, 2012); further work should be done to understand the potential of this unit beyond the single location addressed by the recent study. Work in several of the Bylot basins suggests that siliciclastic units near the base of the successions probably have low potential for unconformity-type U owing to the composition and diagenetic history of the terrigenous clastic units.

Acknowledgments

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Hall Peninsula regional bedrock mapping, Baffin Island, Nunavut: summary of fieldwork

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Abstract

This study is part of the Canada-Nunavut Geoscience Office's Hall Peninsula Integrated Geoscience Program, a multiyear bedrock and surficial geology mapping program with associated thematic studies. Bedrock mapping in 2012 refined previously delineated packages (from oldest to youngest): the Hall Peninsula orthogneiss, the Lake Harbour Group and the Cumberland Batholith (St-Onge et al., 2006). Field observations summarized in this report will form the basis of the legend for new 1:250 000 scale maps of the peninsula. Thematic studies focusing on regional tectonics, metamorphism, structure, geochronology and igneous activity (volcanic and/or plutonic) associated with metasedimentary packages have been initiated by university and government partners involved in the project.

The discovery of ultramafic rocks within supracrustal packages points to possible new sources of carving stone for Nunavummiut, as well as potential for nickel–copper– platinum-group element (PGE) mineralization. The large area underlain by tonalite orthogneiss is prospective for diamond-bearing kimberlites, similar to those found in the northern portion of the peninsula. Based on the reported geology, other types of mineralization can also be considered, such as gold associated with iron formation and volcanogenic massive sulphide (VMS) deposits associated with supracrustal packages.

Résumé

Cette étude fait partie du Programme géoscientifique intégré de la péninsule Hall, du Bureau géoscientifique Canada-Nunavut, un programme pluriannuel de cartographie du substratum rocheux et de la géologie de surface accompagnée d'études thématiques connexes. La cartographie du substratum rocheux en 2012 a apporté des raffinements à la représentation des assemblages précédemment définis (du plus ancien au plus récent) : l'orthogneiss de la péninsule Hall, le Groupe de Lake Harbour et le batholite de Cumberland (St-Onge et al., 2006). Les observations de terrain résumées dans ce rapport constitueront la base de la légende pour de nouvelles cartes de la péninsule au 1/250 000. Les études thématiques portant sur le volet régional de la tectonique, du métamorphisme, de la structure, de la géochronologie et de l'activité magmatique (volcanique ou plutonique) associée à des assemblages métasédimentaires ont été entreprises par les partenaires universitaires et gouvernementaux du projet.

La découverte de roches ultramafiques au sein d'assemblages supracrustaux pointe vers d'éventuelles et nouvelles sources de pierre à sculpter pour les Nunavummiut, et vers un potentiel de minéralisation en nickel, cuivre et éléments du groupe du platine (ÉGP). La grande région reposant sur un orthogneiss tonalitique pourrait contenir des kimberlites diamantifères, semblables à celles que l'on observe dans la partie nord de la péninsule. En se basant sur l'information géologique obtenue à date, on entrevoit la présence possible d'autres types de minéralisation, tel que l'or associé à la formation de fer et les gisements de sulfures massifs volcanogènes (SMV) associés à des assemblages supracrustaux.

Introduction

The Hall Peninsula Integrated Geoscience Program (HPIGP) is being led by the Canada-Nunavut Geoscience Office in collaboration with the Government of Nunavut, Aboriginal Affairs and Northern Development Canada, Dalhousie University, University of Alberta, Université Laval, University of Manitoba, University of Ottawa, University of Saskatchewan, Nunavut Arctic College and the Geological Survey of Canada. It is supported logistically by several local, Inuit-owned businesses. The study area comprises all or parts of six 1:250 000 scale National Topographic System map areas north and east of Iqaluit (NTS 025I, J, O, P, 026A, B).

In the summer of 2012, fieldwork was conducted in the southern half of the peninsula (NTS 025 I, J, O, P) between June 22 and August 8. Fieldwork was supported by a 20–25 person camp located approximately 130 km southeast of Iqaluit. The focus was on bedrock mapping at a scale of 1:250 000 and surficial-sediment mapping at a scale of 1:100 000. A range of thematic studies was also supported. This included Archean and Paleoproterozoic tectonics, geochronology, landscape uplift and exhumation, detailed mapping in mineralized areas, microdiamonds, sedimentary rock xenoliths and permafrost. Summaries and preliminary observations for all of these studies can be found in this volume.

Although geological investigation of Hall Peninsula dates back to Frobisher's 1576 voyage, the peninsula has only been mapped once previously, at reconnaissance scale, during the Geological Survey of Canada's Operation Amadjuak (Blackadar, 1967). Subsequently, detailed mapping of a narrow transect in the northern part of NTS area 025O was carried out by Scott (1996), who sampled the main rock types for U-Pb geochronology (Scott, 1999). This information was incorporated into a compilation map (St-Onge et al., 2006), which divided the peninsula into three packages: the Archean Hall Peninsula block (tonalitic gneiss, monzogranite and minor supracrustal rocks), the Paleoproterozoic Lake Harbour Group (semipelite, psammite and minor marble), and the Paleoproterozoic Cumberland Batholith (amphibolite- to granulite-grade monzogranite). Recent geological work on Hall Peninsula has focused on diamondiferous kimberlites and surrounding rocks of the Chidliak kimberlite field (Ansdell et al., 2012; Heaman et al., 2012; Pell et al., 2012) in the northern part of the peninsula.

In preparation for field mapping, airborne aeromagnetic data was acquired in 2009 at an altitude of 120 m and 400 m line spacing (Dumont and Dostaler, 2010a–l). During the summer of 2012, six weeks from the end of June to the beginning of August were devoted to mapping the southern portion of the peninsula (NTS areas 025P, I and parts of 025O, J), an area of approximately 20 000 km^2 (Figure 1). Work was completed using foot and helicopter traverses by a 15-person bedrock geological crew. Due to terrain morphology, paucity of outcrop or distance from camp, some areas were only mapped by helicopter hopping. The western portion of the map area is characterized by a gently undulating topography with scarce vegetation and a few barren hills. The north-central part of the area is relatively lake free with widespread drift and felsenmeer. Altitude increases toward the east, where hills are capped by numerous small ice fields. The east coast, eastern islands and Loks Land in the south are more rugged and mostly free from vegetation and drift cover.

During the course of the fieldwork, thematic studies focusing on regional tectonics, metamorphism and structure (Skipton et al., 2013; From et al., 2013; Braden et al., 2013); geochronology (Rayner et al., 2013); and igneous activity (volcanic and/or plutonic) associated with metasedimentary packages (MacKay et al., 2013) were initiated by university and government partners. These studies will bring added resolution and enable quantification of the geological history of the peninsula.

General geology

Bedrock mapping in 2012 revealed that southern Hall Peninsula is underlain by two broad lithological domains (Figures 1, 2): an eastern domain, which includes tonalite gneiss with subordinate amphibolite-pelite panels and rare marble; and a western domain, consisting of metasedimentary rocks, including marble, that are intruded by garnet monzogranite and charnockite. The wide contact zone between these domains is pervasively intruded by charnockite and tonalite such that the contact is obscured.

The two lithological domains and contact zone are well reflected in the aeromagnetic signature of Hall Peninsula (Figure 2), the eastern domain being characterized by mottled, moderate low and high magnetic susceptibility with both northeast and northwest trends. The distinct magnetic high in the eastern domain corresponds to a magnetite-bearing monzogranite that cuts the tonalite gneiss. The western domain is characterized by wide swaths of low magnetic susceptibility punctuated by north-northwest-trending, narrow magnetic highs and ovoid patterns reflecting either doubly plunging folds or fold-interference patterns. The distinctly high magnetic susceptibility in the contact zone likely reflects magnetite formation during retrogression of orthopyroxene-bearing rocks (Figure 2). Given that all units except late mafic dikes have been metamorphosed, the prefix 'meta-' prior to the protolith name has been omitted for clarity.

Some crystalline rock units in the area, suspected to be basement, record at least three phases of deformation and appear to have been initially metamorphosed to granulite facies. These rocks are now retrograded to middle amphibolite facies, the predominant metamorphic facies for most map units on Hall Peninsula (Skipton et al., 2013).

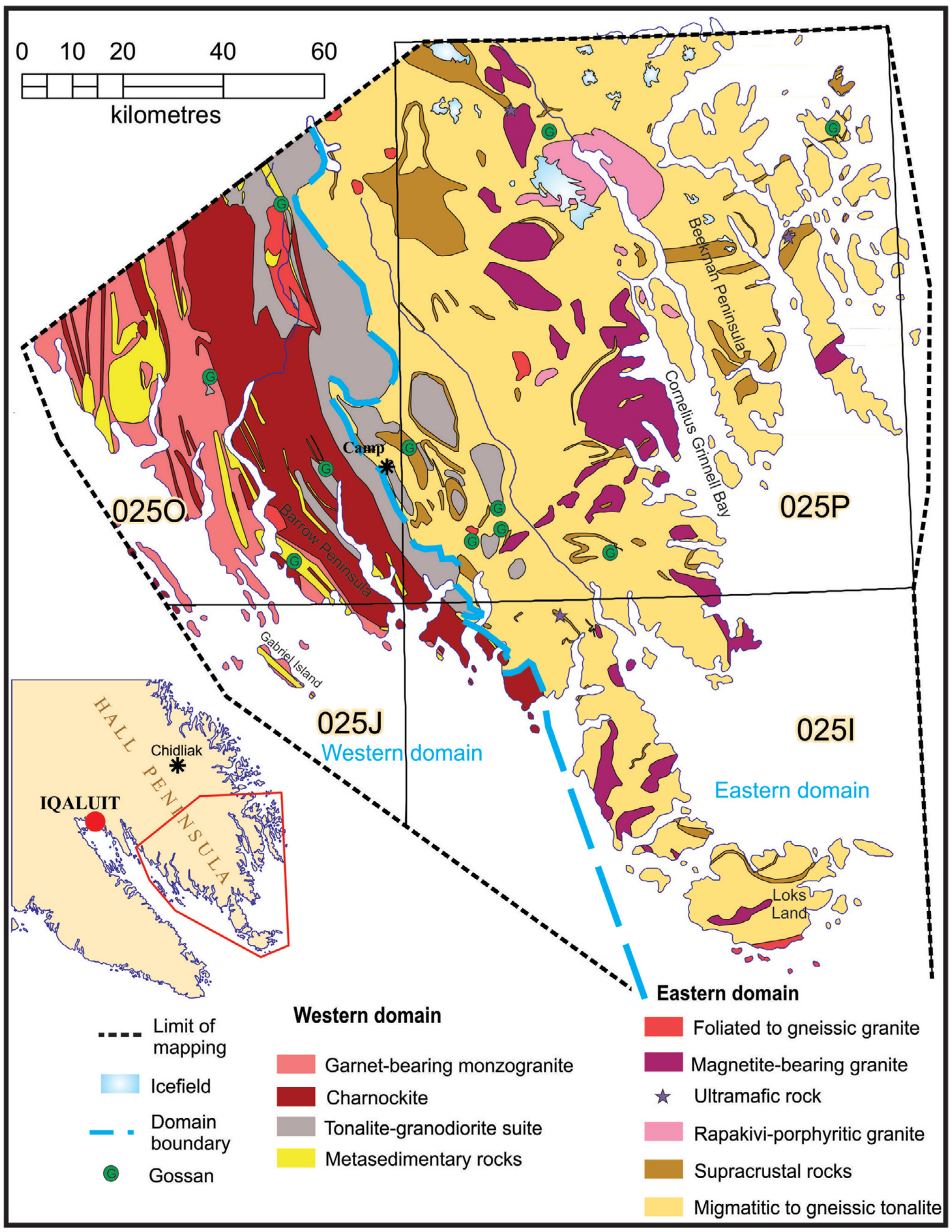

Figure 1: Simplified geology of southern Hall Peninsula based on 2012 mapping.

Eastern domain

Migmatitic to gneissic tonalite

Migmatitic to gneissic tonalite underlies most of NTS areas 025P and I and is the structural and/or depositional crystalline basement to other rock types in the eastern portion of the peninsula (Figure 1). The tonalite has a grey colour and contains numerous, partly resorbed, amphibolite enclaves (Figure 3a). A dominant foliation is defined by the alignment of hornblende and biotite, whereas the gneissic layering comprises alternating bands of leucocratic and melanocratic minerals. Migmatitic tonalite is characterized by biotite schlieren and garnetite-amphibolite restite, and also contains sillimanite-bearing leucosome. In some areas, the tonalite tends toward a more granodioritic composition.

Supracrustal rocks

In NTS areas 025P and I, sequences of rusty-weathering supracrustal rocks either overlie or occur as imbricate panels (20 cm to 2 km wide) with the tonalite described above (Figure 1). The supracrustal units comprise mainly psammite (Figure 3c), semipelite and pelite alternating with amphibolite and diorite sills and/or equivalent metamorphosed volcanic rocks (Figure 3b). Thin beds of grunerite-rich banded iron formation, quartzite and rare calcsilicate (marl) are locally observed, but these are minor components of the eastern supracrustal sequence. The overall rusty weathering colours of these rocks make them easily distinguishable from the tonalite.

Rapakivi-porphyritic granite

A large, moderately deformed, porphyritic granite pluton, centred on the head of Cornelius Grinnell Bay (NTS 025P),

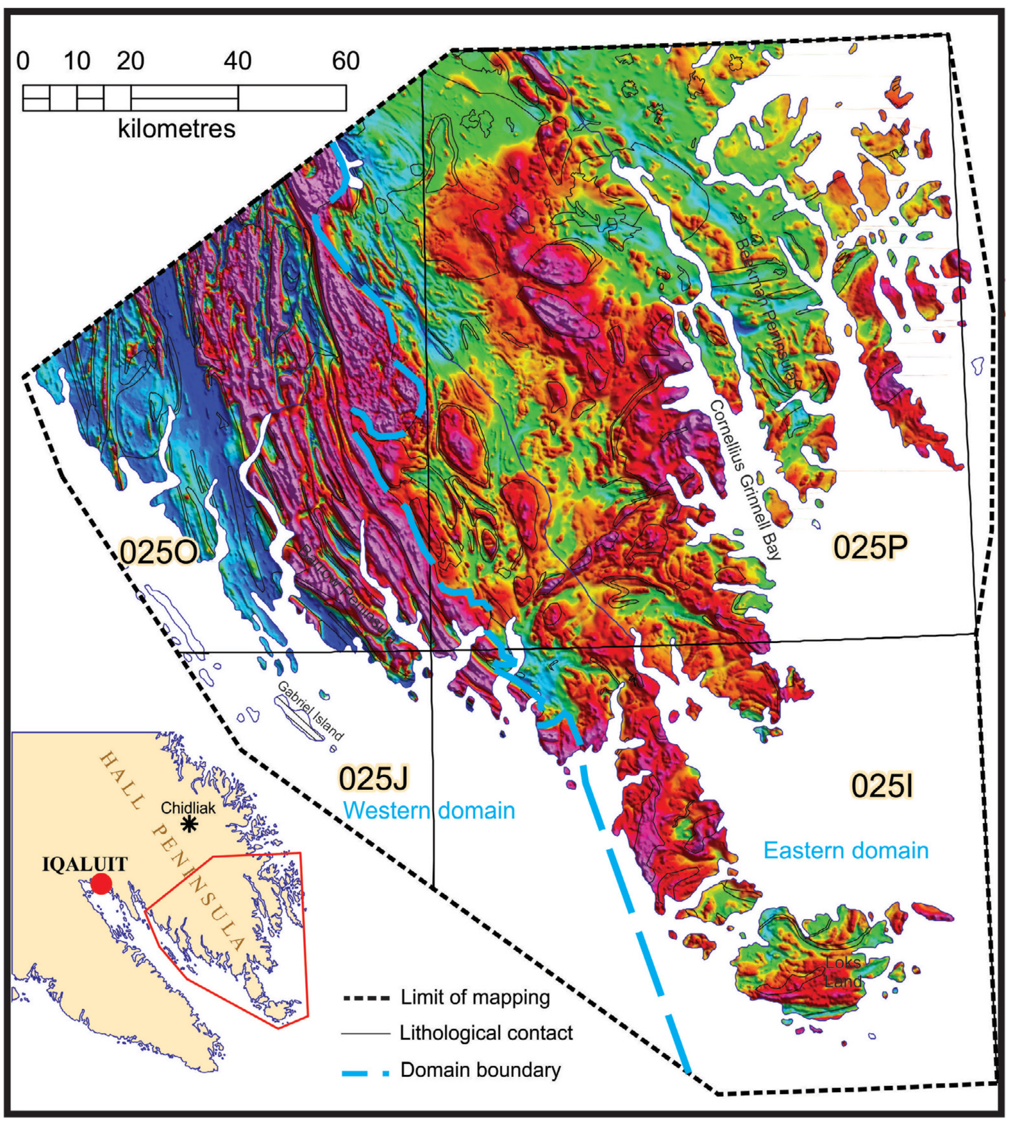

Figure 2: Total-field magnetic susceptibility of southern Hall Peninsula (Dumont and Dostaler, 2010a–l), highlighting defined domains and trends reflected in the bedrock geology.

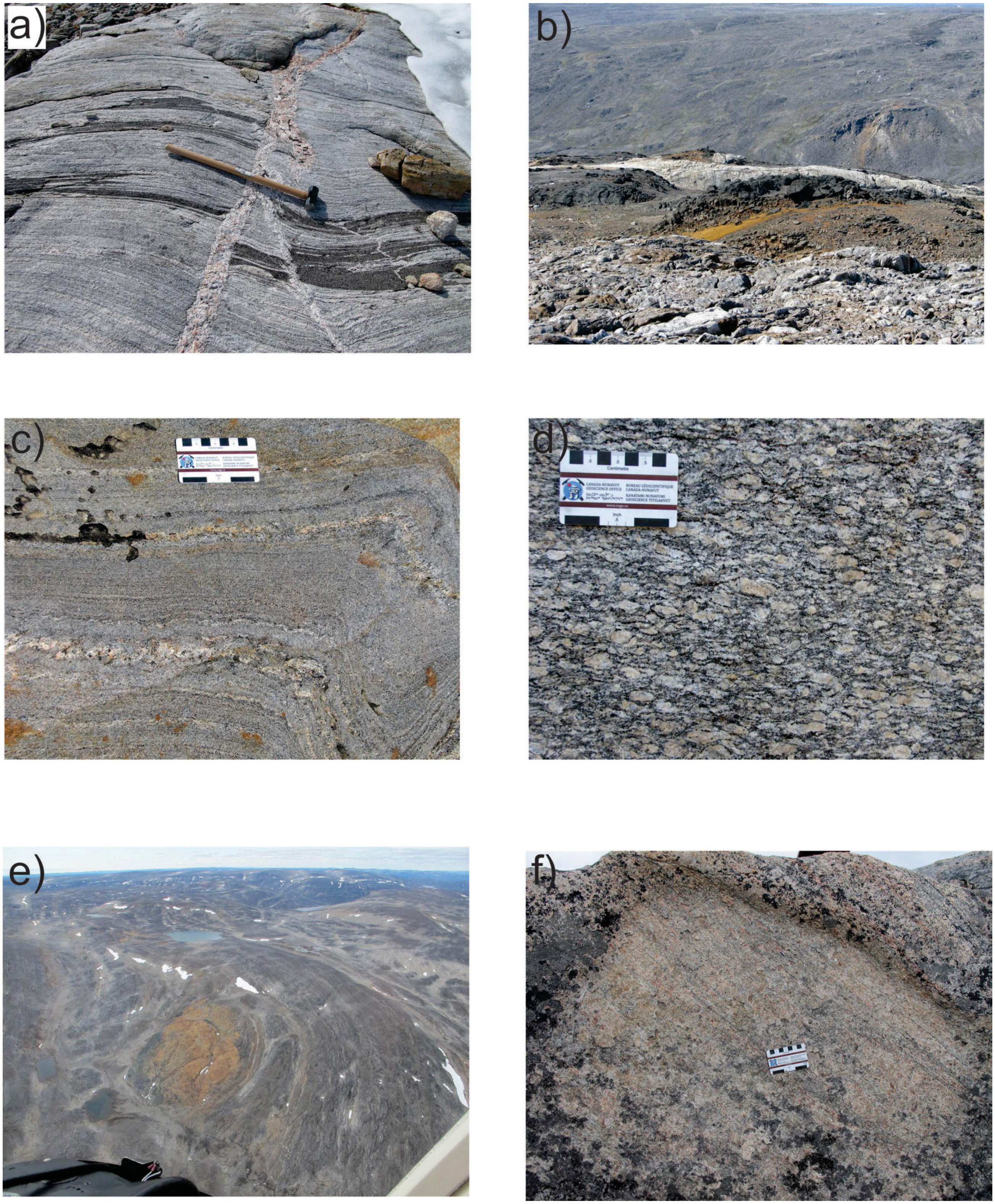

Figure 3: a) Gneissic tonalite with resorbed amphibolite enclaves crosscut by pegmatite dikes. **b)** Psammite (foreground) and dark-green–weathering amphibolite (midground) cut by pegmatite. **c)** Grey-weathering paragneiss of psammitic composition. **d)** Rapakivi granite. **e)** orange-brown–weathered ultramafic intrusion into supracrustal rocks of the eastern domain. **f)** Foliated magnetite-bearing granite.

intrudes the gneissic tonalite and associated supracrustal units described above (Figure 1). This unit contains diorite and amphibolite enclaves, and is characterized by rapakivi texture in which potassic-feldspar phenocrysts are mantled by plagioclase (Figure 3d) and porphyritic or megacrystic textures. In some more highly strained areas, it is characterized by an augen gneiss texture. A few smaller satellite plutons of rapakivi granite also occur in the eastern domain.

Ultramafic rock

A number of ultramafic bodies were mapped in the eastern domain (Figure 1). These comprise peridotite occurring both as xenoliths within the gneissic tonalite and as boudinaged sills within the supracrustal rocks, suggesting more than one ultramafic event. The peridotite is, in large part, metamorphosed to serpentinite, is deep green on a fresh surface and weathers a distinctive brownish-orange (Figure 3e).

Magnetite-bearing granite

A felsic intrusive suite dominated by magnetite-bearing granite is exposed across the eastern domain (Figure 1). This suite is characterized by a high aeromagnetic signature (Figure 2) that correlates with the presence of magnetite and differentiates it from the gneissic tonalite and other rocks of the region. This suite is dominantly granitic and locally dioritic. The granite often contains enclaves of amphibole-biotite diorite, amphibolite or metasedimentary rocks. Outcrops are either massive or weakly foliated (Figure 3f) and strongly lineated. The granite is intrusive into the gneissic tonalite and rapakivi granite. Locally it is porphyritic (potassic-feldspar phenocrysts) and contains garnet.

Foliated to gneissic granite

A suite of spaced granite plutons occurs in both the eastern and western domains. The plutons are distinct from the other plutonic map units described here. They are usually foliated to gneissic and contain biotite-hornblende. Some of them are fine grained and hematized. In the southern Loks Land area, they are more leucocratic and intrude the gneissic metatonalite.

Western domain

Metasedimentary rocks

Several thick panels of metasedimentary rocks, which are correlated with the Lake Harbour Group of southern Baffin Island (St-Onge et al., 2006), occur in NTS areas 025O and J, and less commonly in 025P and I. They consist of biotite-garnet-sillimanite semipelite, psammite and pelite, and tend to weather a rust colour (Figure 4a). Minor marble (Figure 4c), quartzite (Figure 4b) and silicate iron formation are also found.

Tonalite-granodiorite suite

A felsic intrusive suite with a tonalitic to granodioritic composition was mapped at the boundary between the eastern and western domains (Figure 1). It is intrusive into both domains but is intruded by the garnet-bearing monzogranite (below). The tonalite-granodiorite weathers brown and contains variable amounts of biotite, orthopyroxene and magnetite.

Charnockite

A large charnockite body, possibly part of the Cumberland Batholith, is present in NTS areas 025O, 025I and 025J. It is usually intrusive into metasedimentary units (Figure 4c) that are correlated with the Lake Harbour Group and is, in turn, intruded by the garnet-bearing monzogranite (below) with which it forms alternating bands of rusty-white and brown rocks in the field. The hornblende-biotite charnockite has a greasy green fresh surface and an orange-brown–weathering one, and contains local mafic enclaves and/or garnet. The charnockite is generally very friable in outcrop.

Garnet-bearing monzogranite

A biotite-garnet monzogranite intrudes the charnockite and sedimentary rocks correlated with the Lake Harbour Group. It contains up to 20% red-brown to lilac garnet (Figure 4d) and weathers a distinct, patchy, rusty-white pattern. The amount of garnet increases when it contains enclaves of metasedimentary rocks (Figure 4a). The granite locally contains graphite associated with lilac garnets. As initially interpreted by Scott (1996, 1999), close association between supracrustal rocks and the garnet-bearing monzogranite suggests it is the product of partial melting of clastic rocks of the Lake Harbour Group.

Other rock types

The youngest rock types in the area, subophitic diabase of the Franklin swarm and pseudoleucite lamprophyre dikes (Figure 4e), are too thin to be displayed on a 1:250 000 scale map, but represent probably the last magmatic events in the area because they are undeformed and unmetamorphosed. They are found in a number of localities in the Hall Peninsula Block and individually are usually less than 5 m thick. Lamprophyre could be related to the Chidliak kimberlite province (Pell et al., 2012) that occurs in the northern part of the peninsula.

Implications for mineral exploration

Mineral exploration in the area began in 1577, when Martin Frobisher mined “black ores” in the Countess of Warwick Sound area during his second voyage and brought them back to London to be tested for gold and silver (Hogarth and Loop, 1986). In the late 20th century, following GSC Operation Amadjuak, mineral exploration for base and precious metals led to the discovery of a few copper showings.

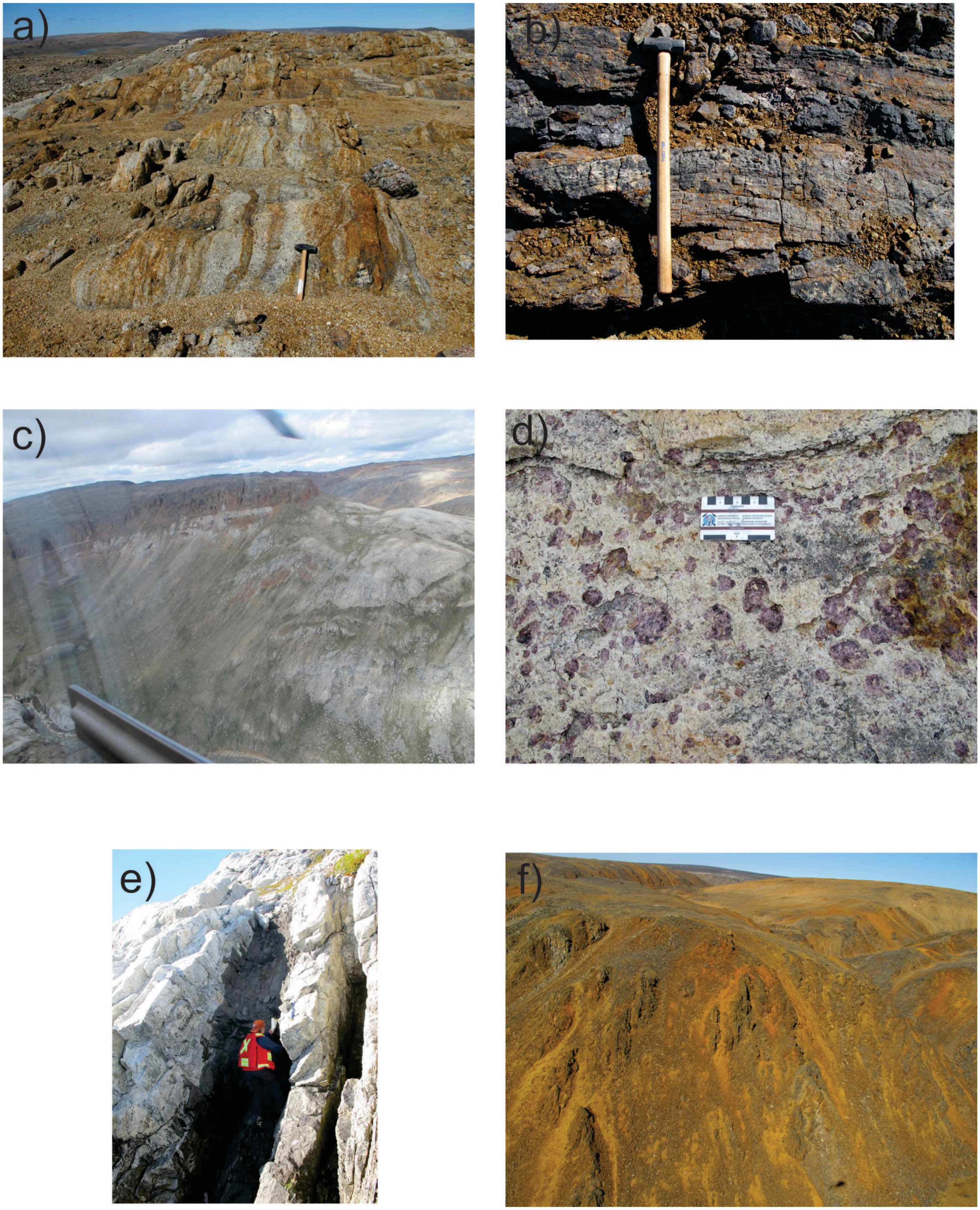

Figure 4: a) Garnet-bearing monzogranite intrusive into metasedimentary rocks. **b)** Thin bed of psammite and quartzite. **c)** Light grey–weathering marble unit capped by brown-weathering charnockite. **d)** Detail of lilac garnet in monzogranite. **e)** Lamprophyre dike intruding gneissic tonalite. **f)** Typical gossan found on eastern domain supracrustal rocks.

At the turn of the 21st century, exploration for diamonds resulted in the discovery of diamond-bearing kimberlites in the northern part of the peninsula (Pell et al., 2012).

Considering the overall geological context of Hall Peninsula, the potential for finding new occurrences of mineralization is multifaceted. The discovery of ultramafic rocks within supracrustal packages points to possibly interesting new sources of carving stone that may also have potential for nickel-copper-PGE mineralization. The large area underlain by crystalline basement (eastern domain) could be host to more diamond-bearing kimberlites. Also, marble correlated with the Lake Harbour Group has potential to host gemstones, as is the case in the Kimmirut area. Other possible types of mineralization include gold associated with iron formation and VMS deposits associated with supracrustal packages.

In the summer of 2012, about ten of the silicified gossans visited (Figures 1, 4f), containing disseminated pyrite and pyrrhotite in metasedimentary–amphibolite/diorite packages, were sampled for assay analysis. At the time this report was written, results were not yet available.

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Uranium-lead geochronological studies of Hall Peninsula, Baffin Island, Nunavut: contributions to mapping and tectonics

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Abstract

This study is part of the Canada-Nunavut Geoscience Office's Hall Peninsula Integrated Geoscience Program, a multiyear bedrock and surficial geology mapping program with associated thematic studies. Modern geological maps not only record lithological observations but incorporate interpretations on the nature of the protolith and the subsequent metamorphic, deformation and tectonomagmatic history. Precise, absolute age constraints are an essential component of modern mapping, as they aid in the calibration of the legend, strengthen regional correlations and place time brackets on tectonometamorphic events. A comprehensive uranium-lead geochronology research program is underway at the Geological Survey of Canada Geochronology Laboratory in support of new 1:250 000 scale geological maps of Hall Peninsula, Baffin Island, Nunavut.

Résumé

Cette étude fait partie du Programme géoscientifique intégré de la péninsule Hall, du Bureau géoscientifique Canada-Nunavut, un programme pluriannuel de cartographie du substratum rocheux et de la géologie de surface accompagnée d'études thématiques connexes. Les cartes géologiques modernes consignent non seulement les observations lithologiques, mais incorporent aussi des interprétations sur la nature du protolite et sur l'histoire du métamorphisme, de la déformation et du tectonomagmatisme ultérieurs. L'établissement de limites circonscrivant précisément l'âge absolu est une composante essentielle de la cartographie moderne, car de telles contraintes aident à étalonner la légende, elles renforcent les corrélations régionales et elles permettent de mieux situer dans le temps les événements tectonométamorphiques. Un programme exhaustif de recherche géochronologique U-Pb est en cours au Laboratoire de géochronologie de la Commission géologique du Canada à l'appui des nouvelles cartes géologiques à l'échelle de 1/250 000 de la péninsule Hall sur l'île de Baffin (Nunavut).

Introduction

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In the summer of 2012, fieldwork was conducted in the southern half of the peninsula (NTS 025 I, J, O, P) between June 22 and August 8. Fieldwork was supported by a 20–25 person camp located approximately 130 km southeast of Iqaluit. The focus was on bedrock mapping at a scale of 1:250 000 and surficial-sediment mapping at a scale of 1:100 000. A range of thematic studies was also supported. This included Archean and Paleoproterozoic tectonics, geochronology, landscape uplift and exhumation, detailed

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mapping in mineralized areas, microdiamonds, sedimentary rock xenoliths and permafrost. Summaries and preliminary observations for all of these studies can be found in this volume.

There exists a critical knowledge gap in our understanding of the geology and tectonic setting of Hall Peninsula. Reconnaissance helicopter mapping across the entire peninsula was undertaken in the mid-1960s by Blackadar (1967). Scott (1996) carried out more detailed mapping of a narrow corridor in the northwestern quadrant of the 2012 mapping area and provided the first modern geochronological constraints (Scott, 1999). The combined mapping and analytical studies of both of these workers led to the subdivision of Hall Peninsula into three lithotectonic domains (Figure 1). Farthest to the east is a domain of tonalitic gneiss, injected monzogranite and minor metasedimentary rocks. A central domain is inferred to correlate with the Paleoproterozoic Lake Harbour group of semipelite, psammite and minor marble (St-Onge et al., 2006). A western domain is composed largely of amphibolite- to granulite-grade monzogranites that were attributed to the Cumberland Batholith (Scott, 1996).

Existing geochronology of Hall Peninsula (Scott, 1999) indicates that the gneissic rocks of the eastern domain are ca. 2.92–2.80 Ga in age and that clastic units associated with the gneiss domain contain only Archean detritus. Detrital zircons recovered from samples from the central metasedimentary domain of Scott (1996) are almost exclusively Paleoproterozoic in age, with a maximum age of deposition of 1.93 Ga. Garnet±orthopyroxene–bearing monzogranites to the west yield ages of 1869–1850 Ma. These are interpreted to be a component of the Cumberland Batholith, a voluminous suite of 1.865–1.845 Ga, mainly granulite-facies, high-K to shoshonitic intracrustal granitoid rocks (Whalen et al., 2010). With the exception of late undeformed pegmatites, all units on Hall Peninsula have experienced pervasive tectonic reworking and have been subjected to thermal effects associated with the Trans-Hudson orogeny between the bounding Superior and Rae cratons.

During the 2012 field season, approximately 20 samples were identified and collected across the entire southern half of Hall Peninsula as potential geochronology targets (Figure 2). This regionally extensive and lithologically diverse suite of samples will contribute to the calibration of the bedrock map legend and enhance our understanding of three fundamental tectonic questions:

- **Delineation, characterization and correlation of Archean crystalline basement:** The assemblage of tonalite-granodiorite-monzogranite gneisses observed on eastern Hall Peninsula is complex, composed of multiple phases that have been strongly deformed and transposed (Figure 2a). A suite of samples encompassing a range of compositions and deformation states has been collected in order to characterize the phases of the gneiss complex. These results will allow testing of some of the proposed cratonic correlations in this region. St-Onge et al. (2009) proposed a link between the Archean gneisses of Foxe and Hall peninsulas and Archean units of the Aasiaat Domain of West Greenland. Alternative interpretations suggest a correlation with the basement of the North Atlantic craton (Corrigan et al., 2012).
- **Characterization and correlation of the supracrustal sequences:** Samples of clastic sedimentary rocks were collected for detrital zircon analysis to determine the maximum age of deposition, as well as to characterize their provenance signature. Outstanding questions include whether metasedimentary rocks within the eastern gneiss domain, commonly associated with amphibolite, are exclusively Archean in age or if units of Paleoproterozoic age are also present (Figure 2b). Comparisons of the provenance profiles of sediments across Hall Peninsula (Figure 2c) with similar datasets from Lake Harbour Group rocks on southern Baffin Island, Tasiuyak gneiss in Labrador (Scott and Gauthier, 1996; Scott, 1999) and possible equivalents in Greenland (Hollis, 2006; Thrane and Connelly, 2006) will contribute to the assessment of regional tectonostratigraphic correlations and associated paleogeographic implications.
- **Paleoproterozoic tectonomagmatic evolution:** Granitoid rocks in the west-central part of Hall Peninsula have been dated at 1.89 Ga and 1.865–1.845 Ga (Scott, 1999), the latter interpreted to belong to the Cumberland Batholith (Figure 2c; Whalen et al., 2010). Recent mapping to the north on Cumberland Peninsula has identified an assemblage of 1.90–1.88 Ga magmatic rocks, informally named the Qikiqtarjuaq suite (Sanborn-Barrie et al., 2011a–c; Rayner et al., 2012). Characterization of the geochemistry, distribution and age of Paleoproterozoic magmatic suites within the project area will shed light on the tectonomagmatic evolution of this segment of the Trans-Hudson Orogen. Constraints on Paleoproterozoic deformation will be provided by samples with clear crosscutting relationships to host rocks and structures (Figure 2d).

The entire suite of samples will also provide a framework for the more detailed work of the student theses. As appropriate, additional geochronological work may be undertaken to enhance the scientific scope of the student projects and provide training to these young researchers in innovative laboratory techniques. Results will be released to the public by the end of the project lifetime (March 2014) as internal reports and in the web-accessible Canadian Geochronology Knowledgebase. Preliminary results will be presented in poster and oral presentations at venues such as the Nunavut Mining Symposium, as they become available.

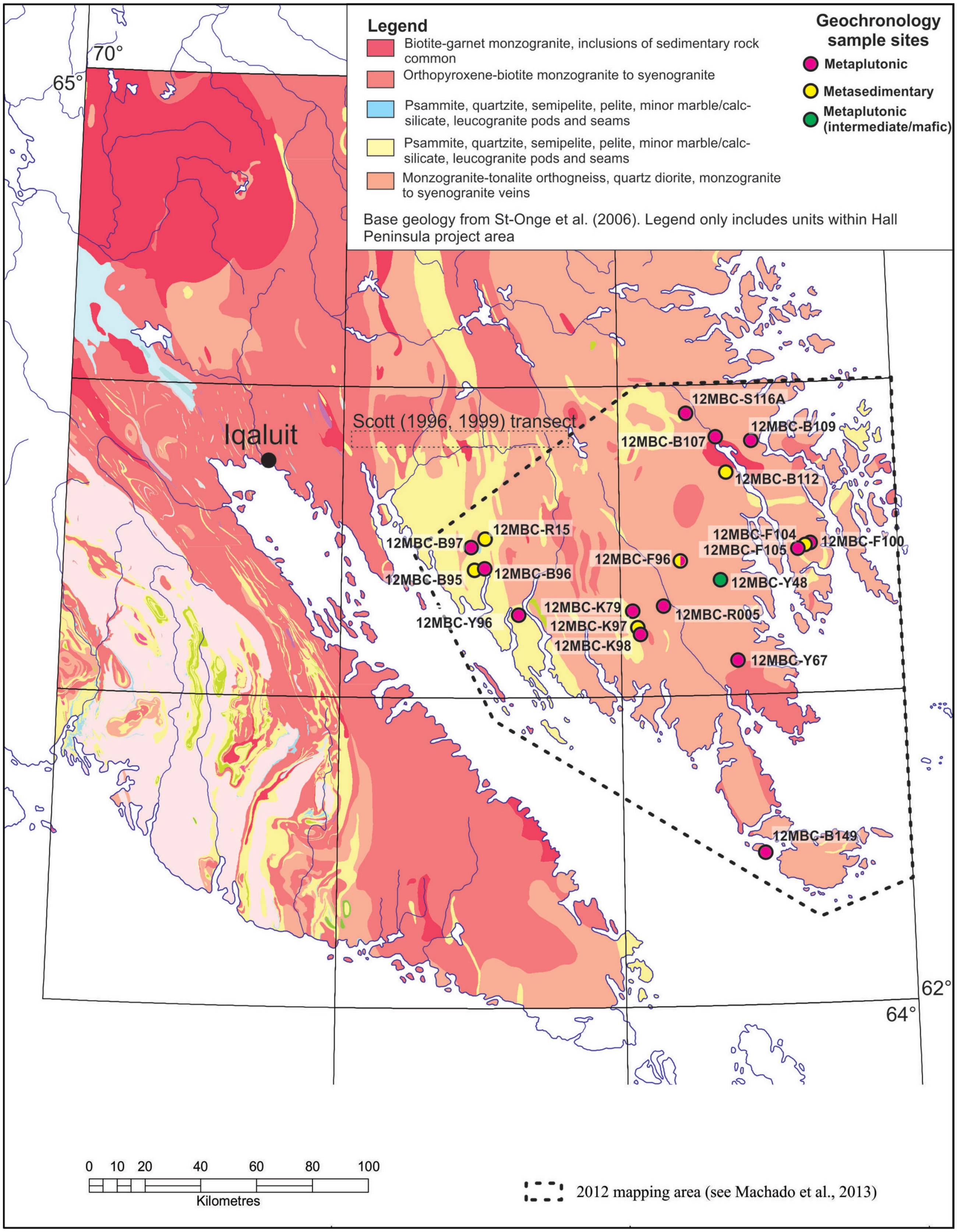

Figure 1: Simplified geology of Hall Peninsula, Baffin Island, Nunavut (from St-Onge et al., 2006). Samples to be assessed for geochronological analyses are shown, colour coded by broad rock type.

Economic considerations

U-Pb geochronology of a suite of well-constrained samples, in conjunction with recent mapping and geophysical surveys, will distinguish between Archean and Proterozoic supracrustal sequences and evaluate their metallogenic potential for precious metals, base metals and rare elements. Correlations with better known packages in Nunavut and elsewhere will be assessed. A better understanding of the Archean basement architecture and the effects of Paleoproterozoic reworking during the Trans-Hudson orogeny will provide a regional tectonic framework for the recent discoveries of diamond-bearing kimberlites on northern Hall Peninsula.

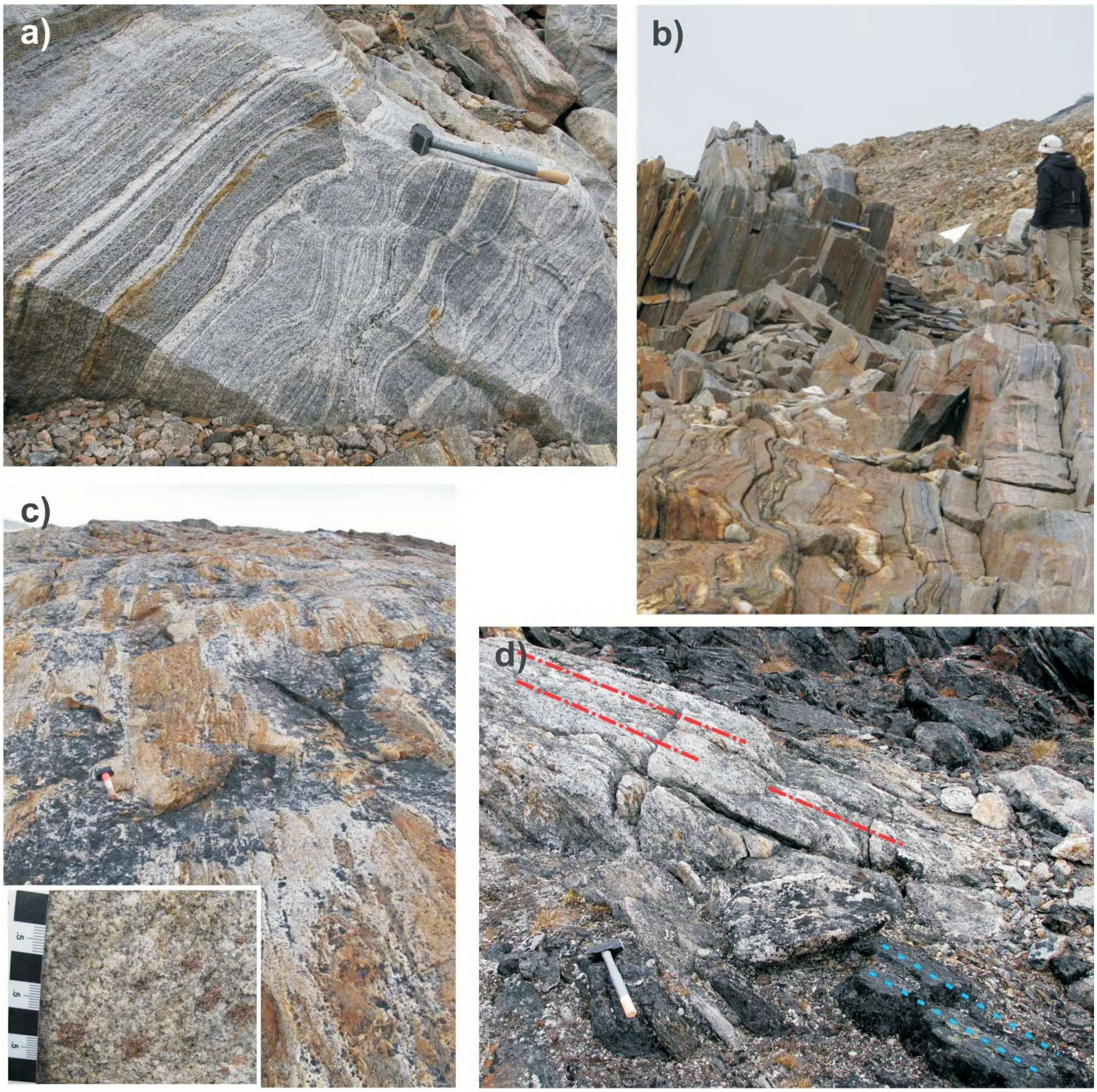

Figure 2: a) Representative photo of the strongly deformed, polyphase nature of the tonalite-granodiorite-monzogranite gneiss complex that dominates eastern Hall Peninsula; 45 cm hammer for scale. **b)** Extensive exposure of psammite associated with amphibolite and calcsilicate from eastern Hall Peninsula (12MBC-F104); geologist (approximately 180 cm) for scale. **c)** Representative photo of the western domain, proximal to 12MBC-R15; rusty rafts of semipelite are preserved in white-weathering monzogranite; 30 cm hammer for scale. Inset: detail of clusters of lilac garnet in white monzogranite; 1 cm scale card. **d)** Foliated, white-weathering monzogranite cutting a deformed amphibolite at station 12MBC-K79; age constraints on the monzogranite will provide a minimum age for the early deformation (dashed blue lines) in the amphibolite and a maximum age for subsequent deformation (red dot-dashed line) of the monzogranite; hammer (45 cm) for scale.

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Preliminary observations on Archean and Paleoproterozoic metamorphism and deformation of the southern Hall Peninsula, Baffin Island, Nunavut

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Abstract

This study is part of the Canada-Nunavut Geoscience Office's Hall Peninsula Integrated Geoscience Program, a multiyear bedrock and surficial geology mapping program with associated thematic studies. The Hall Peninsula on southeastern Baffin Island, Nunavut, is part of the Paleoproterozoic accretion/collision zone of Trans-Hudson Orogen. Reconnaissance-scale mapping and preliminary U-Pb geochronological work on the western Hall Peninsula has shown that it consists of Paleoproterozoic granitic plutons that intrude Paleoproterozoic metasedimentary rocks, and that the eastern Hall Peninsula is dominated by an Archean orthogneiss complex. The plutonic rocks have been considered correlative with the Cumberland Batholith, which composes much of southern Baffin Island. The metasedimentary units have been correlated with the Lake Harbour Group of the Meta Incognita microcontinent on southern Baffin Island and with the Tasiuyak gneiss in the Torngat Orogen of northern Labrador. The tectonic affinity of the Archean orthogneiss complex remains enigmatic but it has been linked with similar reworked Archean gneisses in the Nagssugtoqidian Orogen of West Greenland. Bedrock mapping (1:250 000) on southern Hall Peninsula, by the Canada-Nunavut Geoscience Office, in the summer of 2012 has revealed new insights into metamorphism and deformation, with implications for the tectonic history of the Hall Peninsula. Three regional deformational events are recognized: 1) an early east-directed thin-skinned thrusting event (D_1); 2) a subsequent east-directed thick-skinned thrusting event (D_2); and 3) a late, north-northwest– or south-southeast directed compressional event (D_3) characterized by large (2–7 km wavelength) folds that plunge shallowly to the west-southwest. The D_1 and D_2 deformational events are together responsible for the overall northwest-southeast trends in the map pattern of Hall Peninsula, both are characterized by west- to southwest-dipping penetrative foliation and northwest- or southeast-plunging fold axes and mineral lineations and both are accompanied by amphibolite-facies metamorphism. Evidence of an older granulite-facies metamorphic event predating both D_1 and D_2 is locally observed in the Archean gneisses. In order to resolve the nature and timing of metamorphism and deformation on Hall Peninsula, and implications for Paleoproterozoic tectonics within the Trans-Hudson Orogen, this report outlines the framework for a detailed pressure-temperature-time-deformation (P-T-t-d) analytical study.

Résumé

Cette étude fait partie du Programme géoscientifique intégré de la péninsule Hall, du Bureau géoscientifique Canada-Nunavut, un programme pluriannuel de cartographie du substratum rocheux et de la géologie de surface accompagnée d'études thématiques connexes. La péninsule Hall au sud-est de l'île de Baffin (Nunavut) fait partie de la zone d'accrétion/collision paléoprotérozoïque de l'orogène trans-hudsonien. La cartographie de reconnaissance et les travaux géochronologiques U-Pb préliminaires effectués dans l'ouest de la péninsule Hall ont établi qu'elle se compose à cet endroit de plutons granitiques paléoprotérozoïques qui font intrusion dans les roches métasédimentaires paléoprotérozoïques, et que l'est de la péninsule Hall est dominé par un complexe d'orthogneiss archéen. Les roches plutoniques ont été jugées corrélatives du batholite de Cumberland, dont se compose une grande partie de l'île de Baffin méridionale. Les unités métasédimentaires ont été mises en corrélation avec le Groupe de Lake Harbour du microcontinent Meta Incognita dans le sud de l'île de Baffin et avec le gneiss de Tasiuyak dans l'orogène de Torngat du nord du Labrador. L'affinité tectonique du

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complexe d'orthogneiss archéen n'est toujours pas résolue, mais elle a été associée aux gneiss archéens pareillement retravaillés dans l'orogène nagssugtoqidien de l'ouest du Groenland. La cartographie du substratum rocheux (1/250 000) dans le sud de la péninsule Hall, réalisée à l'été 2012 par le Bureau géoscientifique Canada-Nunavut, a permis de nouvelles avancées au niveau de la compréhension du métamorphisme et de la déformation, et donc de leur incidence sur l'histoire tectonique de la péninsule Hall. Trois épisodes de déformation régionaux sont reconnus : 1) un événement précoce de chevauchement pelliculaire en direction est (D1); 2) un événement subséquent de chevauchement de couches épaisses en direction est (D_2); et 3) un événement tardif de compression nord–nord-ouest, ou sud–sud-est (D_3), caractérisé par des plis de grande taille (longueur d'onde de 2 à 7 km) qui plongent à faible profondeur vers l'ouest–sud-ouest. Les épisodes de déformation D_1 et D_2 sont conjointement responsables des tendances globales nord-ouest–sud-est dans la configuration cartographique de la péninsule Hall, toutes deux caractérisées par une foliation pénétrative à pendage ouest–sud-ouest et des axes de plis et des linéations minérales plongeant vers le nord-ouest ou le sud-est, et tous deux accompagnés de métamorphisme au faciès des amphibolites. Des preuves d'un événement métamorphique au faciès des granulites plus ancien, antérieur à la fois à D_1 et D_2, sont visibles par endroits dans les gneiss archéens. Afin de comprendre la nature et la synchronisation des épisodes de métamorphisme et de déformation sur la péninsule Hall, et les conséquences au niveau de la tectonique paléoprotérozoïque au sein de l'orogène trans-hudsonien, le présent rapport résume les grandes lignes d'une étude analytique détaillée de la pression-température-temps-déformation (P-T-t-d).

Introduction

The Hall Peninsula Integrated Geoscience Program (HPIGP) is being led by the Canada-Nunavut Geoscience Office in collaboration with the Government of Nunavut, Aboriginal Affairs and Northern Development Canada, Dalhousie University, University of Alberta, Université Laval, University of Manitoba, University of Ottawa, University of Saskatchewan, Nunavut Arctic College and the Geological Survey of Canada. It is supported logistically by several local, Inuit-owned businesses. The study area comprises all or parts of six 1:250 000 scale National Topographic System map areas north and east of Iqaluit (NTS 025I, J, O, P, 026A, B).

In the summer of 2012, fieldwork was conducted in the southern half of the peninsula (NTS 025 I, J, O, P) between June 22 and August 8. Fieldwork was supported by a 20–25 person camp located approximately 130 km southeast of Iqaluit. The focus was on bedrock mapping at a scale of 1:250 000 and surficial-sediment mapping at a scale of 1:100 000. A range of thematic studies was also supported. This included Archean and Paleoproterozoic tectonics, geochronology, landscape uplift and exhumation, detailed mapping in mineralized areas, microdiamonds, sedimentary rock xenoliths and permafrost. Summaries and preliminary observations for all of these studies can be found in this volume.

This report describes field observations of deformed and metamorphosed Archean and Proterozoic units. The purpose of this study is to set the stage for future work involving pressure-temperature-time-deformation studies to decipher the tectonometamorphic history of the Hall Peninsula.

The Trans-Hudson Orogen is a Paleoproterozoic collisional orogenic belt that extends in a broad arcuate shape from northeastern to south-central North America (Hoffman 1988; Lewry and Collerson 1990). This orogenic belt separates the lower plate Superior craton from an upper plate collage of Archean crustal blocks (Churchill plate). The Churchill plate includes the Wyoming craton, the Hearne Domain, the Slave craton, the Rae craton and the North Atlantic (Nain) craton of Greenland and Labrador. On Baffin Island, Nunavut, in the northeastern part of the Trans-Hudson Orogen, a well-exposed continental collisional zone records the 1.83–1.80 Ga southward migration of the Churchill plate and its terminal collision with the Superior craton. The upper Churchill plate collage in the Quebec-Baffin segment of the Trans-Hudson Orogen consists of the Rae craton and several microcontinents that were accreted to the southeastern Rae margin between ca. 1.88–1.84 Ga. One of these accreted terranes is the Meta Incognita microcontinent, which accreted to the southeastern Rae margin between ca. 1.883 and 1.865 Ga and is currently exposed on southern Baffin Island (St-Onge et al. 2006b).

The Meta Incognita microcontinent comprises crystalline basement overlain by a Paleoproterozoic clastic-carbonate shelf succession (Lake Harbour Group), and ca. 1.865 to 1.848 Ga quartz diorite to monzogranite plutons (Cumberland Batholith) that intrude both crystalline basement and the Lake Harbour Group (Scott and Wodicka 1998; St-Onge et al. 2000, 2007; Corrigan et al. 2009). The crystalline basement of the Meta Incognita microcontinent consists of Neoarchean crust (ca. 2.7–2.6 Ga), early Paleoproterozoic granitoid intrusions (ca 2.40–2.15 Ga) and ca. 1.95 Ga monzogranite-tonalite orthogneiss (Scott and Wodicka 1998; N. Wodicka, unpublished data, in Corrigan et al. 2009). It has been correlated with ca. 3.02–2.78 Ga orthogneisses in the lower plate Superior margin in Northern Quebec (St-Onge et al. 2000). However, it remains unclear whether the basement of the Meta Incognita microcontinent rifted from the Superior or Rae craton, or whether it constitutes crust that is exotic to both cratons (St-Onge et al. 2009).

Limited work on the Hall Peninsula has shown that it is underlain by Paleoproterozoic plutonic rocks that may be the eastward continuation of the Cumberland Batholith, Paleoproterozoic metasedimentary rocks that may be the northeastern continuation of the Lake Harbour Group, and an Archean orthogneiss complex of unknown tectonic affinity (Blackadar 1967; Scott 1996, 1999; St-Onge et al. 2006a, b). Possible parentage for the Archean orthogneiss complex orthogneisses include the Superior craton, as suggested for the Meta Incognita microcontinent; the North Atlantic craton of southern Greenland (Jackson et al. 1990; Scott 1999; St-Onge et al. 2009); the upper plate Rae craton or, potentially, an Archean block of unknown affinity and exotic to both the Rae and Superior cratons.

The general northwest-southeast strike of the units on the Hall Peninsula aeromagnetic map, which are more subtle on the preliminary geological map (Blackadar 1967), sets it apart from the east-west striking structural features that characterize southern Baffin Island. Furthermore, several purported suture zones, when extrapolated great distances onto the peninsula, appear to converge on the Hall Peninsula, including: the approximately east-west striking Baffin suture, which forms the boundary between the Meta Incognita microcontinent and the Rae craton; the approximately east-west striking Disko Bugt and Nagssugtoqidian sutures, which separate the Aasiaat Domain (St-Onge et al. 2009) from the Rae craton to the north and the North Atlantic craton to the south in West Greenland; and the northwest-southeast striking Abloviak shear zone and associated sutures in the Torngat Orogen, northern Labrador, which separate the North Atlantic craton from the Superior craton. Therefore, the geology of the Hall Peninsula and, in particular, the tectonic affinity of the eastern Archean orthogneiss complex, may provide insight into plate tectonic reconstructions of the Trans-Hudson Orogen in northern Canada and Greenland.

Geological background

Reconnaissance-scale bedrock mapping of the Hall Peninsula was conducted by Blackadar (1967), and an east-west transect located east of Iqaluit was mapped by Scott (1996, 1999). Based on their observations, Hall Peninsula has been divided into three lithological domains: a western domain of Paleoproterozoic garnet- or orthopyroxene-bearing monzogranite, a central domain of Paleoproterozoic metasedimentary rocks, and an eastern domain of Archean tonalite gneiss monzogranite and metasedimentary rocks.

Orthopyroxene monzogranite in the western plutonic domain on Hall Peninsula was emplaced at 1857 +5/–3 Ma, and the less common garnet monzogranite phase crystallized at 1850 +3/–2 Ma (U-Pb zircon, Scott 1999). These magmatic ages are contemporaneous with the emplacement of the Cumberland Batholith from ca. 1865 to 1848 Ma (U-Pb zircon; Jackson et al. 1990; Wodicka and Scott 1997; Scott and Wodicka 1998; Whalen et al. 2010), and thus the western plutonic domain on Hall Peninsula has been interpreted to correlate with the Cumberland Batholith (Scott 1999). Whalen et al. (2010) postulated that this magmatic event resulted from large-scale, post-accretion lithospheric mantle delamination during the Trans-Hudson orogeny.

The western limit of the central metasedimentary domain is defined by an intrusive contact with the western plutonic domain (Scott 1999). Rocks in the metasedimentary domain include biotite–garnet±sillimanite psammite and semipelite with concordant mafic sheets and marble (Scott 1996). Detrital zircon ages in psammite and semipelite yield U-Pb ages that are almost exclusively Paleoproterozoic, with an age population at ca. 2.2 Ga and a depositional range of ca. 1.93–1.89 Ga (Scott 1999). Due to lithological similarities and similar detrital zircon U-Pb age distributions, the central metasedimentary domain on Hall Peninsula may have been deposited in the same basin system as the Lake Harbour Group of the Meta Incognita microcontinent on south Baffin Island and the Tasiuyak gneiss of the Torngat Orogen in northern Labrador (Scott 1999; Scott et al. 2002; St-Onge et al. 2009).

Euhedral monazite in psammite from the central Hall Peninsula yielded a U-Pb age of 1862 ±2 Ma, which is considered to date the thermal peak of metamorphism (Scott 1999). Another sample of psammite from the same location recorded a slightly younger age of metamorphism, represented by zircon overgrowths at 1852 ±2 Ma (Scott and Gauthier 1996). Tabular bodies of garnet-bearing monzogranite commonly occur parallel to compositional layering in the metasedimentary rocks, and a U-Pb age of ca. 1869 Ma was determined from euhedral zircon overgrowths on rounded, xenocrystic crystals (Scott 1999). The petrological relationship and age have been interpreted to be the products of partial melting (Scott 1999). Although only preliminary, this spread of metamorphic ages coincides approximately with Cumberland Batholith magmatism (ca. 1.865–1.848 Ga).

The contact between the central metasedimentary domain and the eastern Archean tonalite gneiss has been described as tectonic (Scott 1996). The tonalite gneiss contains hornblende and biotite, indicative of amphibolite-facies metamorphism, and localized orthopyroxene cores suggest an older, granulite-facies event (Scott 1999). Zircon crystallization ages of the tonalite gneiss range between 2920 + 8/–6 and 2797 +27/–15 Ma, and zircon overgrowths possess ages of ca. 1.85–1.83 Ga, attributed to regional metamorphism that is also documented by 1.84 Ga granitic veins (Scott 1999). Quartzite from a panel of metasedimentary rocks in the orthogneiss yielded detrital zircon ages that were exclusively Archean, and a monazite age of 1877 ±3 Ma is considered to date early metamorphic conditions (Scott 1999). The Archean crystallization ages and Paleoproterozoic metamorphic history of the eastern orthogneiss domain on the Hall Peninsula support correlations with the Archean gneisses of the Nagssugtoqidian Orogen (Aasiaat Domain) in West Greenland (Jackson et al. 1990; Scott 1999; St-Onge et al. 2009).

Hints of a younger tectonothermal event in the Archean orthogneisses on Hall Peninsula are exhibited by 1.76 Ga granitic veins (U-Pb zircon), which is also suggested by 1.74–1.73 Ga U-Pb titanite ages in several samples of tonalite gneiss. It is unclear whether the titanite ages represent ‘final cooling’ (Scott 1999) or a distinct metamorphic pulse. There are also several post-1.80 Ga K-Ar cooling ages reported for the Hall Peninsula, including biotite ages ranging from ca. 1507 to 1700 Ma (Wanless et al. 1968, 1974), a muscovite age of ca. 1610 Ma (Lowdon 1960), and a hornblende age of ca. 1670 Ma (Wanless et al. 1979).

Previous bedrock mapping on the Hall Peninsula (Blackadar 1967; Scott 1996) and geochronological work (Scott 1999) determined the principal lithological framework and provided preliminary ages of crystallization, deposition and metamorphism, enabling tentative tectonic interpretations. The 1:250 000 scale bedrock mapping, on the southern Hall Peninsula during the summer of 2012, has shed light on the lithological complexity, deformation and meta-

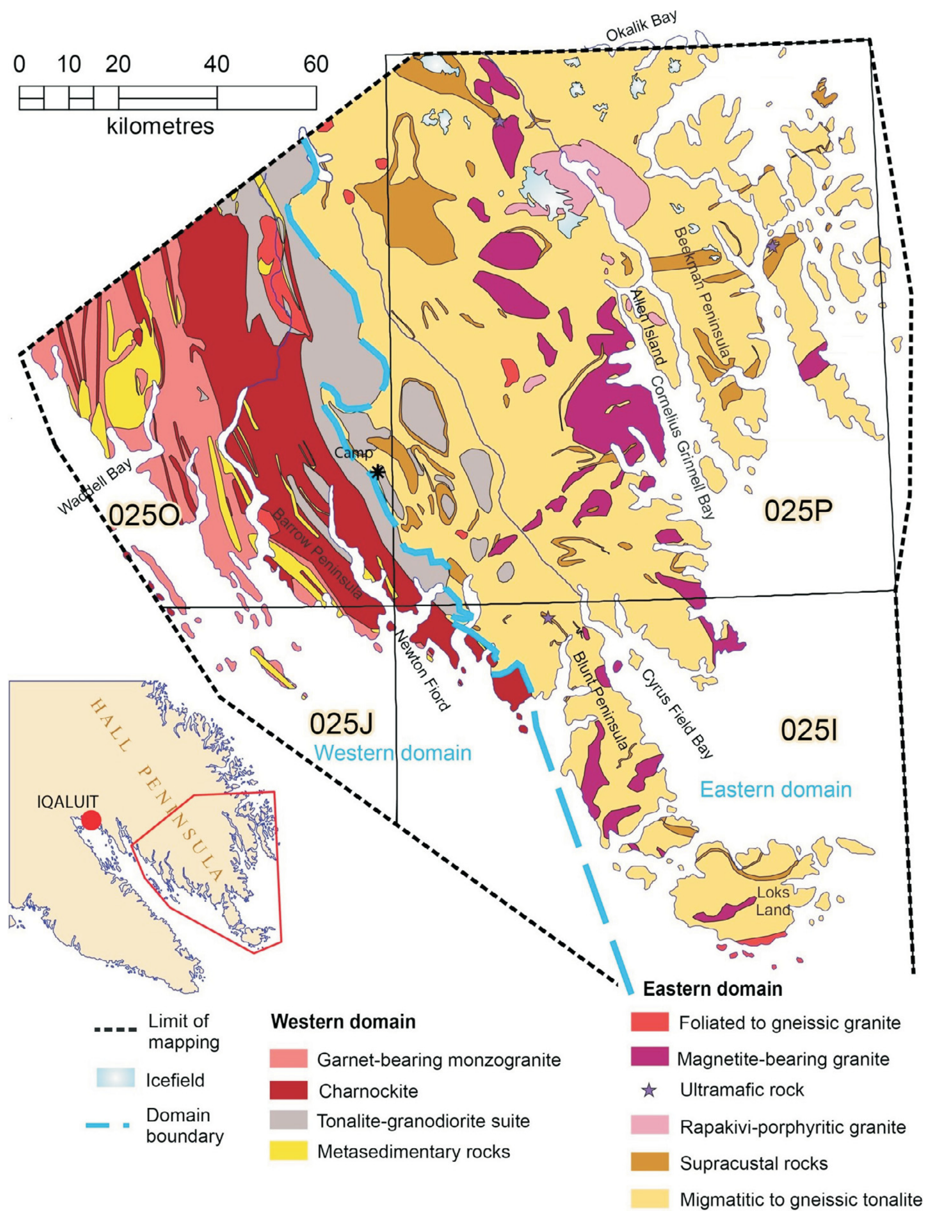

Figure 1: Simplified geological map of southern Hall Peninsula from Machado et al. (2013).

morphism within the three principal domains. Geological mapping (Figure 1), detailed lithological descriptions, relationships and representative field photos are presented in Machado et al. (2013), and a brief summary of lithological units is provided below.

Western Plutonic Domain (ca. 1860 Ma)

The Western Plutonic Domain is dominated by medium-grained biotite–orthopyroxene±magnetite granodiorite and garnet-biotite monzogranite. Biotite-orthopyroxene-magnetite granodiorite has orange weathered surfaces and green-brown fresh surfaces, and it typically forms strongly weathered, friable outcrop. Granodiorite locally surrounds zones of fine-grained diorite and gabbro, which may represent boudinaged dikes or xenoliths. Contacts between granodiorite and metasedimentary rocks are sharp, and parallel to foliation, and it is unclear whether they are intrusive, depositional or tectonic.

Biotite-garnet monzogranite intrudes granodiorite and metasedimentary rocks. Biotite-garnet monzogranite weathers to white, but the white-weathered rind is typically fractured or eroded to reveal rusty-weathered rock, resulting in the patchy white– and rusty–weathering pattern that is characteristic of this unit. Biotite-garnet monzogranite contains 5–20 vol. % red-brown to lilac-coloured garnet. This unit forms extensive intrusive bodies, locally contains rafts of metasedimentary rocks and can exhibit layering defined by garnet-rich and garnet-poor layers. Therefore, biotite-garnet monzogranite may represent the product of widespread anatexis of metasedimentary rocks (Scott 1996, 1999). Rare pods and panels of diorite, gabbro and pyroxenite occur parallel to foliation in biotite-garnet monzogranite, and represent either younger dikes that have been stretched or enclaves of older mafic-to-intermediate rocks. Pegmatitic biotite syenogranite to monzogranite dikes occur throughout the Western Plutonic Domain, both parallel to and crosscutting foliation.

Eastern Orthogneiss Domain (ca. 2900–2800 Ma)

The Eastern Orthogneiss Domain is dominated by fine- to medium-grained biotite±hornblende±magnetite tonalite and monzogranite, with coarse-grained syenogranite to monzogranite layers that are oriented parallel to foliation and may represent a vein network. The tonalite and monzogranite gneisses contain enclaves of biotite diorite, mafic tonalite, amphibolite and pyroxenite, and are crosscut by undeformed coarse-grained to pegmatitic monzogranite to syenogranite dikes. The lithological complexity of the Eastern Orthogneiss Domain is described in detail by From et al. (2013).

Metasedimentary rocks

A significant outcome of the mapping conducted during summer 2012 is that the metasedimentary rocks are not localized in the former central metasedimentary domain of Scott (1996, 1999). Instead, panels of metasedimentary rocks are distributed throughout the Hall Peninsula, ranging from 10 m to about 10 km in width.

In the Western Plutonic Domain, garnet-biotite monzogranite exhibits irregular, intrusive contacts with panels of metasedimentary rocks. Contacts between the metasedimentary rock packages and biotite-orthopyroxene granodiorite are sharp and concordant to foliation. The metasedimentary rocks consist of interbedded biotite–garnet± sillimanite pelite, semipelite and quartzite, with minor marble occurrences in the Waddell Bay area, southwestern Hall Peninsula.

In the Eastern Orthogneiss Domain, panels of metasedimentary rocks are interleaved with tonalitic to monzodioritic gneisses. The panels occur both structurally above and below the gneisses, with sharp, straight contacts that are parallel to foliation and have been interpreted as tectonic or depositional, based on the tectonostratigraphic and structural context. The metasedimentary intervals occur with irregular frequency. For example, along a single 5 km transect across-strike, there can be up to eight metasedimentary packages, ranging from 5–20 m in thickness, separated by 20 m to 1 km wide intervals of tonalite gneiss. Elsewhere, 2 km wide intervals of metasedimentary rocks regularly alternate with intervals of tonalite gneiss. This unit repetition can possibly be attributed to thrust imbrication or fold repetition, as discussed in more detail below. The metasedimentary rocks in the Eastern Orthogneiss Domain include biotite psammite and biotite–garnet±sillimanite±muscovite pelite and semipelite. Marble and quartzite were observed about 30 km west of Cornelius Grinnell Bay, southeastern Hall Peninsula. In contrast to the metasedimentary rocks in the Western Plutonic Domain, those in the Eastern Orthogneiss Domain are more lithologically variable, and they almost always occur in association with layers of amphibolite that are parallel to bedding and foliation and locally contain garnet. These mafic zones may represent sills or dikes that intruded along bedding prior to metamorphism and deformation.

Deformation

D_1: East-west compression

The D_1 deformational event is the earliest recognizable event that affects both the metasedimentary rocks of the Western Plutonic Domain and the orthogneiss complex and metasedimentary rocks in the Eastern Orthogneiss Domain. The Archean orthogneiss complex on eastern Hall Peninsula may have arguably experienced earlier deformational events, but D_1 is considered to represent the earliest recognizable regional deformational event that is not limited to the Archean orthogneiss complex, and may therefore represent younger, possibly Paleoproterozoic, tectonism. The D_1 deformational event is characterized by moderately to steeply west- to southwest-dipping foliation and northwest-plunging fold axes and mineral lineations, with some west-over-east kinematic indicators. Due to transposition of S_1 by S_2, S_1 is only discernible in the hinges of F_2 folds and in areas of low-D_2 strain (e.g., Braden et al., 2013). For example, in an open F_2 fold in semipelite in the Newton Fiord area, southwestern Hall Peninsula, S_1 is defined by the alignment of biotite, is parallel to relict bedding, and is crosscut by southwest-dipping axial-planar S_2 cleavage (Figure 2a). The S_1 fabric is also defined by aligned sillimanite, biotite and lozenge-shaped garnet porphyroblasts in pelite folded by D_2 (Figure 2b, c). In the Newton Fiord area, D_1 is characterized by a flattening fabric (S_1), with little to no L_1 mineral lineations (Braden et al., 2013).

On the northeastern Hall Peninsula, west of Okalik Bay, evidence of D_1 is well preserved in an area of low-D_2 strain in biotite-hornblende monzogranite gneiss. The F_1 folds of syenogranite veins and diorite enclaves in monzogranite gneiss exhibit well-developed, southwest-dipping axial-planar S_1 foliation defined by biotite and hornblende (Figure 2d). The F_1 folds in this area verge to the northeast, suggesting apparent southwest-over-northeast displacement (Figure 2e). The F_1 fold axes and L_1 mineral stretching lineations plunge shallowly to the northwest (Figure 2f), but in zones of higher cumulative strain, L_1 lineations occur as southwest-plunging stretching lineations that are interpreted to have formed during simple southwest-to-northeast shear.

D_2: Pervasive east-directed thrusting

Fabrics related to D_2 are widespread throughout the map area and affect all rock units except for late pegmatitic syenogranite to monzogranite dikes that crosscut foliation in the plutonic rocks, orthogneisses and associated metasedimentary rocks. The D_2 deformation event is characterized by moderately to steeply west- to southwest-dipping foliation, northwest- or southeast-plunging fold axes and L_2 stretching lineations, and generally west-over-east kinematic indicators, although opposing kinematics can be found, which suggests local strain partitioning. The fabrics associated with D_1 and D_2 are typically parallel, and they are both defined by amphibolite-facies mineral assemblages. Therefore, D_1 and D_2 fabrics can only be distinguished in areas that have been folded during D_2, where S_1 foliation is folded by F_2 folds and crosscut by S_2 axial-planar foliation. In areas that have undergone low-D_2 strain, or have not been affected by D_2, D_1 is also recognizable. Throughout most of Hall Peninsula, S_1 foliation is visible in F_2 fold hinges and, therefore, D_1 and D_2 probably represent two episodes of deformation with similar regional extents.

In metasedimentary rocks in the Newton Fiord area, southwestern Hall Peninsula, northwest-plunging folds have west-dipping axial-planar S_2 foliation (Figure 2a), and northwest-plunging L_2 mineral lineations that are parallel to F_2 fold hinges and are defined by sillimanite and biotite (Figure 3a). In the Eastern Orthogneiss Domain, shallow northwest- or southeast-plunging F_2 folds and L_2 lineations are preserved in tonalite gneiss and associated metasedimentary and amphibolite layers (Figure 3b, c). Evidence of top-to-east displacement is recorded by stepped quartz rods on southwest-dipping foliation planes in Newton Fiord area metasedimentary rocks (Figure 3d), and southwest- or northeast-directed shear is suggested by southwest-plunging lineations in higher strain areas.

While D_2 is characterized by penetrative west- to southwest-dipping foliation and macro-scale isoclinal or open folds, there are north-northwest–plunging open folds in the Waddell Bay area that are several kilometres from limb to limb and exhibit localized, poorly developed southwest-dipping foliation. These may represent F_2 folds that developed in an area of low-D_2 strain. In the Eastern Orthogneiss Domain, irregular repetition of orthogneiss and metasedimentary rock packages may be due to folding or thrust imbrication, or a combination of these processes, as a result of east-directed thrusting during D_2.

D_3: North-northwest–south-southeast directed compression

Late strain is characterized by large, open fold trains with wavelengths on the order of 2–7 km, and fold axes that plunge shallowly to the west-southwest. These folds are common in the Eastern Orthogneiss Domain but there is limited evidence of D_3 in the Western Plutonic Domain, perhaps due to the paucity of mapping conducted there in 2012. Deformation related to D_3 is well documented in the Eastern Orthogneiss Domain in the central Hall Peninsula, where a D_2 synform with a northwest-trending fold axis has been refolded by a D_3 synform with a southwest-trending fold axis, creating a 4 by 8 km structural basin (Mackay et al., 2013). Deformation related to D_3 in the Eastern Orthogneiss Domain is also recognized on the Blunt Peninsula, on the west coast of Cyrus Field Bay. In this area, biotite tonalite encloses a ~50 m thick package of garnet-biotite-sillimanite pelite and biotite±hornblende diorite, and the rocks are folded by an ~7 km wide F_3 fold that plunges shallowly to the southwest. Several smaller-scale, southwest-plunging folds occur near the hinge zone of the larger F_3 fold (Figure 4a), and lineations defined by quartz and plagioclase plunge shallowly to the southwest (Figure 4b). The S_2 fabric in tonalite gneiss, diorite and metasedimentary rocks is folded by the large F_3 fold (Figure 4c).

Some areas on northeastern Hall Peninsula are characterized by penetrative foliation that dips shallowly to moderately to the south-southeast, with localized moderately north-dipping foliation. Because these areas were mapped by helicopter, with few ground-truthing traverses, it is un-

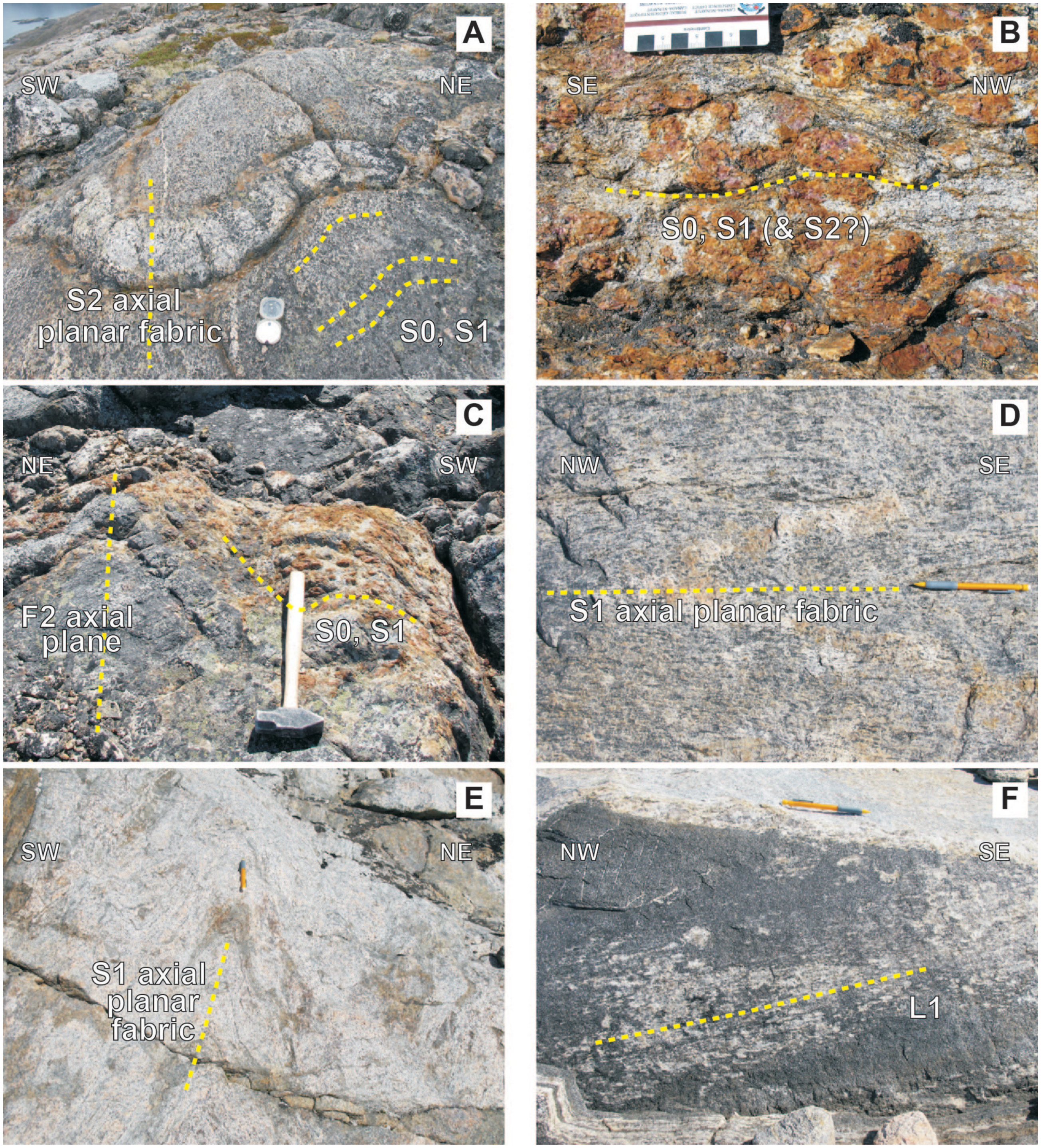

Figure 2: Field photographs of D_1 and D_2 deformation fabrics on Hall Peninsula: **a)** a folded monzogranite dike in biotite semipelite in the Newton Fiord area; the S_1 biotite schistosity is parallel to relict bedding and is crosscut by southwest-dipping axial planar S_2 foliation; **b)** bedding-parallel S_1 fabric (and possibly S_2 fabric) defined by sillimanite and biotite wrapping garnet porphyroblasts in garnet-sillimanite-biotite pelite, Newton Fiord area; **c)** an F_2 fold in interbedded garnet-biotite quartzite and garnet-sillimanite-biotite pelite in the Newton Fiord area, with clear S_1 fabric defined by biotite and sillimanite wrapping garnet porphyroblasts; **d)** an F_1 fold of a syenogranite vein and compositional layering in biotite-hornblende monzogranite gneiss, west of Okalik Bay; well-developed axial planar S_1 foliation is defined by aligned biotite and hornblende; **e)** diorite enclaves and syenogranite layers folded by F_1 folds in biotite-hornblende monzogranite gneiss, west of Okalik Bay; the axes of the F_1 folds plunge shallowly toward the northwest; fold asymmetry suggests they are northeast-verging, with west-over-east displacement; **f)** shallow-northwest-plunging L_1 lineation on an amphibolite enclave in biotite hornblende monzogranite gneiss on the northeastern Hall Peninsula, west of Okalik Bay; in the upper left part of the photo, fractures have formed due to orthogonal extension during shear; the mineral lineation is defined by hornblende, plagioclase and quartz.

clear whether this subdomain with distinct fabrics is related to a separate, penetrative deformation event, or whether it represents S_2 fabric that has been re-oriented by large-scale F_3 folds. In north-central Hall Peninsula, localized ptygmatic folding suggests D_3 strain at a macroscopic scale (Figure 4d). Alternatively, because the ptygmatic folds occur in metasedimentary rocks that are adjacent to the west-dipping, high-strain contact with tonalite gneiss they may have resulted from prolonged deformation along the west-dipping high-strain zone during D_2.

Metamorphism

Granulite-facies metamorphism

Possible granulite-facies assemblages were locally observed in tonalite gneiss in the Eastern Orthogneiss Domain. In some places on eastern Hall Peninsula, west of Allen Island, tonalite gneiss exhibits the assemblage orthopyroxene-hornblende-biotite-plagioclase-quartz (Figure 5). In the same area, upper-amphibolite–facies tonalite gneiss contains clinopyroxene-orthopyroxene gabbro enclaves. The gneissic banding and granular texture of these mineral assemblages suggests that they likely grew during granulite-facies metamorphism (Vernon 2004). Amphibolite-facies minerals (hornblende-biotite) occur on the edges of diorite enclaves, near the contact with surrounding tonalite gneiss. This suggests that granulite-facies metamorphism was overprinted by later amphibolite-facies conditions.

The biotite-orthopyroxene assemblage in granodiorite in the Western Plutonic Domain, on the Hall Peninsula, and in the Paleoproterozoic Cumberland Batholith, on southern Baffin Island, suggests that these granitoid intrusions are charnockites, in which the low water activity and the high temperature of the magma ensured the stability of orthopyroxene (Frost and Frost 2008). Alternatively, the occurrence

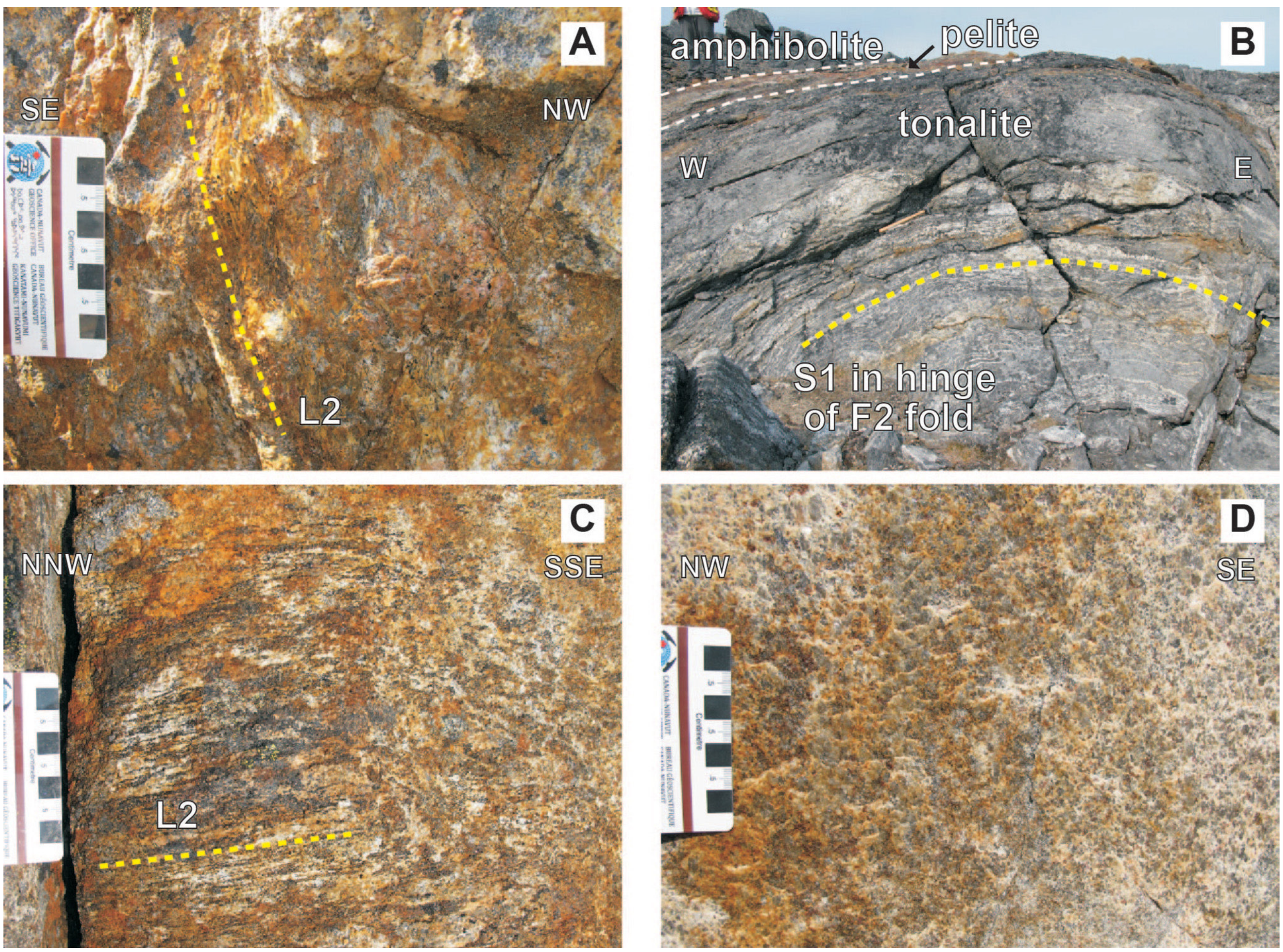

Figure 3: The D_2 deformation fabrics on Hall Peninsula: **a)** steeply northwest-plunging L_2 mineral lineations defined by sillimanite and biotite in garnet-biotite-sillimanite pelite, Newton Fiord area; these lineations are parallel to F_2 fold hinges; **b)** shallowly northwest-plunging F_2 antiform of tonalite gneiss and associated biotite-garnet-sillimanite pelite and amphibolite, central Hall Peninsula; **c)** shallowly northwest-plunging L_2 sillimanite lineation and southwest-dipping biotite schistosity in biotite-sillimanite pelite near the hinge of the F_2 antiform shown in (b); **d)** quartz rodding on a southwest-dipping foliation plane in quartzite in the Newton Fiord area; the 'stepping' on quartz rods indicates up-to-the-east displacement.

of orthopyroxene in the granitoid intrusions may have resulted from dehydration during granulite-facies metamorphism. Preliminary petrographic analysis has confirmed granulite-facies assemblages in pelite from the western Hall Peninsula, with the assemblage garnet-orthopyroxene-plagioclase-quartz (Spear 1993). Granulite-facies assemblages also occur in the metasedimentary rocks of the Paleoproterozoic Lake Harbour Group in the Meta Incognita microcontinent on southern Baffin Island, where they are similarly overprinted by amphibolite-facies metamorphism (St-Onge et al. 2007).

Widespread amphibolite-facies metamorphism

Amphibolite-facies assemblages are present in the entire 2012 map area. In tonalite and monzogranite gneisses in the Eastern Orthogneiss Domain, middle- to upper-amphibolite–facies metamorphism is characterized by the assemblage biotite–plagioclase±hornblende (Figure 2d), locally with clinopyroxene or garnet. Biotite diorite enclaves in the orthogneisses commonly contain hornblende; amphibolite enclaves locally contain clinopyroxene; and ultramafic enclaves are rich in tremolite-actinolite. In some higher strain zones, the assemblage biotite-hornblende-epidote indicates lower-amphibolite–facies metamorphism.

In the Western Plutonic Domain, upper-amphibolite–facies conditions are indicated in biotite-garnet monzogranite by the assemblage biotite-garnet-plagioclase. In biotite-orthopyroxene-magnetite granodiorite, orthopyroxene has

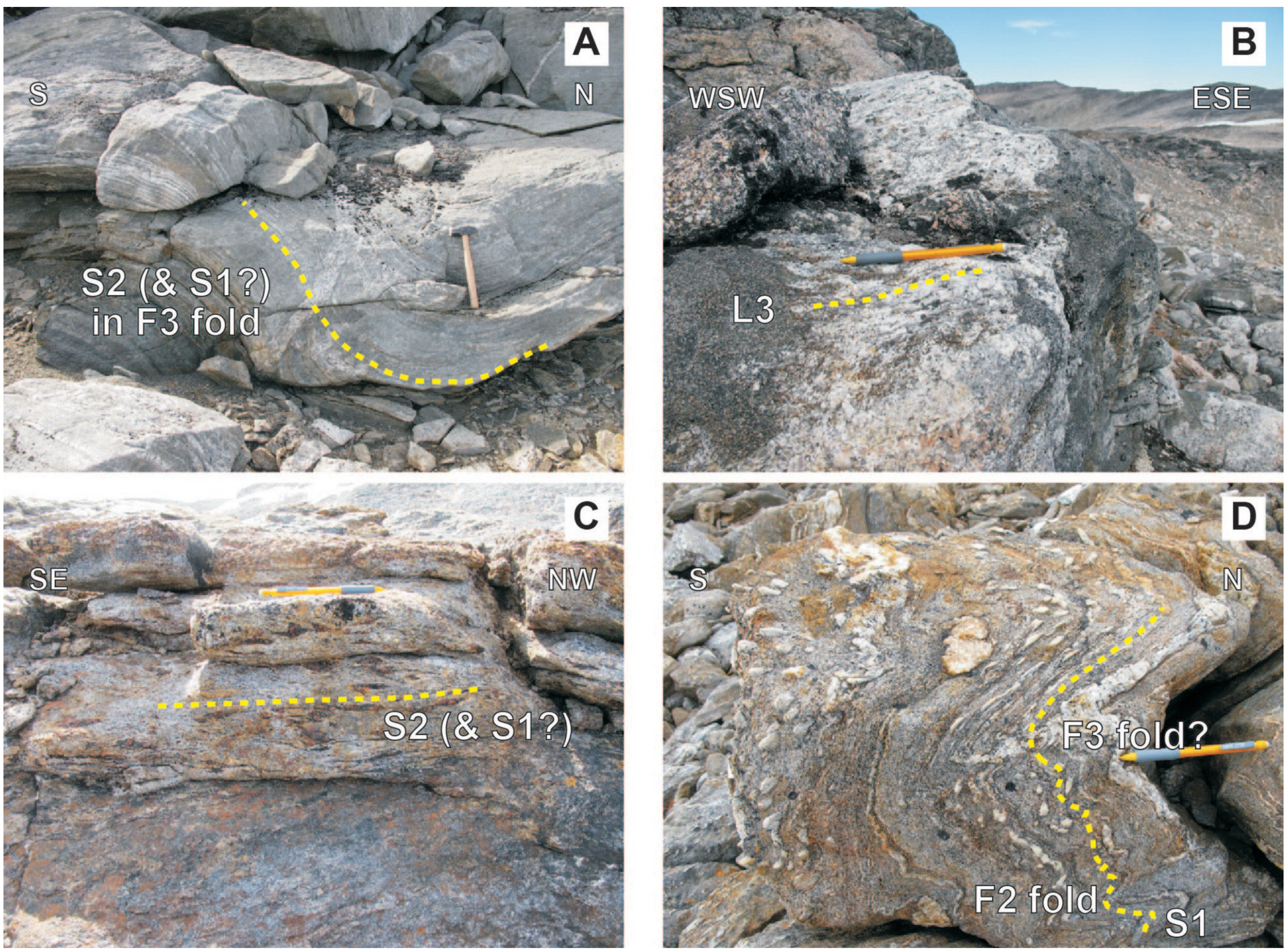

Figure 4: a) Shallow southwest-plunging F_3 folds in diorite in the Eastern Orthogneiss Domain, Blunt Peninsula. **b)** Rodded quartz and feldspar define a shallow southwest-plunging lineation in a monzogranite dike hosted by diorite in the Eastern Orthogneiss Domain, Blunt Peninsula. **c)** Garnet-biotite-sillimanite pelite with subhorizontal foliation (138/08) near the hinge zone of a ~7 km wide F_3 fold. Aligned garnet porphyroblasts and surrounding biotite tails define a lineation that probably formed during D_2, whereas rodded monzogranite veins/leucosomes on foliation planes define a shallow southwest-plunging lineation that is attributed to D_3. **d)** Ptygmatic folds in biotite-sillimanite semipelite in the Eastern Orthogneiss Domain on the north-central Hall Peninsula. Fold orientations are variable, but fold noses generally point north-south, parallel to the adjacent west-dipping high-strain zone. The ptygmatic folds represent two generations of folding, and several possible scenarios: 1) the smaller folds may be F_2, subsequently folded by a larger F_3 fold; 2) the smaller folds may be F_2, subsequently folded again during D_2; 3) the larger fold may have formed during D_2, and the smaller folds formed as a result of S_2 foliation development. The white pods or knots are faserkiesel, which is composed of fine sillimanite surrounded by quartz. Since the faserkiesel is rodded in the hinge zones and stretched along the limbs of both generations of folds, it predates or is synchronous with both folding events.

Figure 5: Greasy green–coloured tonalite to quartz-diorite gneiss from the eastern Hall Peninsula, west of Allen Island, with the granulite-facies assemblage orthopyroxene-hornblende-biotite-plagioclase-quartz.

undergone variable replacement by biotite-magnetite during amphibolite-facies metamorphism.

Metamorphic mineral assemblages in the metasedimentary rocks also indicate upper-amphibolite–facies metamorphism. The metamorphic mineral assemblage in quartzite is biotite-garnet-quartz, and in psammite it is commonly biotite–quartz–plagioclase–K-feldspar±garnet. In pelite and semipelite, the assemblages are as follows, in order of frequency (quartz–K-feldspar–plagioclase): biotite-garnet; biotite-garnet-sillimanite (Figures 2b, 4c); biotite-sillimanite (Figures 3c, 4d); biotite-muscovite-sillimanite (fibrolite); biotite-muscovite; graphite±biotite. Pelite locally contains faserkiesel, which are white pods or knots of fine fibrous sillimanite surrounded by quartz. Amphibolite layers in metasedimentary rocks in the Eastern Orthogneiss Domain have the assemblage hornblende–plagioclase± quartz±garnet. Biotite is ubiquitous in the metasedimentary rocks, but its abundance is variable. For example, pelite in the Newton Fiord area contains about 10–15% biotite, a much lower biotite content than pelite elsewhere (25–35%), which either reflects differences in bulk rock composition, or suggests that temperatures were high enough to drive biotite dehydration reactions. Overall, the mineral assemblages in the metasedimentary rocks record upper-amphibolite–facies metamorphism with very little evidence of greenschist-facies retrogression, and no recognizable younger mineral assemblage. The quantitative P-T conditions and metamorphic reactions are the subject of ongoing work.

Preliminary petrographic analysis of pelite from the Newton Fiord area shows that lozenge-shaped, garnet porphyroblasts are wrapped by a strong foliation defined by prismatic sillimanite crystals and minor biotite. Inclusions of quartz, biotite and sillimanite in garnet are weakly aligned. These textures suggest that garnet growth was syn- to post-tectonic. Asymmetric quartz–K-feldspar tails on garnet porphyroblasts suggest sinistral D_2 (and possibly D_1) shear toward the northwest. This rock records a progression through D_1+M_1 and D_2+M_2, but it is difficult to distinguish between these events because D_1 and D_2 fabrics are typically parallel, and both are defined by amphibolite-facies assemblages. Since open F_2 folds may indicate a low-D_2 strain zone in the Newton Fiord area (Braden et al., 2013), it is possible that D_1 was the dominant fabric-forming event in this rock.

In pelite in the Eastern Orthogneiss Domain, near the centre of Hall Peninsula, lozenge-shaped garnet porphyroblasts are wrapped by fibrous sillimanite intergrown with biotite. Since fibrolite tends to grow at lower metamorphic temperatures than prismatic sillimanite, this pelite may have reached a lower peak temperature than pelite at Newton Fiord. Asymmetric F_2 microfolds in the sillimanite-biotite bands suggest D_2 shear toward the southeast. This may represent a lateral strain component during west-over-east thrusting. In pelite from the Blunt Peninsula, in the Eastern Orthogneiss Domain, oval-shaped garnet porphyroblasts are wrapped by symmetric biotite tails. The garnets are zoned, with biotite–quartz±sillimanite inclusions concentrated in the centres, defining a near-spiral–shaped pattern that is typical of syndeformational 'snowball' garnets. These textures suggest that the garnet cores are syntectonic and overprinted a biotite-quartz-sillimanite assemblage. Additional detailed analyses of mineral-fabric relationships are necessary to resolve the nature and timing of metamorphism and deformation.

Planar fabrics and lineations associated with D_1 and D_2 are defined by upper-amphibolite–facies mineral assemblages (Figures 2b, d, f, 3a, c, 4c). There is no definitive evidence that amphibolite-facies conditions persisted during D_3 since no new metamorphic mineral growth was observed in association with D_3. The L_3 lineations, which are the only outcrop-scale structures associated with D_3, are defined by stretching (rodding) of quartz and feldspar, which may have formed prior to D_3. The large-scale open folding associated with D_3, and the lack of D_3-related penetrative fabric, suggest that D_3 was relatively low-strain and probably lacked the conditions required for a pervasive metamorphic overprint.

Preliminary tectonic interpretation

The D_2 event is likely responsible for widespread, penetrative southeast-striking, west-southwest–dipping fabric, apparent east-directed thrust imbrication and folding, and controls the broad southeast-trending map pattern on the Hall Peninsula. Because S_1 and S_2 fabrics are typically parallel and record similar strain orientations, it is possible that D_1 represents an initial thin-skinned stage, and that D_2 corresponds to a subsequent thick-skinned stage within the same general convergence scenario. Prolonged amphibolite-facies metamorphism (M_1+M_2) may have accompanied D_1+D_2.

Preliminary age estimates for metamorphism on the Hall Peninsula suggest a protracted (~50 m.y.) thermal event: 1852 ±2 Ma zircon overgrowths and 1862 ±2 Ma monazite in psammite from the central Hall Peninsula (Scott and Gauthier 1996; Scott 1999); ca. 1869 Ma zircon overgrowths in a monzogranite layer, interpreted to represent the age of partial melting of metasedimentary rocks in the Western Plutonic Domain (Scott 1999); 1877 ±3 Ma monazite from quartzite in the Eastern Orthogneiss Domain (Scott 1999); and ca. 1.85–1.83 Ga zircon overgrowths in tonalite gneiss in the Eastern Orthogneiss Domain (Scott 1999). Since zircon and monazite growth occurred in metasedimentary rocks and orthogneisses that have amphibolite-facies assemblages, and there is no mention of (relict) granulite-facies assemblages in these geochronology samples, it is probable that the zircon and monazite growth occurred under amphibolite-facies conditions. Therefore, ca. 1.88–1.83 Ga zircon and monazite growth likely record the timing of M_2 and D_2, or even perhaps a combination of M_1+M_2/D_1+D_2.

The ca. 1.85–1.86 Ga zircon overgrowths and monazite ages in the metasedimentary rocks in the central Hall Peninsula and ca. 1.83–1.85 Ga zircon overgrowths in Archean tonalite gneiss are concordant with the timing of extensive felsic plutonism on southern Baffin Island. These granitoids include garnet monzogranite (1850 +5/–3 Ma, Scott 1999) and orthopyroxene-biotite monzogranite (1857 +5/–3 Ma, Scott 1999) on Hall Peninsula, and the ca. 1865–1850 Ma Cumberland Batholith (Jackson et al. 1990; Wodicka and Scott 1997; Scott and Wodicka 1998; St-Onge et al. 2007; Whalen et al. 2010). The interpreted age of partial melting in the metasedimentary rocks (ca. 1869 Ma) is slightly older than the early stages of Cumberland Batholith magmatism, and coincides with the waning stages of felsic plutonism in the Torngat Orogen of northern Labrador (Scott 1999). Metamorphic zircon growth between ca. 1850 and 1830 Ma in the Archean orthogneisses is approximately coeval with the accretion of the Narsajuaq arc along the southern margin of the Meta Incognita microcontinent at ca. 1845 Ma, which produced granulite-facies metamorphism in the Lake Harbour Group (St-Onge et al. 2007). The majority of the preliminary metamorphic ages on the Hall Peninsula are slightly younger than the timing of Meta Incognita accretion to the southeastern Rae margin dated between ca. 1883 and 1865 Ma (St-Onge et al. 2006b). Consequently, M_1+D_1 and M_2+D_2 broadly coincide with extensive felsic plutonism during ca. 1865–1850 Ma and the subsequent accretion of the Narsajuaq arc to the Meta Incognita microcontinent at ca. 1845 Ma.

Preserved granulite-facies metamorphism in pelite on the west-central Hall Peninsula may be attributed to the accretion of the Narsajuaq arc to the southern margin of the Meta Incognita microcontinent at ca. 1845 Ma, since this event was also responsible for granulite-facies metamorphism in the Lake Harbour Group (St-Onge et al. 2007). Possible granulite facies metamorphism in the ca. 1.865–1.850 Ga biotite-orthopyroxene granitoids on the western Hall Peninsula may also be attributed to this event. This implies a general west to east decrease in metamorphic grade on the Hall Peninsula during M_1+M_2. Notably, variations in metamorphic mineral assemblages may reflect variations in the bulk rock chemistry of the protolith, which presents difficulties in constructing an isograd map. Thus, variations in mineral assemblages within the same lithotype need to be evaluated at the regional scale by combining field data with petrography and paleotemperature-paleopressure estimates.

Since preserved granulite-facies metamorphism on the central and eastern portions of Hall Peninsula is limited to the Archean orthogneisses and is overprinted by amphibolite-facies metamorphism (M_1 and M_2), it is interpreted to represent an early metamorphic event (M_0) that predates D_1 and D_2. If Archean rocks on the Hall Peninsula represent the westward continuation of Archean gneisses (Aasiaat Domain) of the Nagssugtoqidian Orogen in western Greenland (Jackson et al. 1990; Scott 1999; St-Onge et al. 2009), the early granulite-facies metamorphism may be linked to Archean tectonism that has been documented in western Greenland (ca. 2.81–2.75 Ga, Connelly and Mengel 1996).

No recognizable crustal suture zones were encountered during mapping in the summer of 2012, and it is therefore possible that the basement rocks that underlie the entire Hall Peninsula are of the same cratonic affinity. The D_1+D_2 and coeval amphibolite-facies metamorphism (M_1+M_2) may represent east-directed shortening of the basement and supracrustal rocks on the Hall Peninsula. However, it is possible that discrete mylonitic deformational zones, possibly suggesting crustal sutures, were not covered during the 1:250 000 scale mapping effort. Alternatively, the sutures may have been intruded by later magmatism or thermally overprinted, or were present at a higher structural level (and have been eroded away). Geochemical and isotopic characterization of the basement rocks on Hall Peninsula is needed to fully understand their continuity and cratonic affinity.

Stratigraphic analysis of the metasedimentary rocks may also shed light on the relationship between the Western Plutonic Domain and the Eastern Orthogneiss Domain. Although stratigraphic interpretations are limited by the discontinuity of the panels of metasedimentary rocks, current mapping provides no conclusive evidence that the metasedimentary rocks in the east are exotic with respect to those in the west. Nonetheless, the lithological variation of metasedimentary rocks in the Eastern Orthogneiss Domain, and their association with mafic layers, are markedly different from those in the Western Plutonic Domain. Limited detrital zircon work has shown that the metasedimentary rocks on the central Hall Peninsula contain almost exclusively Paleoproterozoic detrital zircons and were deposited prior to ca. 1.93 Ga, whereas the supracrustal rocks in the Eastern Orthogneiss Domain were derived from an exclusively Archean source and deposited prior to ca. 1.88 Ga (Scott 1999). Further stratigraphic and geochronological work is needed to resolve possible correlations between the metasedimentary rocks across the two domains.

The Hall Peninsula is considered to be the westward continuation of the Aasiaat Domain in West Greenland (Scott 1999; Hollis et al. 2006; Thrane and Connelly 2006; St-Onge et al. 2009), a microcontinent of unknown cratonic affinity that is separated from the Rae craton to the north and the upper plate North Atlantic craton to the south by the south-dipping Disko Bugt and Nagssugtoqidian sutures (Connelly et al. 2006; St-Onge et al. 2009). The Meta Incognita microcontinent, the Hall Peninsula and the Aasiaat Domain may share the same Archean basement and comprise a single (micro)continent that experienced apparent east-directed thrusting coincident with the dominantly north-south convergence of the Rae and North Atlantic cratons. It is possible that the apparent east-directed shortening on the Hall Peninsula, and generally southeast-trending map pattern, is a product of late- to post-orogenic crustal-scale folding of an east-west-striking collisional zone.

This possible crustal-scale folding event could potentially be related to D_3 on Hall Peninsula, which is characterized by southwest-plunging antiforms and synforms that indicate a late- to post-orogenic north-northwest–south-southeast directed compressional event. Late- or post-orogenic folding during D_3 may be a consequence of orogenic collapse after cessation of west-over-east thrusting and crustal thickening. Folding would postdate the terminal collision of the Trans-Hudson Orogen, which occurred ca. 1.82–1.80 Ga (Lewry and Collerson 1990). Similar folding about north-northeast–south-southwest trending axes was also recognized as the youngest regional deformation event (post-1.76 Ga) on the Meta Incognita Peninsula on southern Baffin Island (St-Onge et al. 1998). Orogenic collapse and midcrustal flow may be driven by a purported lower crustal delamination event reported for Baffin Island (Whalen et al. 2010). Delamination beneath Baffin Island is supported by a relatively subhorizontal Moho at a depth of 43 km identified by receiver function and ‘SKS-splitting’ analyses of the lithosphere (Snyder 2010). Moreover, D_3 may be recorded as post-1.80 Ga ages in the Archean orthogneisses on the Hall Peninsula, including ca. 1.76 Ga granitoids and ca. 1.74–1.73 Ga titanite ages (Scott 1999), as well as K-Ar cooling ages, including biotite ages (1.50–1.70 Ga, Wanless et al. 1968, 1974), muscovite ages (1.61 Ga, Lowdon 1960) and hornblende ages (1.67 Ga, Wanless et al. 1979). The nature and magnitude of this late-orogenic event and the stabilization of the craton is part of the future work to be accomplished as part of this project.

Ongoing and future work

Preliminary observations from this project, on the metamorphism and deformation on the Hall Peninsula have added to the current knowledge of Baffin Island, yet many questions remain unresolved, and additional analytical work is required to unlock the tectonic history of this important terrane. In particular, the paleotemperature and paleopressure conditions under which the two or three possible stages of metamorphism occurred will need to be determined, as well as the timing of these thermal events. Samples from metasedimentary rocks in the Western Plutonic and the Eastern Orthogneiss domains have been targeted for thermobarometry and mineral chemistry. Garnet Lu-Hf and Sm-Nd analyses will be performed to elucidate the ages of peak metamorphism and high-temperature cooling. In situ zircon, monazite and titanite U-Pb geochronology will be conducted on selected samples from the area, with the goal of analyzing the accessory minerals in their structural and petrological context to shed light on the relationship between metamorphism and deformation. Mica and hornblende $^{40}Ar/^{39}Ar$ thermochronology will be used to illuminate the extent and duration of the younger enigmatic 1.76 Ga event.

During the 2013 field season of the Canada-Nunavut Geoscience Office, the Hall Peninsula Integrated Geoscience Project, 1:250 000 scale bedrock mapping will continue in the northern portion of the Hall Peninsula in hopes of advancing the understanding of the metasedimentary sequences and the Western Plutonic Domain. Detailed observations on the metamorphism and structural deformation in this area will add to the existing geological framework and provide context for future P-T work and geo- and thermochronological data.

Economic considerations

This work is, in part, providing the framework for a better understanding of the architecture and geological history of the Hall Peninsula. The discovery of diamond-bearing kimberlites on the northeastern Hall Peninsula by Peregrine Diamonds Ltd. in 2008 may suggest that the Archean Eastern Orthogneiss Domain possesses the necessary characteristics for additional deposits. Because kimberlite fields are associated with thick, stable cratons, a notable feature of the Hall Peninsula (Snyder 2010), and are associated with major crustal structures, determining the basement geometry and tectonic evolution may enable more effective mineral exploration. The CNGO bedrock-mapping program (2012) identified several additional targets for preliminary mineral exploration (Machado et al., 2013). In the Eastern Orthogneiss Domain, ultramafic enclaves in tonalite gneiss and ultramafic sills within packages of supracrustal rocks may contain potential carving stone material and possible Ni-Cu-PGE mineralization, and metasedimentary rock packages locally contain banded iron formations and silicified gossans. In the Western Plutonic Domain, marble in metasedimentary rock packages may have the potential to host semiprecious gemstones. Since the distribution of panels of metasedimentary rocks may be related to apparent east-directed thrusting during D_2, understanding the deformational history is a fundamental component of strategic exploration. Characterizing the metamorphic geology and identifying discrete alteration patterns of the Hall Peninsula will also help to evaluate zones of mineralization and target areas of these valuable commodities.

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Preliminary observations on the nature and origin of the eastern orthogneiss complex of southern Hall Peninsula, Baffin Island, Nunavut

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Abstract

This study is part of the Canada-Nunavut Geoscience Office's Hall Peninsula Integrated Geoscience Program, a multiyear bedrock and surficial geology mapping program with associated thematic studies. Southern Hall Peninsula on Baffin Island, in Nunavut, has been separated into eastern and western domains in accordance with observations made during the 2012 field season. A large orthogneiss complex dominates the eastern domain of Hall Peninsula, consisting of tonalitic gneiss that contains enclaves of mafic to ultramafic rocks and that is variably intruded by granodiorite, monzogranite, syenogranite and granitic pegmatite bodies. Reconnaissance geochronology work by Scott (1999) identified multiple tonalitic gneiss sequences in eastern Hall Peninsula to be Archean. This tonalitic gneiss is very similar in age and appearance to Archean tonalitic to granitic gneiss found elsewhere throughout Baffin Island and the subarctic region as a whole (St-Onge et al., 2009). The Archean gneisses and metasedimentary cover rocks of Baffin Island have been correlated with other adjacent crustal blocks, such as the Meta Incognita microcontinent (St-Onge et al., 2009) and the Aasiaat domain of west-central Greenland (Scott 1999; Hollis et al., 2006; Thrane and Connelly, 2006). With many of these terrane correlations appearing to converge on Hall Peninsula, the rocks of this peninsula may provide insight into better defining the regional tectonic assembly of northeastern Canada and the paleo-reconstruction of the Archean terranes. Research goals over the next few years will be to determine through detailed petrological, geochemical and geochronological studies the extent and characteristics of the voluminous orthogneiss complex on the peninsula, whereas its origin and source will be examined through Nd-isotopic analyses. Intrusive rocks that pierce crustal rocks at depth inherit the unique Nd-isotopic signature of the underlying crust, allowing comparison to Nd-isotopic data from the subarctic region. These basic data and maps will be beneficial to the mineral exploration industry, as well as to the local indigenous people of Nunavut who rely on the carving-stone trade for their livelihood.

Résumé

Cette étude fait partie du Programme géoscientifique intégré de la péninsule Hall, du Bureau géoscientifique Canada-Nunavut, un programme pluriannuel de cartographie du substratum rocheux et de la géologie de surface accompagnée d'études thématiques connexes. Le sud de la péninsule Hall sur l'île de Baffin (Nunavut) a été divisé en domaines oriental et occidental en conformité avec les observations faites au cours de la campagne d'exploration de 2012. Un grand complexe d'orthogneiss domine le domaine oriental de la péninsule Hall, composé de gneiss tonalitique qui renferme des enclaves de roches mafiques à ultramafiques et qui est recoupé de façon variable par des corps de granodiorite, de monzogranite, de syénogranite et de pegmatite granitique. Les travaux de reconnaissance géochronologique effectués par Scott (1999) ont permis d'établir que plusieurs séquences de gneiss tonalitique dans l'est de la péninsule Hall datent de l'Archéen. Ce gneiss tonalitique est très similaire en âge et en apparence au gneiss tonalitique à granitique de l'Archéen trouvé ailleurs sur l'île de Baffin et dans l'ensemble de la région subarctique (St-Onge et al., 2009). Les gneiss archéens et les roches de couverture métasédimentaires de l'île de Baffin ont été mis en corrélation avec d'autres blocs crustaux voisins, comme ceux que l'on trouve sur le microcontinent Meta Incognita (St-Onge et al., 2009) et le domaine Aasiaat du centre-ouest du Groenland (Scott, 1999; Hollis et al., 2006; Thrane et Connelly, 2006). Comme bon nombre de ces corrélations de terranes semblent converger sur la péninsule Hall, il semblerait que les roches de cette presqu'île pourraient aider à mieux définir l'assemblage tectonique régional du nord-est du Canada et la paléoreconstruction des terranes de l'Archéen. Au cours des

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prochaines années, les objectifs de la recherche seront de déterminer par des études pétrologiques, géochimiques et géochronologiques détaillées l'ampleur et les caractéristiques du volumineux complexe d'orthogneiss sur la péninsule, tandis que son origine et sa source seront examinées par analyse isotopique du Nd. Les roches intrusives qui percent les roches crustales en profondeur héritent de la signature isotopique unique du Nd de la croûte sous-jacente, ce qui permet une comparaison des données d'analyse isotopique du Nd provenant de la région subarctique. Ces données et ces cartes de base seront utiles à l'industrie de l'exploration minérale, et aux populations autochtones locales du Nunavut dont la subsistance repose sur le commerce des sculptures de pierre.

Introduction

The Hall Peninsula Integrated Geoscience Program (HPIGP) is being led by the Canada-Nunavut Geoscience Office in collaboration with the Government of Nunavut, Aboriginal Affairs and Northern Development Canada, Dalhousie University, University of Alberta, Université Laval, University of Manitoba, University of Ottawa, University of Saskatchewan, Nunavut Arctic College and the Geological Survey of Canada. It is supported logistically by several local, Inuit-owned businesses. The study area comprises all or parts of six 1:250 000 scale National Topographic System map areas north and east of Iqaluit (NTS 025I, J, O, P, 026A, B).

In the summer of 2012, fieldwork was conducted in the southern half of the peninsula (NTS 025 I, J, O, P) between June 22 and August 8. Fieldwork was supported by a 20–25 person camp located approximately 130 km southeast of Iqaluit. The focus was on bedrock mapping at a scale of 1:250 000 and surficial-sediment mapping at a scale of 1:100 000. A range of thematic studies was also supported. This included Archean and Paleoproterozoic tectonics, geochronology, landscape uplift and exhumation, detailed mapping in mineralized areas, micro-diamonds, sedimentary rock xenoliths and permafrost. Summaries and preliminary observations for all of these studies can be found in this volume.

The HPIGP also seeks to reveal the complex geological history of this part of the northeastern Canadian Arctic and assess the region's potential for economic deposits and carving-stone material. Systematic surficial and bedrock helicopter-supported mapping transects carried out over the southeastern portion of the peninsula (NTS 025P, 025I, parts of 025O, 025J) covered approximately 20 000 km^2 (Figure 1).

Previous mapping of Hall Peninsula at the reconnaissance scale took place more than 45 years ago (Blackadar, 1967). More recent mapping efforts and analytical studies by Scott (1996, 1999) along a narrow east-west transect provided a first indication of the geological complexities that characterize the peninsula. This article will focus on the eastern domain of Hall Peninsula and, more specifically, on the large eastern orthogneiss complex. Detailed descriptions of the regional geology and the Paleoproterozoic evolution of Hall Peninsula appear in Machado et al. (2013) and Skipton et al. (2013).

Geological background

Previous analytical work on the eastern orthogneiss complex has been carried out by Scott (1999). Geochronology, utilizing the isotope dilution–thermal ionization mass spectrometry U-Pb method, was employed on zircon and titanite separates within four distinct samples of tonalitic gneiss from the eastern domain of Hall Peninsula. All samples contained zircon grains that have colourless, euhedral, prismatic cores, with light to medium brown overgrowths. The colourless, euhedral cores document Archean ages ranging from 2920 to 2797 +8/-15 Ma that are interpreted as magmatic, and the light to medium brown overgrowths document probable tectonothermal overprints at ca. 2770 Ma, and between 1844 and 1736 Ma. Zircon ages from metasedimentary rock packages found intercalated within eastern tonalitic gneiss were also reported; single-crystal U-Pb ages from a garnet-bearing quartzite yielded a dominantly Archean population. Three of the 24 zircon grains analyzed yielded ages younger than 2500 Ma, which is attributed to significant Pb loss (Scott, 1999). As a whole, these preliminary results indicate that the eastern orthogneiss complex is dominantly Archean, with locally interleaved Archean metasedimentary rocks. Moreover, in addition to Paleoproterozoic metasedimentary rocks to the west, one or more tectonic events have occurred at ca. 2700 Ma and during the Paleoproterozoic (1844–1736 Ma; Scott, 1999).

The tonalitic gneiss in the eastern orthogneiss complex is very similar in age range, lithological characteristics and texture to Archean tonalitic to granitic gneiss found elsewhere throughout Baffin Island and the surrounding subarctic region as a whole (St-Onge et al., 2009). Baffin Island Archean gneisses have been correlated with other adjacent crustal blocks through lithological similarities, geochronology, geochemistry and aeromagnetic characteristics. The Archean Rae craton of central and northern Baffin Island has been correlated with the Rae craton in western Greenland (Hoffman, 1988). Archean rocks of the Meta Incognita microcontinent that form southern Baffin Island may correlate with the Aasiaat domain of west-central Greenland (Scott 1999; Hollis et al., 2006; Thrane and Connelly, 2006). Other correlations between the North Atlantic (Nain) craton of northern Labrador and the North Atlantic craton of western Greenland remain speculative (van Gool et al., 2004). In addition, Paleoproterozoic Lake Harbour Group metasedimentary rocks have been correlated from the Meta Incognita microcontinent down to the Torngat Orogen of northern Labrador (Knight and Morgan, 1981; Scott and Gauthier, 1996, Scott, 1999). Hall Peninsula Archean rocks have yet to be unequivocally correlated with any of the surrounding crustal blocks and remain enigmatic in terms of how they fit into the regional tectonic assembly of Baffin Island (Figure 2). Currently, there are several possibilities for Hall Peninsula:

- it is a distinct Archean microcontinent (Hoffman, 1989)
- it is correlative to the Archean gneiss of the Rae craton
- it is correlative to the Archean gneiss of the Meta Incognita microcontinent (St-Onge et al., 2009)
- it is correlative to Archean gneiss of the Nagssugtoqidian orogen of western Greenland (Jackson et al., 1990)

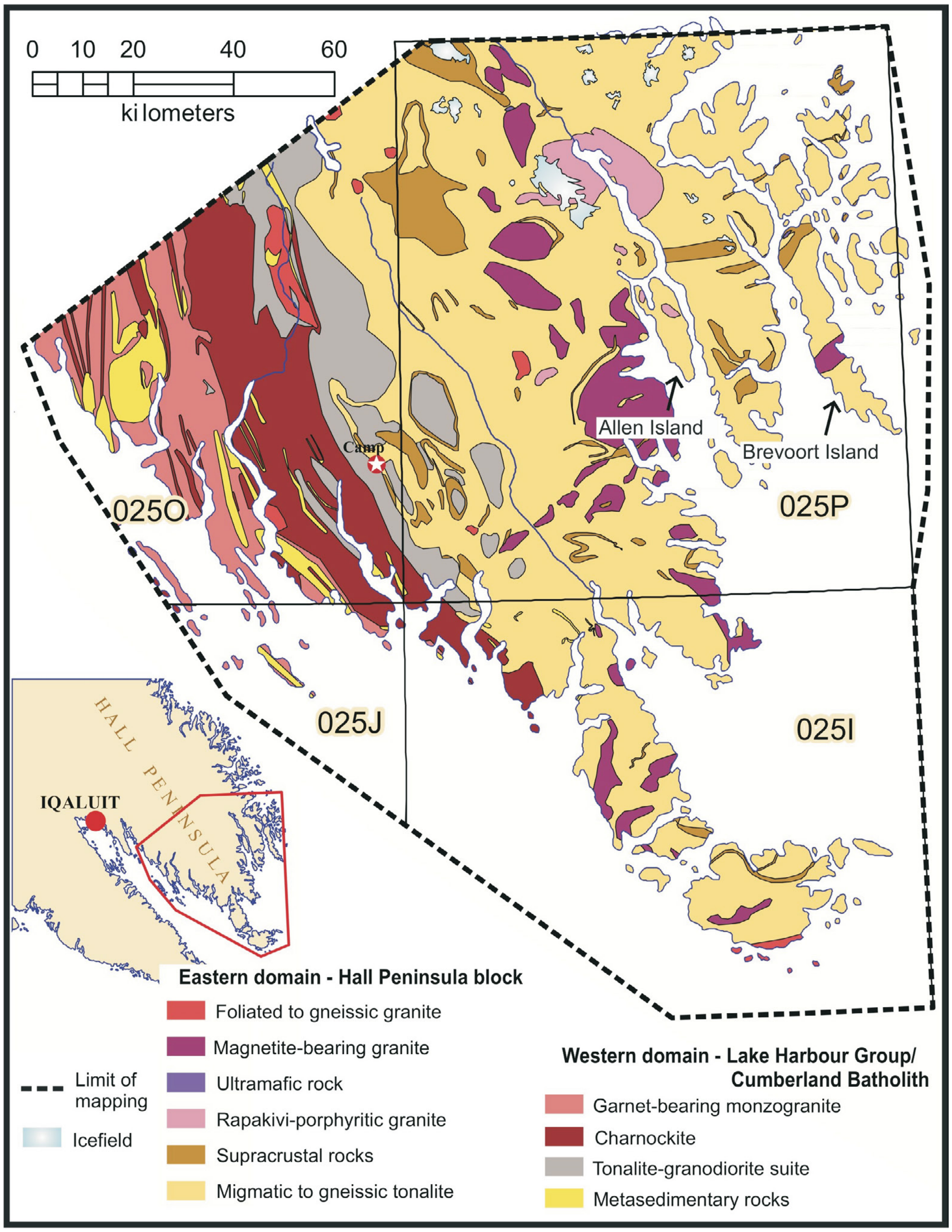

Figure 1. Simplified geological map of southern Hall Peninsula, Baffin Island, Nunavut (modified from Machado et al., 2013).

- it is a northern continuation of the Torngat Orogen of the Archean Nain craton (Scott and Campbell, 1993; Scott, 1999; Connelly, 2001; Wardle et al., 2002).

The last two scenarios are not mutually exclusive because the Nagssugtoqidian collision (<1890 Ma) may predate the Torngat collision (<1870 Ma), as suggested by Scott (1999). Moreover, different interpretations on the location of orogenic sutures on southern Baffin Island by Corrigan et al. (2009) and St-Onge et al. (2009) highlight the fact that Hall Peninsula represents one of the last pieces of the regional tectonic puzzle of the Canadian subarctic (Figure 2).

The eastern orthogneiss complex

The metamorphosed gneissic rocks that underlie the eastern portion of Hall Peninsula are notably variable in composition and are probably best considered as being part of a large plutonic complex. All rocks in the orthogneiss complex, except for young undeformed pegmatites, have been deformed by at least one of the four phases recognized in the field and exhibit a metamorphic gneissosity. The rock sequences described below are considered metamorphic; however, the usage of the term 'meta' is omitted for brevity.

The most abundant component of the eastern orthogneiss complex is a biotite±hornblende±magnetite tonalite that constitutes approximately 70% of the total exposed area. The tonalitic gneiss is variably intruded by granodiorite, white-weathering monzogranite and syenogranite, which occur parallel to and crosscut the gneissosity. Mafic and rare ultramafic enclaves are observed throughout the orthogneiss complex as discrete layers and lenticular pods. The units of the orthogneiss complex will be described in detail from oldest to youngest, as observed from crosscutting relationships in the field. Although exposed as a large plutonic body in the eastern domain, the Rapakivi-porphyritic granite of Machado et al. (2013) will not be discussed since the authors did not observe this particular unit. The following descriptions are an elaboration of the 'magnetite-bearing granite' and 'migmatitic to gneissic tonalite' units of Machado et al. (2013).

Ultramafic rocks

Exposed within kilometre-scale outcrops, medium- to coarse-grained ultramafic rocks occur as pods surrounded by the dominant biotite±hornblende±magnetite tonalite. Although a probably metamorphic assemblage, the mineralogy is distinctly dominated by actinolite+tremolite+

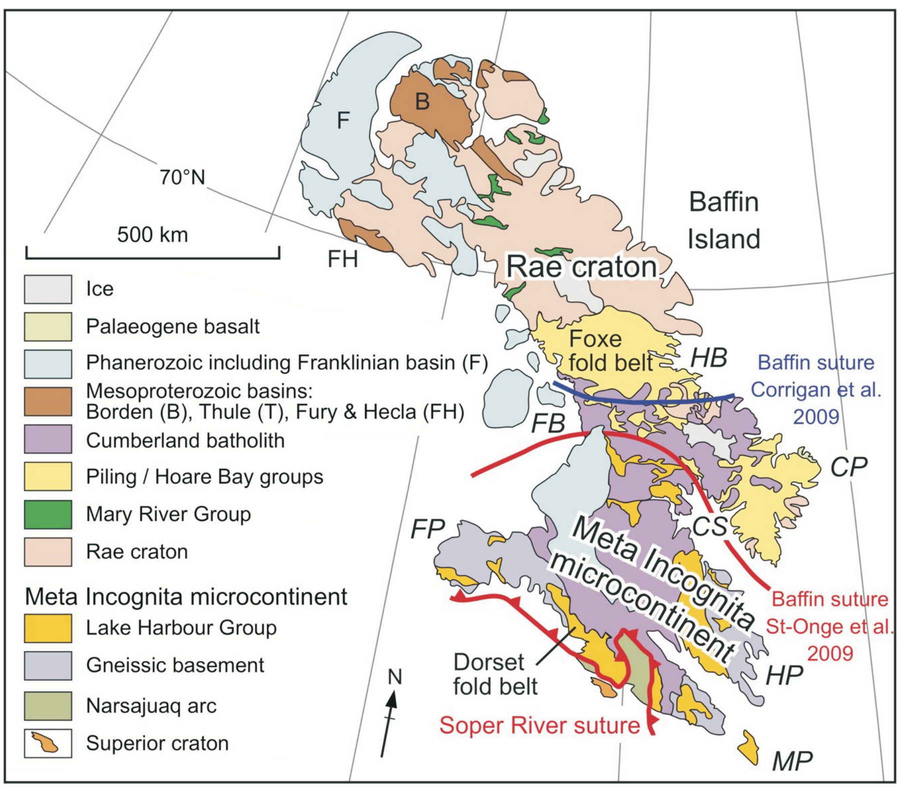

Figure 2. Compilation map of Baffin Island, Nunavut, which predates the initiation of the Canada-Nunavut Geoscience Office Hall Peninsula Integrated Geoscience Project (modified from St-Onge et al., 2009). Hall Peninsula is interpreted as being composed of Lake Harbour Group supracrustal rocks and gneissic basement both belonging to the Meta Incognita microcontinent. Abbreviations: B, Borden Basin; CP, Cumberland Peninsula; CS, Cumberland Sound; F, Franklinian Basin; FB, Foxe Basin; FH, Fury and Hecla Basin; FP, Foxe Peninsula; HP, Hall Peninsula; MP, Meta Incognita Peninsula; T, Thule Basin.

chrome diopside (Figure 3a). The 'chrome' prefix is given because of the colour of the diopside-mineral type. Zoning or segregation within the pods was not evident from field observation. These pods were only recognized in a few localities but, where observed, they range in size from 10 cm to <3 m in diameter.

Diorite to gabbro

Fine- to medium-grained diorite to gabbro occurs as discrete layers and lenticular bodies generally parallel to foliation within the dominant tonalitic gneiss. The mineralogy of the diorite to gabbro lithotype is biotite+hornblende+ plagioclase±clinopyroxene±orthopyroxene. The diorite pods range in size from ~5 cm to 10 m in diameter (Figure 3b, c), with the layers ranging in thickness from 1 cm to 5 m, and are variably continuous along strike. The larger enclaves of diorite preserve a clinopyroxene±orthopyroxene assemblage with orthopyroxene commonly occurring only within the core of the large enclaves. Diorite containing quartz (<15% total-rock volume) was observed in a few localities throughout the gneissic complex and assigned the name quartz diorite. In zones of higher strain, the diorite is sheared into thin millimetre-scale layers and folded within the tonalitic gneiss. Due to contributions from shearing and partial melting of these rocks, mineral segregation makes the exact original composition of these rocks upon emplacement difficult to determine.

Tonalite

Fine- to medium-grained tonalitic gneiss is the dominant unit throughout the eastern region of Hall Peninsula and its mineralogy consists of plagioclase+quartz+biotite±hornblende±magnetite. The gneissic segregation of mafic and felsic minerals commonly results in thin concentrations of hornblende and biotite alternating with layers of quartz and plagioclase (Figure 3d). Tonalite (sensu stricto) exposures, free from inclusions of other rock material, are rare as they are consistently intruded by granodiorite, monzogranite, syenogranite and granitic pegmatite (Figure 3e). In zones of higher strain, the tonalitic gneiss exhibits sheared gneissic banding a few millimetres thick that locally approaches protomylonitic texture. Dioritic enclaves and younger intrusive units are deformed with the tonalite in these zones of higher strain. In other lower-strain regions, the tonalite can exhibit an irregular and migmatitic texture.

Panels of metasedimentary rocks ranging from 5 m to 2 km in size are interleaved with tonalitic gneiss. The panels may be structural in nature or consist of igneous-related screens. The composition of these rocks is variable, including pelite to semi-pelite, psammite, quartzite and rare marble. Typically the mineral assemblage of these rocks consists of biotite+garnet±sillimanite±muscovite. Layers of (±)garnet amphibolite, 10 cm to 5 m in thickness, are commonly found within the metasedimentary rocks parallel to foliation (Figure 3f). In some localities, the contacts between the metasedimentary units and the gneissic complex are sharp, straight and parallel to foliation (Figure 4a), contain graphite, and possess a flaggy texture indicative of higher strain. Other contacts between these two rock types are irregular and obscured by intrusive pegmatite and quartz veining. Well-defined leucosomes rimmed by biotite-rich melanosome are abundant within psammitic and, to a lesser degree, within semi-pelitic rocks just west of Brevoort Island (Figure 1, 4b)

Granodiorite

Fine- to medium-grained quartz+plagioclase+biotite+K-feldspar±magnetite granodiorite occurs as an intrusive phase into the tonalitic gneiss. The granodiorite is commonly observed as large metre-scale crosscutting bodies, with local megacrysts of K-feldspar (Figure 4c); K-feldspar 'clasts' were observed to be apparently disaggregated, likely from shearing of syenogranite veining, and are preserved now as porphyroclasts within the granodiorite (Figure 4c). Nevertheless, the granodiorite most commonly exhibits a massive texture.

Monzogranite

Fine- to medium-grained monzogranite also occurs as an intrusive phase into the tonalite. The mineralogy is quartz+ plagioclase+biotite±hornblende±garnet±magnetite±epidote, commonly with a white-weathering surface. The monzogranite commonly occurs as discrete, centimetre- to metre-scale layers parallel to foliation within the tonalitic gneiss and granodiorite; it has also been observed as more irregularly–shaped intrusive bodies within the tonalitic to granodioritic gneiss (Figure 4d). The concentration of hornblende is variable across the domain, with some monzogranite consisting of up to 25% hornblende. In the tonalitic gneiss, the millimetre- to centimetre-scale monzogranite layers tend to have a well-defined foliation, whereas the irregular shapes retain a more massive texture, likely the result of differing states of strain.

Syenogranite

Fine- to coarse-grained syenogranite occurs as an intrusive phase into the tonalite. The mineral assemblage, consisting of K-feldspar+quartz+plagioclase+biotite±magnetite, occurs as discrete millimetre to centimetre-scale veins, which are parallel to and crosscut foliation within the tonalitic gneiss, granodiorite and monzogranite (Figure 4e). It is common to see the two phases of foliation-parallel and crosscutting syenogranite present in the same outcrop. In zones of high strain, these syenogranite veins become sheared into millimetre- to centimetre-scale layers parallel to the dominant gneissosity. In lower-strain zones, the syenogranite is more irregular with a more massive texture.

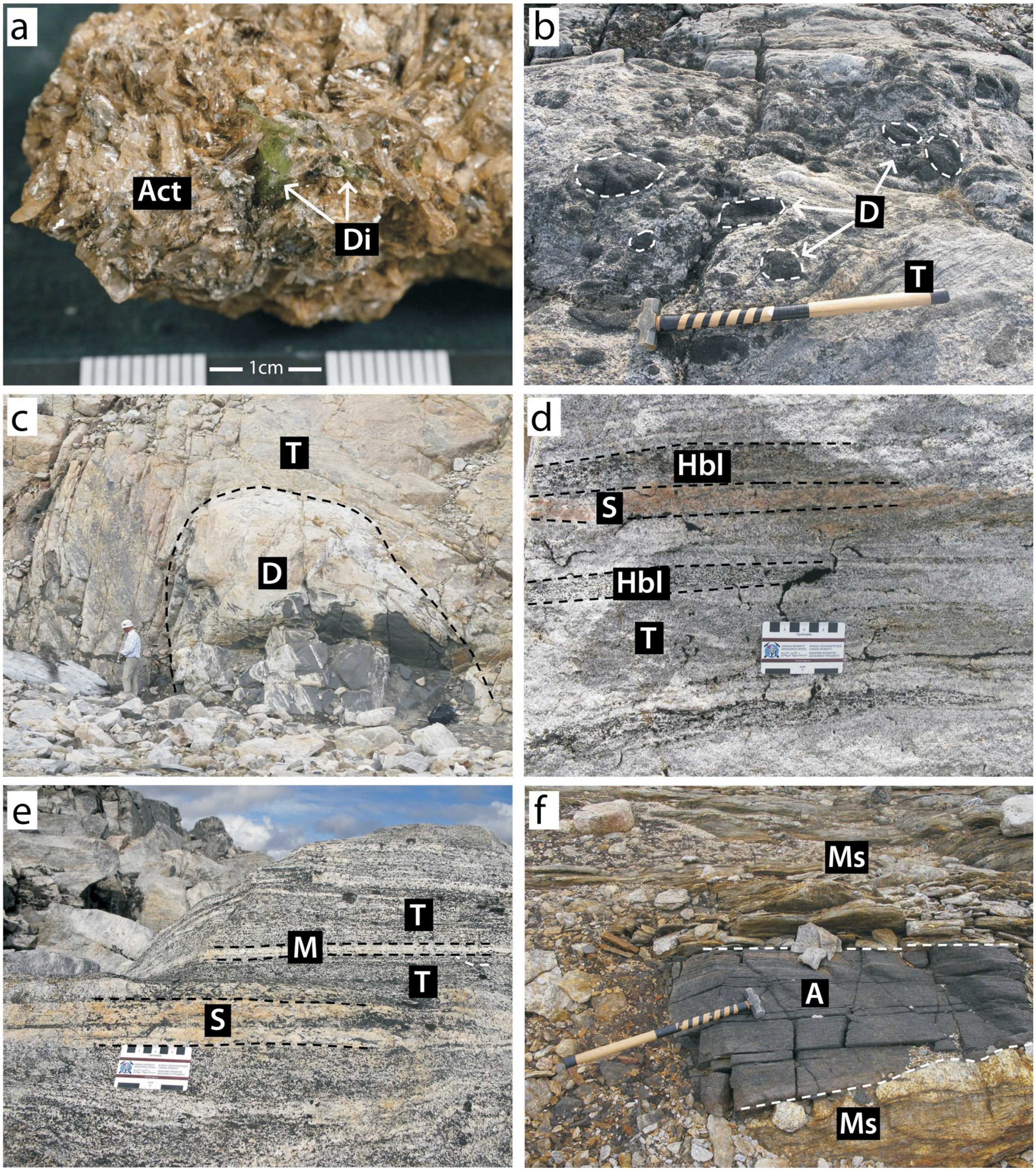

Figure 3. Field photographs from the eastern orthogneiss complex of Hall Peninsula, Baffin Island, Nunavut, showing a) the mineral assemblage of the ultramafic pods; b) small diorite to gabbro enclaves within tonalitic gneiss; c) a larger diorite pod that preserves a granulite-grade assemblage in its interior; d) tonalitic gneiss with thin segregations of hornblende and a small syenogranite vein; e) the heterogeneous nature of the tonalitic gneiss being variably intruded by monzogranite and syenogranite; f) a garnet-rich–amphibole layer parallel to bedding and foliation in metasedimentary rock. Abbreviations: A, amphibolite; Act, actinolite/tremolite; D, diorite to gabbro; Di, diopside; Hbl, hornblende segregation; M, monzogranite; Ms, metasedimentary rocks; S, syenogranite; T, Tonalitic gneiss.

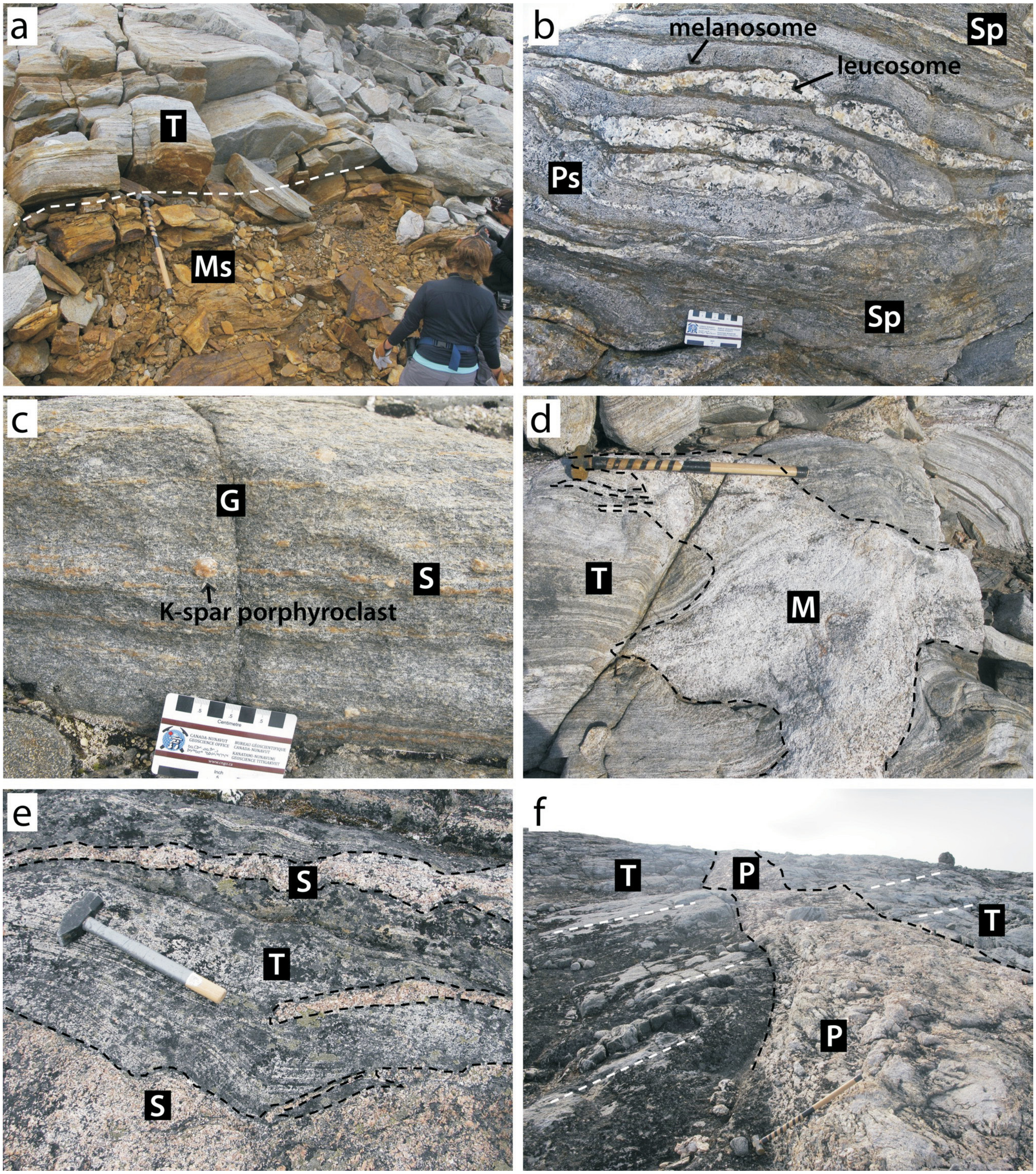

Figure 4. Field photographs from the eastern orthogneiss complex of Hall Peninsula, Baffin Island, Nunavut, showing a) a sharp contact with tonalitic gneiss overlying rusty-brown metasedimentary rocks; b) well defined quartz+feldspar leucosome segregations in psammitic rocks rimmed by biotite-rich melanosome; c) granodiorite with local K-feldspar porphyroclasts derived from disaggregation of a syenogranite vein due to high strain; d) irregularly-shaped monzogranite crosscutting tonalitic gneiss; e) syenogranite veins intruding and crosscutting the foliation in the tonalitic gneiss; f) undeformed granitic pegmatite crosscutting tonalitic gneiss. Abbreviations: G, granodiorite; M, monzogranite; Ms, metasedimentary rocks; P, pegmatite; Ps, psammite; S, syenogranite; Sp, semi-pelite; T, tonalitic gneiss.

Granitic pegmatite

Centimetre- to metre-scale granitic pegmatite intrudes and crosscuts all other units of the gneissic complex (Figure 4f). The mineralogy, consisting of K-feldspar+quartz+plagioclase+biotite±magnetite, is very similar to that of the syenogranite. At least two phases of granitic pegmatite have been identified, with one population being overprinted by the regional fabric and the other, which is massive, truncating all other fabrics.

Structural and metamorphic observations

The dominantly gneissic character of the eastern orthogneiss complex is well developed with four distinct phases of deformation recognized. An early gneissosity is observed and predates the more commonly agreed upon Paleoproterozoic structural elements (Machado et al., 20113: Skipton et al., 2013). The specific age of this early gneissosity will be assessed in future studies but it could be correlative with the metamorphic event dated in this region at 2770 Ma (Scott, 1999). There were likely multiple deformation events that affected the eastern orthogneiss complex in the Archean but, to be consistent with field terminology and other publications in this volume, the deformational fabric, folding and metamorphism will be labelled starting with the first recognizable Paleoproterozoic deformation event.

The first deformational event (D_1) recognized in the eastern orthogneiss complex also affects monzogranite in western Hall Peninsula that has been dated as Paleoproterozoic (Scott, 1999), thus resolving the D_1 pervasive fabric to be no older than Paleoproterozoic in age. This D_1 strain event is expressed as a regionally penetrative fabric that transposes and recrystallizes the earlier Archean gneissosity. The deformation signature is characterized by F_1-fold hinges that plunge shallowly to moderately to the southeast and northwest, with axial-planar foliation (S_1) defined by aligned biotite and layers of hornblende dipping to the southwest (Figure 5a, b). Local kinematic indicators, including asymmetric folds and sigma- and/or delta-type porphyroblasts, indicate west over east displacement. Mineral lineations (L_1) associated with D_1 are locally preserved as aligned hornblende±plagioclase in tonalitic to monzogranitic gneiss. In addition, L_1 lies within the axial plane to F_1 folds, plunges shallowly to the southwest and is locally preserved in overlying metasedimentary units as downdip lineations (cf. MacKay et al., 2013). Evidence of D_1 strain is only recognizable in areas of low D_2 strain, where S_1 fabric can be identified independently from S_2 fabric. The F_1 generation that folds compositional layering with only one recognizable fabric (axial-planar S_1 foliation) is rare in comparison to the more dominant F_2 generation that folds S_1 fabric.

The second deformational event (D_2) is characterized by open to isoclinal folds (F_2) with north-northwest–trending fold axes and variable strain gradients across the region (Figure 5c). A northwest to northeast or southwest-plunging lineation (L_2) defined by quartz and feldspar rodding (Figure 5d), and locally aligned hornblende is parallel to F_2-fold hinges. Moreover, both west-over-east and east-over-west kinematic indicators, including S and C' fabrics, are observed to be related to D_2. In one locality, just east of Allen Island (Figure 1), S_2 domains are observed within an earlier S_1 fabric (Figure 5e, f). The S_1 fabric is southeast-trending and dipping shallowly to the southwest, whereas S_2 fabric domains are northwest-trending and steeply dipping to the northeast.

A later (D_3) strain event is characterized by large, open folds (F_3) trending east-west and shallowly plunging to the west-southwest, with wavelengths ranging from 2 to 7 km. The large D_3 crossfolds produce dome-and-basin fold interference patterns, as observed from aerial reconnaissance. This folding also influences the topography throughout the eastern orthogneiss complex, locally creating tectonic 'windows' on anticlines and structural basins in the synclines. The Qaqqanittuaq study area (cf. MacKay et al., 2013) may be a structural basin created by F_3 folding a large F_2 fold. Moreover, L_2 features that are observed to plunge both toward the northwest to northeast and southwest (above) may have been initially parallel and now exhibit this variability of plunge as a result of D_3 crossfolding. The only rocks that are largely unaffected by any of these three major and pervasive strain events are the pegmatitic dikes, which crosscut all other fabrics, and the diorite to gabbro enclaves, which exhibit a massive texture.

Metamorphism throughout the eastern orthogneiss complex is characterized by the general assemblage biotite±plagioclase±hornblende±clinopyroxene±garnet in tonalitic gneiss and mafic rock units; this assemblage is indicative of upper-amphibolite–grade metamorphism. Epidote is locally present as part of the metamorphic assemblage in regions preserving lower-amphibolite–grade metamorphism. Tremolite and actinolite are major constituents of the ultramafic pods. The metasedimentary rocks also record assemblages of upper-amphibolite facies, including biotite+garnet±sillimanite. Granulite-grade assemblages, including orthopyroxene+biotite or garnet+clinopyroxene, are variably preserved in the larger diorite pods and/or enclaves throughout the eastern orthogneiss complex. The orthopyroxene, which is indicative of granulite-facies conditions, disappears toward the outer rims of the diorite pods that are in contact with the host tonalitic gneiss.

Migmatitic textures are seen locally throughout the eastern orthogneiss complex, appearing as layers of mineral segregations, leucosome development and large, irregular bodies of leucocratic material 10 cm to >1 m in size. It is

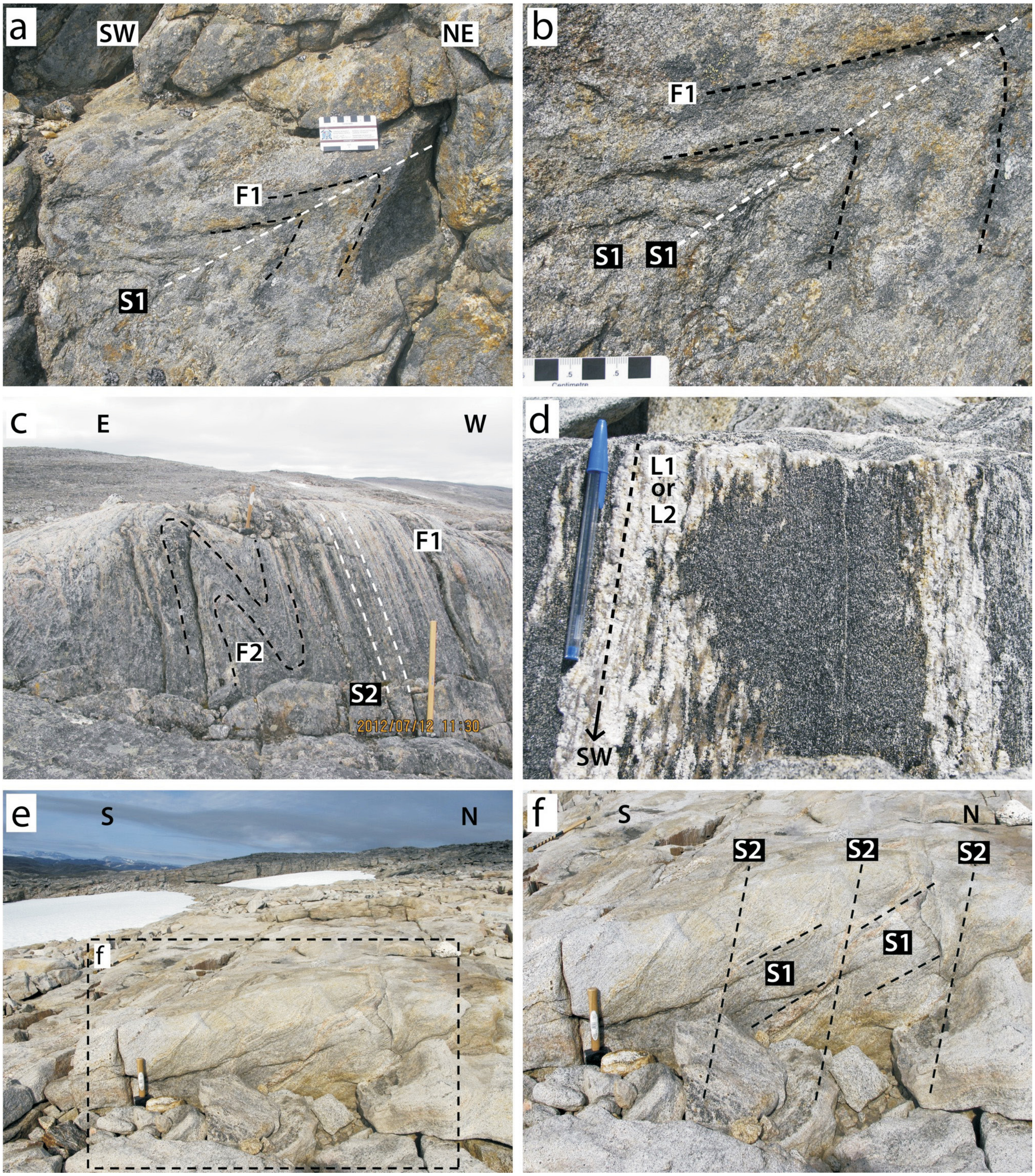

Figure 5. Field photographs of tonalite within the eastern orthogneiss complex of Hall Peninsula, Baffin Island, Nunavut, showing: **a)** an F_1 fold, where only one axial-planar fabric (S_1) is visible, defined by aligned biotite; **b)** an enlarged view of the F_1 fold from a); **c)** an F_2 fold in tonalitic gneiss verging to the east, with a west-dipping axial plane parallel to the S_2 fabric; **d)** southwest-dipping quartz and feldspar rodding lineation (L_1 or L_2), which is parallel to F_2 or re-aligned F_1-fold axes; **e)** a vertical face in tonalitic gneiss, showing dipping S_2 corridors within earlier S_1 fabric; **f)** an enlarged view of (e). Abbreviations: E, east; N, north; NE, northeast; S, south; SW, southwest; W, west.

possible that some of the monzogranitic to syenogranitic intrusive phases within the tonalite are a result of partial melting and remobilization.

Preliminary interpretations

The sequence, from oldest to youngest, of ultramafic rocks to gabbro, diorite, tonalite, monzogranite and syenogranite is evidence of an evolving crustal-magma source during generation of the eastern orthogneiss complex. Variations in these particular igneous rock compositions may indicate a continuum of changing magmatic conditions during tectonic assembly and modification of the Archean terrane. The general sequence of more mafic to felsic compositions is a common trend for igneous rocks associated with convergent-plate boundaries (Philpotts, 1990). Although plate tectonics during the Archean was not operating in the same manner as it does today, onset of the Wilson cycle of plate tectonics is thought to have initiated after 3.0 Ga, with subduction and collision becoming the main process of continental formation (Tappe et al., 2011). The occurrence of mafic and ultramafic rocks as enclaves within the tonalitic gneiss indicates that these rocks would have existed prior to emplacement of the tonalitic gneiss. Alternatively, it is possible that the mafic and ultramafic rocks were emplaced as later dikes and sills, after crystallization of the tonalite. Subsequent strain and deformation may have deformed (boudinaged) these rocks into the lenticular enclaves and discontinuous layers.

A garnet-bearing quartzite interleaved with the Archean tonalitic gneiss was reported to yield dominantly Archean detrital zircon ages (Scott, 1999). The presence of other Archean sedimentary rocks throughout the eastern orthogneiss complex is likely. Metasedimentary rocks from the western domain of Hall Peninsula were observed to have differing characteristics with regard to mineral assemblages and pervasive fabrics (Skipton et al., 2013) than those exposed within the eastern orthogneiss complex. The western metasedimentary panels, which have been dated as Proterozoic, appear to be better preserved, continuous (ranging from 10 m to 1 km in width) and sometimes display rhythmic layering, whereas some of the metasedimentary panels in the eastern region of Hall Peninsula are more weathered, rich in the metamorphic minerals garnet and sillimanite and, ranging from 2 m to 10 m in width, are less continuous. Both eastern and western metasedimentary rocks contain large and distinct leucosomes rimmed by biotite-rich melanosome indicating the presence of in situ partial melting.

At one locality just west of Brevoort Island (Figure 1), the tonalitic rocks within 1–5 m of the contact with metasedimentary panels contain garnet. This garnet in the tonalitic rocks may represent contamination by metasedimentary melt, possibly during an intrusion of Archean tonalite into Archean metasedimentary rocks or during subsequent remobilization events. The true nature of the contacts is obscured by later, intrusive pegmatite. Moreover, if there were Archean sediments deposited and preserved within the eastern orthogneiss complex, it is possible that some of the plutonic phases intruding the tonalitic gneiss were sourced by the partial melting of the Archean metasedimentary rocks during regional tectonism.

Other contacts between the eastern orthogneiss complex and metasedimentary panels observed just west of Allen Island (Figure 1) are sharp and parallel to foliation, with the metasedimentary rocks containing graphite and exhibiting a flaggy texture (Figure 4a). In addition, these metasedimentary rocks preserve well-defined rhythmic layering and are part of a larger continuous panel compared with the metasedimentary rocks just west of Brevoort Island. This observation, coupled with the composite nature of the gneiss and the absence of crosscutting relationships with the metasedimentary rocks, argues against a simple intrusive contact (screen structure) between these two rock types and instead favours a tectonic or depositional contact in this case. An intrusive relationship cannot be completely ruled out as subsequent high strain with large displacements can obliterate any evidence of an intrusive contact and also create these sharp contacts. In this alternative scenario, the observed graphite could be a product of later hydrothermal activity. Repetition of these metasedimentary panels with the same contact relationships was observed in adjacent areas; the repetition of interleaved gneiss/metasedimentary units in the eastern orthogneiss complex may be due to folding or thrust imbrication.

The preservation of possible granulite-grade assemblages within diorite enclaves in the orthogneiss complex leads to a number of interpretations. A possible early metamorphic event may have metamorphosed the eastern orthogneiss complex to granulite facies prior to the amphibolite-facies overprint. Alternatively, the ‘granulite-grade assemblage’ preserved in the diorite may be a reflection of an orthopyroxene-bearing (magmatic) protolith. In the latter case, the disappearance of orthopyroxene near the contact with the surrounding tonalite might be the result of re-equilibration of the diorite due to compositional differences with the host tonalite. If the former interpretation is correct, then the early granulite-facies event could potentially be related to tonalitic gneiss of the Nagssugtoqidian orogen (Aasiaat domain) in western Greenland, which is characterized by preserved granulite-facies assemblages, magmatic Archean ages of ca. 2880 to 2820 Ma and a possible tectonothermal event ca. 2810 to 2750 Ma (Jackson et al., 1990; Connelly and Mengel, 1996). These Archean ages are broadly similar to those documented by Scott (1999) for Hall Peninsula tonalitic gneiss. Notably, Archean tonalitic gneiss can be found on all other adjacent crustal blocks in the region, indicating the necessity of future analytical studies to further assess the tectonic reconstructions of Hall Peninsula.

Future work

The main objective of this project is to provide a framework for the eastern orthogneiss complex of Hall Peninsula. This will be an integral part of the overall HPIGP and will also have regional implications for reconstructing the assembly of Baffin Island and the subarctic region as a whole. Goals of the study are twofold: lithological and geochemical characterization of the eastern orthogneiss complex of Hall Peninsula and utilization of intrusive rocks as crustal probes to assess the isotopic signature of the variably exposed crust of Hall Peninsula.

Emplacement and evolution of the eastern orthogneiss complex will be investigated in detail through petrological and geochemical studies on the different plutonic phases. This will lead to a better understanding and characterization of the eastern orthogneiss complex, and comparisons can be made with other Archean complexes in the region. Geochronology can be used to further constrain the temporal relationships between the different phases of the eastern orthogneiss complex and the relationships to other known plutonic phases of Baffin Island. The tonalitic gneiss, which is dominant throughout the eastern orthogneiss complex, is of special interest as it raises many questions. For example, was it emplaced during one large pulse of intrusive activity or were there several smaller pulses of varying age, texture and composition? What is the source and cause of the observed partial melting? Was it emplaced as sheets or ballon-type plutons? When was it deformed and metamorphosed? What is its relationship to the sedimentary sequences?

Hall Peninsula has variably exposed portions of the orthogneiss complex, as well as areas where the gneissic complex may only occur at depth. With the eastern orthogneiss complex exhibiting a structural deepening to the west, it is plausible that these rocks continue underneath the younger plutonic and metasedimentary rocks of western Hall Peninsula. This limits the current level of understanding of the true extent of Hall Peninsula orthogneiss complex. If these younger plutonic phases to the west intruded though older crustal rocks at depth, then they can be used as a tool to assess the character of this underlying crust. Two of these plutonic rock types (charnockite and monzogranite, as described in Machado et al., 2013) occur with a large enough distribution and frequency throughout Hall Peninsula to be used as crustal probes to analyze the Nd-isotopic signature of the crust (e.g., Whalen et al., 2011). The unique Nd-isotopic signature of the underlying crust is inherited by the intrusive body that pierces it. This unique signature can then be compared directly with the Nd signature of the tonalitic gneiss in the eastern orthogneiss complex, to see if the orthogneiss complex does indeed extend underneath the rest of Hall Peninsula to the west. Subsequent comparisons can then be made with adjacent crustal blocks of the Rae craton, Meta Incognita microcontinent, western Greenland and Nain craton to better constrain models of the crustal evolution of Hall Peninsula. An east-west–sampling transect across Hall Peninsula exclusively to collect charnockite and monzogranite is planned for the 2013 field season.

Economic considerations

A detailed structural, petrological and isotopic characterization of the eastern orthogneiss complex can provide important emplacement relationships for these plutonic phases. With this information, correlations between rock types across Baffin Island and the entire subarctic can be conducted to improve the current level of understanding of basement architecture. Moreover, these data and maps provide a framework that can help target both areas of possible mineralization and carving-stone locales, two economically important industries for the communities of Nunavut. The ultramafic pods described above have a similar petrology to carving-stone material that is in demand and highlight the potential for larger and better quality carving-stone deposits to be found in this region. The associated geochemical and Nd-isotope investigations of the plutonic phases can help delineate the unique signature of both the exposed and buried crust on Hall Peninsula, in an attempt to compare it with the adjacent crustal domains. In addition, the geochemical and isotopic studies of intrusive units that were potentially sourced from the mantle can give insight into the genesis and possible location of diamond-bearing kimberlites on the peninsula. If the known diamondiferous kimberlites on Hall Peninsula can be associated with a particular geochemical signature or occurrence within a certain crustal domain, then improved strategies can be developed for vectoring toward additional deposits.

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Geological relationships in the Qaqqanittuaq area, southern Hall Peninsula, Baffin Island, Nunavut

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Abstract

This study is part of the Canada-Nunavut Geoscience Office's Hall Peninsula Integrated Geoscience Program, a multiyear bedrock and surficial geology mapping program with associated thematic studies. The Qaqqanittuaq area (QA), a southeast-trending, doubly plunging, synformal structural basin on the southern Hall Peninsula, Nunavut, contains rock units and relationships representative of the supracrustal rocks and mafic and ultramafic intrusions in the eastern domain of Machado et al. (2013). Biotite tonalite and intrusions of monzogranite and syenogranite form the crystalline, gneissic structural basement of the QA. The structural basin comprises a series of supracrustal rocks dominated by micaceous psammite with lesser quartzite and pelite. The supracrustal rocks are intruded by a series of mafic and ultramafic intrusions and younger monzogranite sills and dikes. Two distinct deformational events (D_1 and D_2) are thought to have occurred in the QA, with peak metamorphic conditions (upper amphibolite; M_1) being reached during D_1. The gneissic layering containing the peak metamorphic assemblage of sillimanite–garnet–K-feldspar–biotite was folded during D_2, when the structural basin developed. Post-D_2 monzogranite intrusions occur in the supracrustal sequence but are not observed in the crystalline, gneissic structural basement. Gossanous areas are locally present in the QA, most of which are attributed to the weathering of biotite. However, some are associated with quartz veining and contain minor sulphide (pyrite-pyrrhotite) mineralization.

Résumé

Cette étude fait partie du Programme géoscientifique intégré de la péninsule Hall, du Bureau géoscientifique Canada-Nunavut, un programme pluriannuel de cartographie du substratum rocheux et de la géologie de surface accompagnée d'études thématiques connexes. La zone Qaqqanittuaq (QA), un bassin structural synforme à double plongement de direction sud-est dans le sud de la péninsule Hall (Nunavut) comporte des unités lithologiques et des relations représentatives des roches supracrustales et des intrusions mafiques et ultramafiques du domaine oriental déterminé par Machado et al. (2013). La tonalite à biotite et des intrusions de monzogranite et de syénogranite forment le socle structural gneissique et cristallin de la zone QA. Le bassin structural comprend une série de roches supracrustales dominées par de la psammite micacée avec de petites quantités de quartzite et de pélite. Les roches supracrustales sont recoupées par une série d'intrusions mafiques et ultramafiques ainsi que de filons couches et de dykes de monzogranite plus récents. On pense que deux épisodes de déformation distincts (D_1 et D_2) ont eu lieu dans la zone QA, et les conditions maximales de métamorphisme (amphibolite supérieur; M_1) ont été atteintes pendant l'événement D_1. La stratification gneissique contenant l'assemblage métamorphique maximal de sillimanite-grenat- feldspath potassique-biotite a été plissé au cours de D_2, lors de la mise en place du bassin structural. Des intrusions de monzogranite post-D_2 se manifestent dans la séquence supracrustale, mais elles sont absentes du socle structural gneissique et cristallin. Des zones ferrugineuses sont présentes par endroits dans la zone QA, dont la plupart sont attribuées à l'altération de la biotite; cependant, certaines sont associées à des veines de quartz et renferment une minéralisation mineure en sulfures (pyrite-pyrrhotite).

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Introduction

The Hall Peninsula Integrated Geoscience Program (HPIGP) is being led by the Canada-Nunavut Geoscience Office in collaboration with the Government of Nunavut, Aboriginal Affairs and Northern Development Canada, Dalhousie University, University of Alberta, Université Laval, University of Manitoba, University of Ottawa, University of Saskatchewan, Nunavut Arctic College and the Geological Survey of Canada. It is supported logistically by several local, Inuit-owned businesses. The study area comprises all or parts of six 1:250 000 scale National Topographic System map areas north and east of Iqaluit (NTS 026A, B, 025I, J, O, P).

In the summer of 2012, fieldwork was conducted in the southern half of the peninsula (NTS 025 I, J, O, P) between June 22 and August 8. Fieldwork was supported by a 20–25 person camp located approximately 130 km southeast of Iqaluit. The focus was on bedrock mapping at a scale of 1:250 000 and surficial-sediment mapping at a scale of 1:100 000. A range of thematic studies was also supported. This included Archean and Paleoproterozoic tectonics, geochronology, landscape uplift and exhumation, detailed mapping in mineralized areas, microdiamonds, sedimentary rock xenoliths and permafrost. Summaries and preliminary observations for all of these studies can be found in this volume.

During the summer of 2012, a mapping project was conducted in the Qaqqanittuaq area (QA) to study the geological relationships in an approximately 50 km^2 area of the southern Hall Peninsula, Baffin Island, Nunavut (Figures 1, 2). The study area has strategic value in that it has excellent exposure and contains rock units and relationships that are representative of the supracrustal rocks found in the eastern domain of the Hall Peninsula, as defined by Machado et al. (2013). The supracrustal rocks in the QA may represent an eastern facies of the Lake Harbour Group of southern Baffin Island (St-Onge et al., 2006; Figure 1).

The QA was previously mapped at reconnaissance scale in 1966 during the Geological Survey of Canada's Operation Amadjuak (Blackadar, 1966). The 1966 study interpreted the QA to consist principally of biotite-quartz-feldspar gneiss, sillimanite gneiss and schist, and garnet-biotite-quartz-feldspar gneiss. The mineral rights for parts of the QA were previously held by International Capri Resources Ltd. during the 1990s under mineral permits 1884 and 1892 (Lichtblau, 1997).

In general, the QA forms a synformal structural basin, approximately 15 km long by 3.5 km wide, that trends southeast (Figure 2). Field relationships described below suggest that a tonalite gneiss complex forms the stratigraphic and structural crystalline basement to a supracrustal sequence comprising siliciclastic strata intruded by a series of mafic and ultramafic sills and monzogranite intrusions. Mineral assemblages indicate that rocks in the QA were subjected to upper-amphibolite-facies metamorphic conditions. In addition, there is clear evidence that the area was subjected to at least two distinct deformational events. This paper describes the distinct rock units and their field relationships, discusses the evidence for and implications of the observed metamorphic and deformational events, and outlines the economic potential of the QA.

Detailed mapping of the QA was completed by combining focused mapping in key areas, helicopter-assisted reconnaissance and a detailed east-west transect across the entire width of the central QA synformal structural basin (Figure 2). Locations and measurements in the field were recorded on an HP iPAQ 210 device running GPS-integrated GIS software. All interpretations of mineralogy, structure and metamorphism are derived from field observations.

Description of rock types

Tonalite gneiss complex

The tonalite gneiss complex (Figure 3a) comprises predominantly biotite tonalite (70%), and younger, crosscutting, white-weathering monzogranite (20%) and pink syenogranite (10%). Both the monzogranite and the syenogranite occur as thin sheets and stringers that are typically centimetres to decimetres in thickness. However, metre-scale monzogranite intrusions have been observed. The monzogranite and syenogranite intrusions crosscut an earlier gneissosity—visible in lower strain regions described below—but are themselves deformed and metamorphosed. Mafic enclaves, which are typically lenticular and range in scale from several centimetres to more than 10 m, are observed throughout the tonalite gneiss complex. The enclaves are interpreted to be deformed mafic inclusions and/or deformed, boudinaged, premetamorphic mafic dikes. Two generations of pegmatite dikes intrude the tonalite gneiss complex. The first is of syenogranite composition and is overprinted by the regional fabric. This type of dike is thought to represent a pegmatitic phase of the syenogranite intrusions pervasive throughout the tonalite gneiss complex. The other pegmatite is broadly granitic in composition and crosscuts all fabrics. One of the deformed syenogranite pegmatite dikes in the QA was sampled by N.M. Rayner for U-Pb geochronology, in order to place a minimum age on the regional fabric and a maximum age on the deposition of the supracrustal rocks (Figure 2).

Quartzite

Fine- to medium-grained quartzite occurs as discrete, thin (<1 m), laterally continuous layers that commonly contain up to 1% graphite. Quartzite occurs at or just above the contact between the tonalite gneiss complex and the supracrustal rocks at all observed localities. Graphitic quartzite also

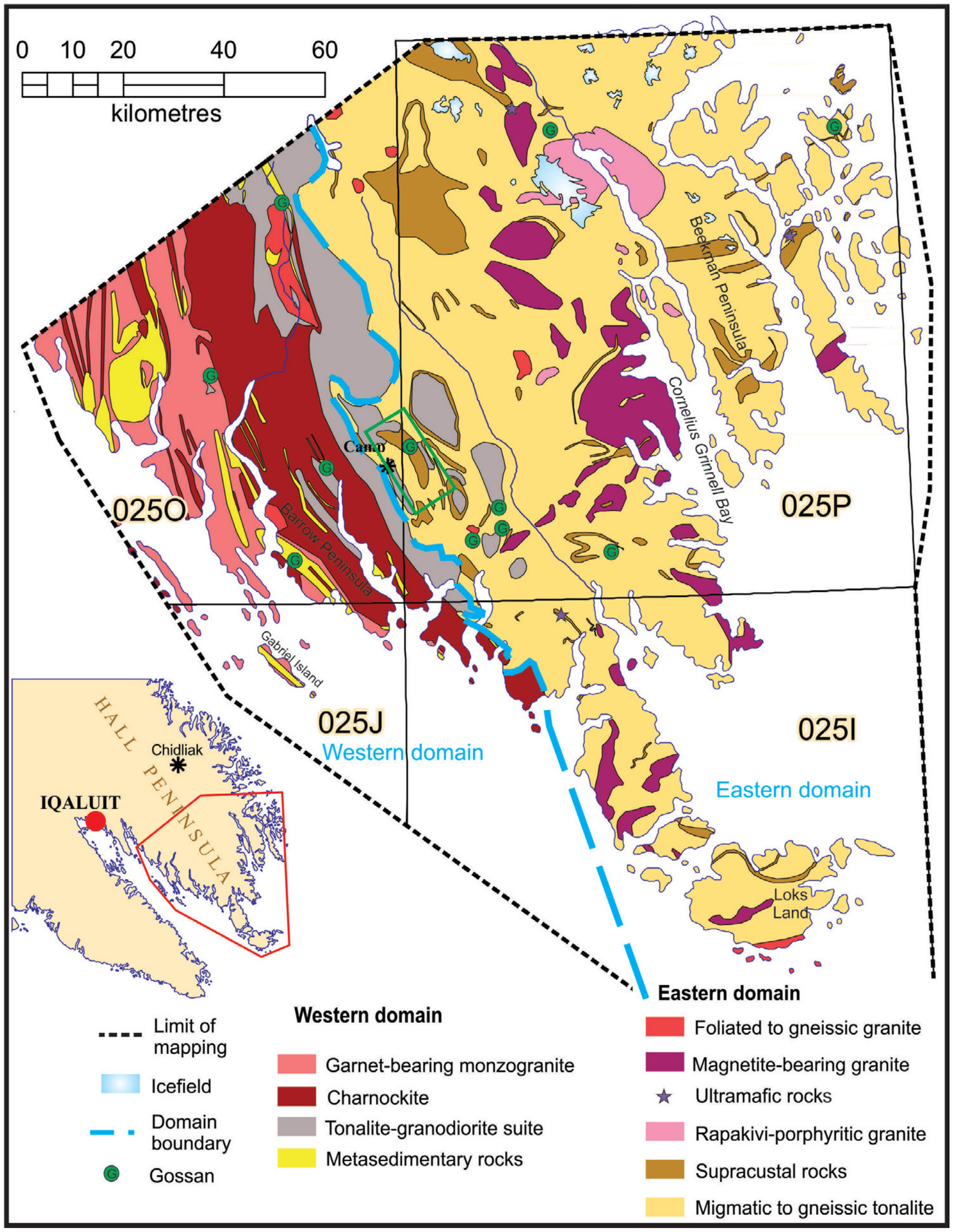

Figure 1: Geology of southern Hall Peninsula, Baffin Island, Nunavut (after Machado et al., 2013). Green box outlines the Qaqqanittuaq area (Figure 2).

occurs in a distinct, 1–2 m thick boudinaged layer within the micaceous psammite that is traceable along strike (Figure 3b). A sample of quartzite was taken from the QA by N.M. Rayner for detrital zircon U-Pb geochronology (Figure 2).

Micaceous psammite

Micaceous psammite (Figure 3c) comprises the bulk of the supracrustal rocks within the QA structural basin. Quartz-plagioclase-biotite±sillimanite±garnet is dominant metamorphic mineral assemblage. Sillimanite occurs as faserkiesel aggregates. The garnet porphyroblasts are commonly rimmed by plagioclase and biotite.

Pelite

Pelite is found throughout the supracrustal package and ranges from centimetre-scale layers within the micaceous psammite to discrete intervals up to 2 m thick. Mineralogically, the pelite contains biotite–plagioclase–quartz±garnet±sillimanite±K-feldspar. Near fold hinges, garnet porphyroblasts greater than 10 cm in length are observed (Figure 3d).

Mafic and ultramafic rocks

Mafic rocks of the QA range from thin (<2 m), continuous and discontinuous amphibolite layers within the siliciclastic supracrustal rocks to thick (>5 m), discrete, laterally continuous amphibolite units. All mafic rocks within the supracrustal sequence are found within 500 m of the underlying contact with the tonalite gneiss complex and are interpreted as mafic sills and dikes. On the west limb of the QA adjacent to the contact with the tonalite gneiss complex, mafic rocks occur as thin, discontinuous, highly deformed layers (Figure 4a). Higher in the supracrustal package, on the west limb, there is a thicker (3–5 m), discrete mafic layer within the supracrustal rocks. On the east limb of the QA, mafic rocks occur as three thick (3–5 m), laterally continuous layers and as minor, thin (<1 m) discontinuous layers near the contact with the tonalite gneiss complex. Hornblende-plagioclase-biotite±garnet is the dominant mineral assemblage in the mafic rocks.

Ultramafic rocks occur primarily within a distinct, layered, boudinaged unit traceable along strike. Structurally lower layers of this boudinaged ultramafic unit are massive and contain centimetre-scale orthopyroxene oikocrysts (Figure 4b). Upper layers are strongly foliated and consist almost entirely of amphibole. Isolated ultramafic pods also occur near the contact with the tonalite gneiss complex; one such pod is thoroughly recrystallized and contains abundant actinolite, chlorite, talc and chromium diopside (Figure 4c).

Monzogranite

Dikes and sheets, up to 2 m thick, of white-weathering, medium-grained, garnet-bearing monzogranite are found throughout the supracrustal sequence but occur primarily in contact with mafic rocks. The monzogranite intrusions are observed both concordant and discordant with the regional fabric (Figure 4d). The occurrence of concordant monzogranite intrusions is interpreted to be controlled by rheological contrasts between the amphibolite and the supracrustal rocks, not as a predeformation intrusive phase. The garnet monzogranite makes up less than 1% of the region and individual intrusions are too small to be shown on the map (Figure 2). A sample of a large (2 m wide) discordant monzogranite dike in the QA was taken by N.M. Rayner for U-Pb geochronology, in order to determine minimum age of the supracrustal rocks within the QA (Figure 2).

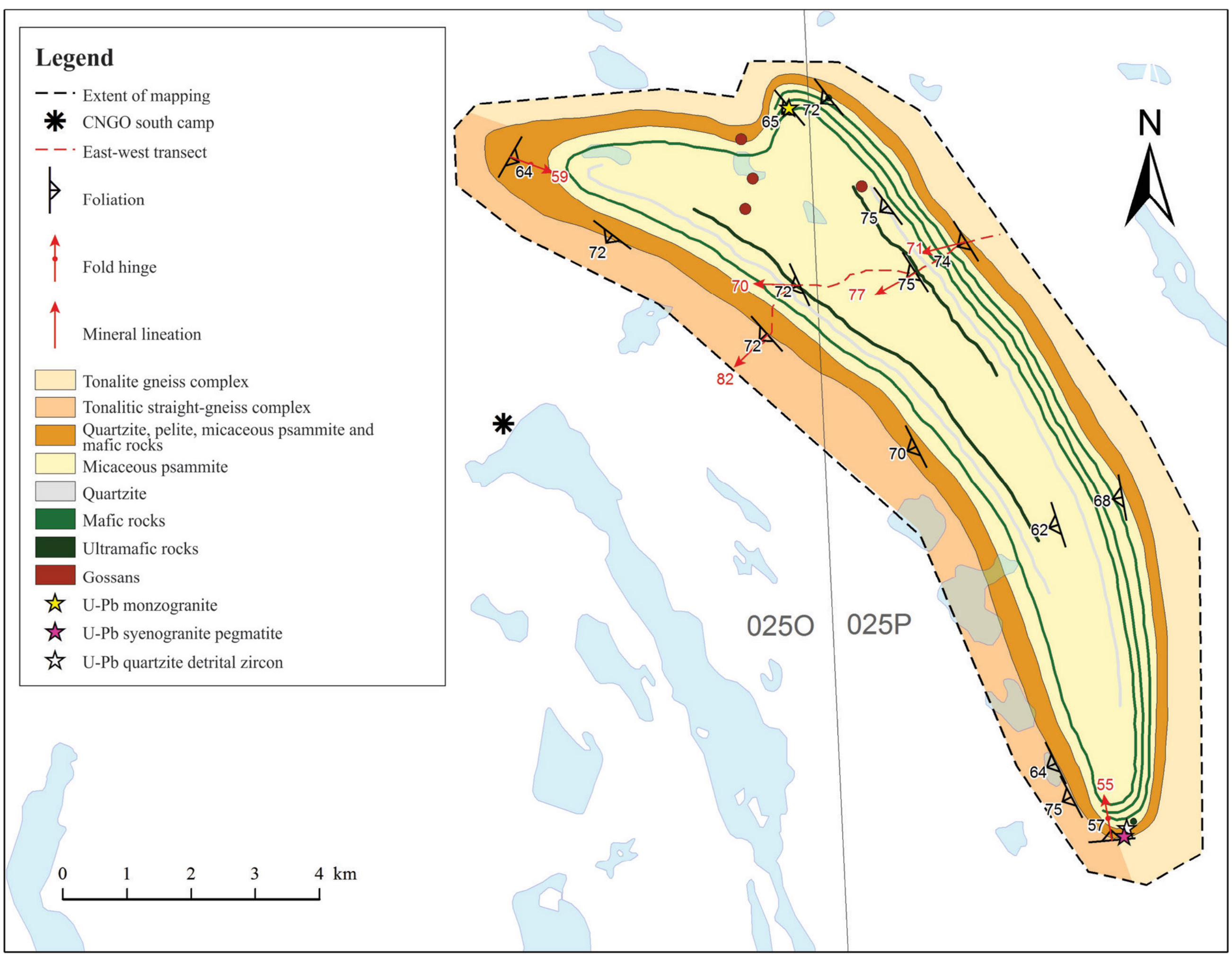

Figure 2: Geology of the Qaqqanittuaq area.

Deformation and metamorphism

The QA comprises a southeast-trending, doubly plunging, synformal structural basin with a large (approximately 800 m across), well-preserved parasitic fold on its eastern limb (Figure 5a). Limb repetition of all major rock types was observed during a detailed transect across the QA conducted in August 2012 (Figure 2), indicating lateral continuity of units across the basin.

Within the pelitic rocks, sillimanite–K-feldspar–garnet–biotite–plagioclase–quartz assemblages indicate that upper-amphibolite-facies conditions were reached during M_1. A southeast-trending, west-dipping schistosity (S_1) is observed in all rock types. The S_1 fabric, which may have been overprinted by a parallel S_2 fabric, is folded by southeast-trending F_2 folds (Figure 5b).

On the limbs of the QA structural basin, a down-dip, transverse L_1 lineation defined by sillimanite and sillimanite+K-feldspar faserkiesel is commonly observed in pelite, with L_1 lying in the plane of S_1 (S_1=L_1). The S_1 fabric varies from very strong, protomylonitic ‘straight gneiss’ (Figure 5c) on the west limb to weak on the east limb. In the hinge of the fold, there are hinge-parallel lineations (L_2), defined by faserkiesel (Figure 5d), that are interpreted to be the result of extension during F_2 folding. The consistency of strike and dip direction across the basin indicates tight folding. The S_1=L_1 fabric may be the result of east-verging thrust imbrication during a D_1 event that was later folded during a second deformational event (D_2). If this is the case, the S_1=L_1 fabric is coplanar with an overprinted S_2 fabric, indicating that ó$_1$ was broadly collinear for both the D_1 and D_2 deformational events. Alternatively, the down-dip lineations (L_1) and the hinge-parallel lineations (L_2) may have been formed during the same folding event. In this case, the down-dip lineations represent the long axis of the strain ellipsoid for the F_2 folding event.

Faserkiesel are prevalent throughout the micaceous psammite and common in pelite in the QA. Using the model that invokes thrust imbrication followed by folding, the shape of faserkiesel across the basin can be used to interpret the cumulative influence of each deformational event at a particular locality. Near the contact with the tonalite gneiss

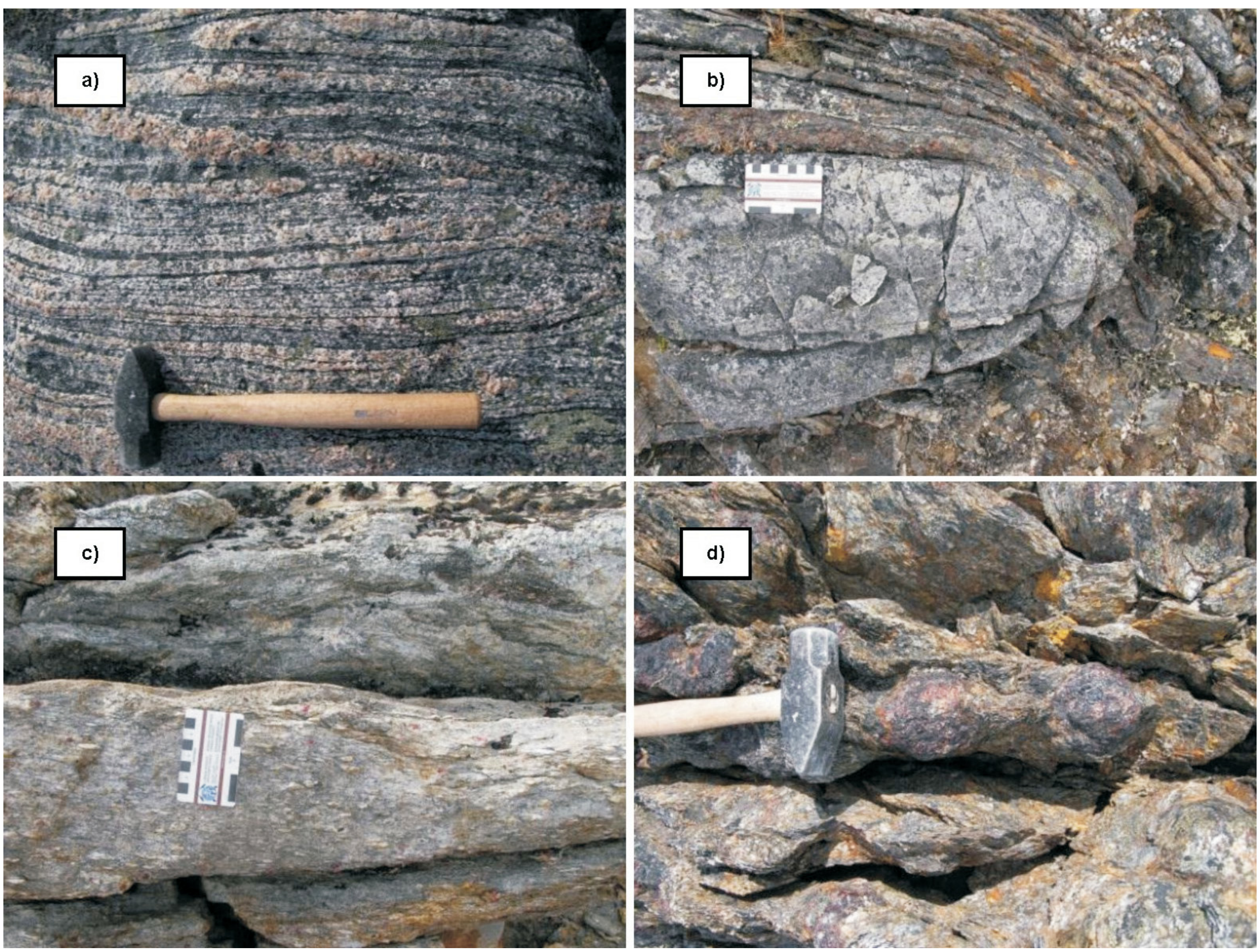

Figure 3: a) Tonalite gneiss complex, outcrop K069. **b)** Boudinaged quartzite, outcrop K121. **c)** Micaceous psammite, outcrop K126. **d)** Garnet porphyroblast in biotite-quartz-plagioclase-sillimanite pelite, outcrop K153.

complex, faserkiesel define a strong, down-dip, transverse lineation, indicating that $D_1>D_2$ (Figure 5d). Garnet, biotite and plagioclase appear in textural equilibrium and, together with sillimanite, will be used to determine the pressure-temperature conditions during D_1. At some distance from the contact with the tonalite gneiss complex, faserkiesel are more pancake shaped, indicating a roughly equal contribution from the two deformational events ($D_1 \approx D_2$; Figure 5e). In the core of the fold, faserkiesel define a hinge-parallel lineation, indicating that $D_2>D_1$ (Figure 5f). Garnet porphyroblasts rimmed by both plagioclase and biotite are observed in the same hinge-parallel orientation as the faserkiesel (Figure 5f). The rimmed garnet porphyroblast assemblage will be analyzed to determine the pressure-temperature conditions of the D_2 deformational event. If both pressure-temperature analyses reflect the same metamorphic conditions, then it is more likely that D_2 folding resulted in both L_1 and L_2, in which case the faserkiesel shape is a reflection of differences in pure shear versus simple shear across the basin during folding.

Nearly all contacts between rock types in the QA have been transposed about the main, regional, southeast-trending, west-dipping planar fabric. However, on the east limb of the QA structural basin, where schistosity is weakest, the contact between the tonalite gneiss complex and the supracrustal rocks has not been completely transposed into the dominant regional orientation (Figure 6a). Along the eastern contact, there is a transition from the structurally lower tonalite gneiss upward through a 20 m thick zone containing blocks of tonalite gneiss in a pelitic to psammitic matrix (Figure 6b) into the siliciclastic supracrustal rocks. This blocky zone may represent a locally preserved paleoregolith, which would imply that the supracrustal units originally accumulated on top of the underlying tonalite gneiss complex prior to subsequent structural transport. Alternatively, the tonalite blocks may have been tectonically entrained, in which case the stratigraphic relationship between the tonalite gneiss complex and the supracrustal rocks remains unclear.

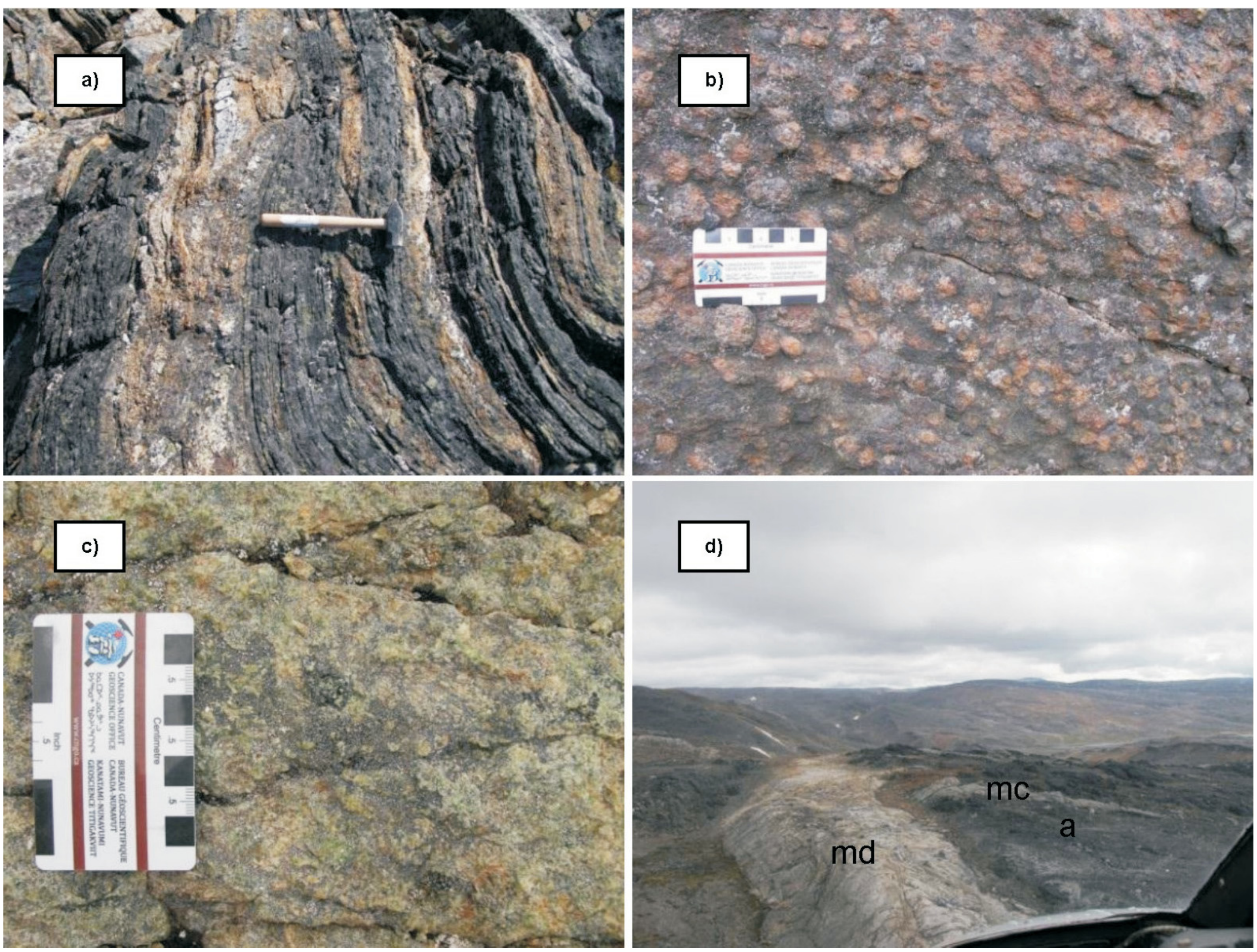

Figure 4: a) Mafic layers interbedded with micaceous psammite and pelite, outcrop K079. **b)** Orthopyroxene oikocrysts in peridotite, outcrop K127. **c)** Altered ultramafic rock, outcrop K099. **d)** West-facing aerial photograph of discordant monzogranite (md) crosscutting amphibolite (a) and concordant monzogranite (mc), outcrop K079.

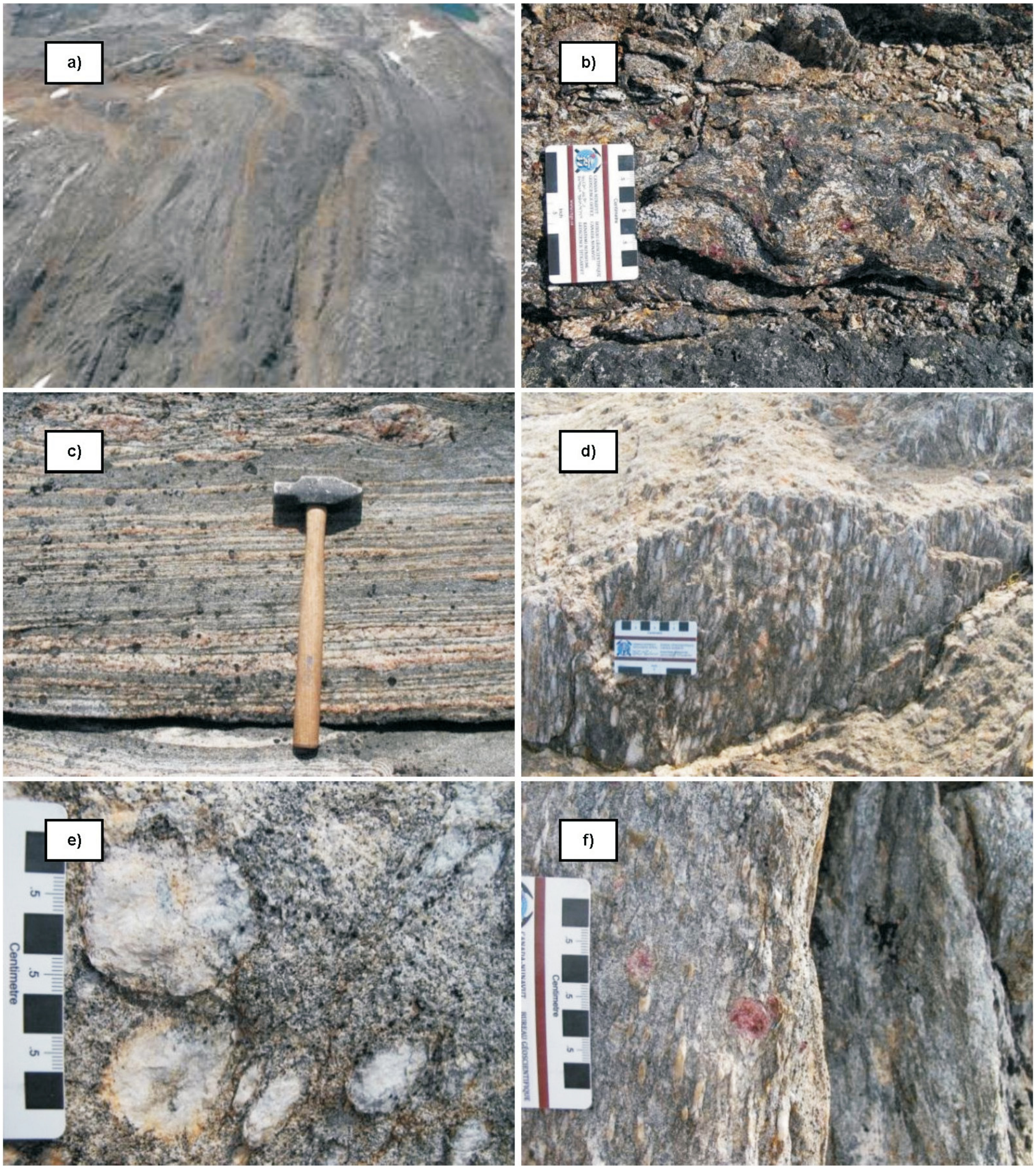

Figure 5: a) North-facing aerial photograph of parasitic fold on east limb of QA; horizontal distance of photograph is approximately 600 m. **b)** Biotite–garnet–sillimanite–K-feldspar mineral assemblage folded by D_2, outcrop K074. **c)** Protomylonitic 'straight gneiss' in tonalite gneiss complex, outcrop K094, west limb of QA. **d)** Faserkiesel where $D_1>D_2$, outcrop K124. **e)** Faserkiesel where $D_1 \approx D_2$, between outcrops K124 and K125. **f)** Faserkiesel where $D_1<D_2$, with biotite and plagioclase rimming garnet porphyroblasts parallel to faserkiesel, outcrop K125.

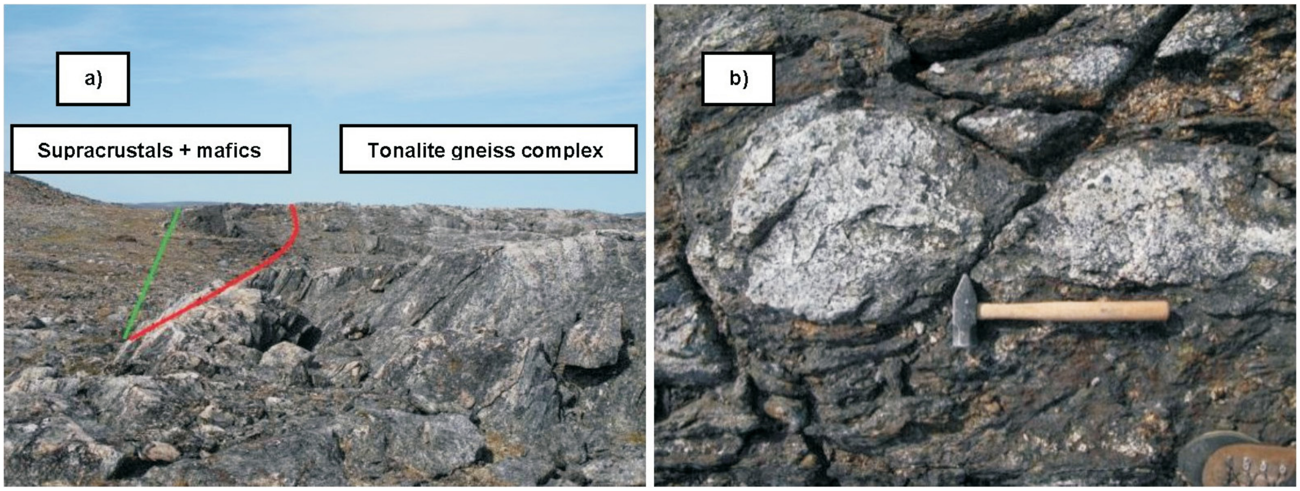

Figure 6: a) Contact between tonalite gneiss complex and supracrustal rocks (red line) not transposed into S_1 orientation (green line), outcrop K069. **b)** Blocks of tonalite in pelitic-psammitic groundmass, possibly representing paleoregolith, outcrop K069.

It should be noted that deformation events, folds and fabric elements described in this paper were observed from a local area and the nomenclature surrounding them may not align with regional observations. For instance, the S_1 fabric described herein may correspond to an earlier or later fabric when viewed from a regional perspective.

Economic considerations

Mineral rights for a portion of the QA were held by International Capri Resources Ltd. during the 1990s under mineral permits 1884 and 1892. The company produced a 1:7 500 scale geological map; conducted a 1:50 000 scale VLF-EM–magnetic survey of the area; and assayed four grab samples for Au, Cu, Ni, Zn, Pt, Pd and Ag. The company reported results as high as 823 ppm Cu, 218 ppm Ni, 149 ppm Zn and 89 ppb Au (Lichtblau, 1997). Large (>100 m across) gossanous areas (Figure 7a) are present in the QA. When investigated in outcrop, most of the gossans were attributed to the breakdown of biotite; however, minor gossanous quartz veining (Figure 7b) showed anomalously high concentrations of pyrite (~2%) and pyrrhotite (~2%). A sample of this material was taken for analysis. The association with quartz veins may suggest that mineralization formed from a hydrothermal source. The metamorphic grade may suggest that the potential for gold mineralization in the region is low; however, a recent paper by Garde et al. (2012) showed that an Archean epithermal gold deposit from southwestern Greenland was preserved through upper-amphibolite-grade metamorphic conditions.

Summary

Tonalitic gneiss—possibly correlative with tonalitic rocks of the eastern Archean gneiss domain defined by Scott (1999) and described further by From et al. (2013)—was intruded by both syenogranite and monzogranite to form an intrusive complex of crystalline rocks. Next, a sequence of

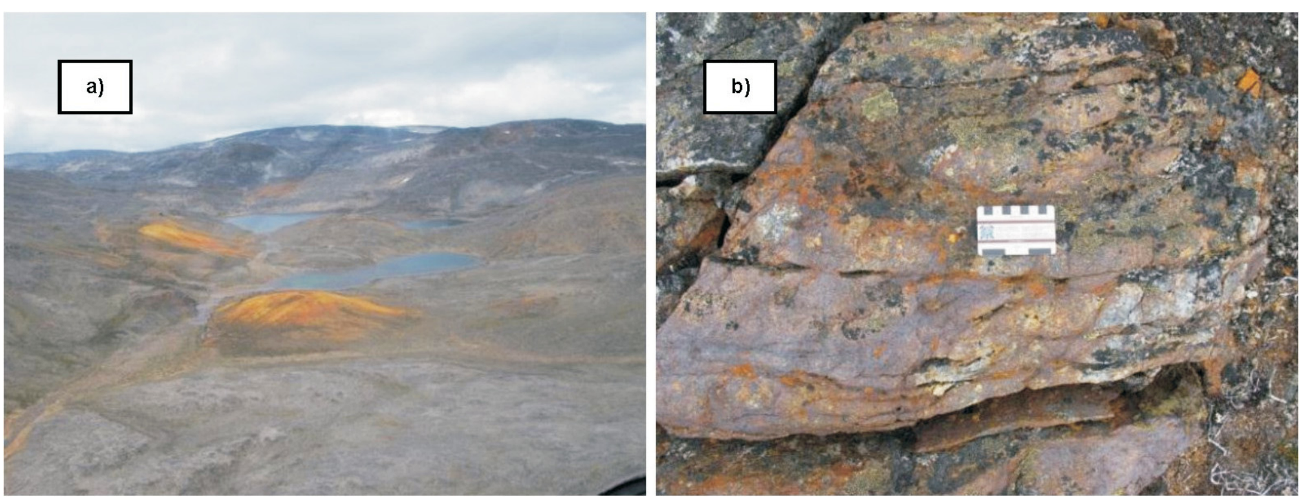

Figure 7: a) West-facing aerial photograph of large gossanous areas, UTM Zone 19, 64945125E, 702207964N, NAD 83 (foreground) and 64935227E, 702161446N (background). **b)** Sulphide-bearing quartz vein, outcrop K120.

supracrustal rocks, comprising pelite, micaceous psammite and quartzite, was likely deposited on top of the tonalite gneiss complex and a suite of mafic and ultramafic dikes and sills was emplaced into the supracrustal rocks. Regional deformation (D_1) and metamorphism (M_1), possibly linked to the Trans-Hudson orogeny and involving west over east transport in the QA, is suggested by down-dip mineral lineations observed in pelite. During M_1, upper-amphibolite-grade peak metamorphic conditions were attained and the dominant southeast-trending schistosity was developed. A second regional deformational event (D_2) resulted in folding of this schistosity and the development of the QA synformal basin. Hydrothermal activity, possibly associated with fluid flow during deformation and/or metamorphism, resulted in the formation of quartz veins containing sulphide (pyrite and pyrrhotite) mineralization.

Acknowledgments

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Field observations on D_1 and D_2 deformation fabrics and metamorphic mineral growth in the Newton Fiord region of Hall Peninsula, Baffin Island, Nunavut

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Abstract

This study is part of the Canada-Nunavut Geoscience Office's Hall Peninsula Integrated Geoscience Program, a multiyear bedrock and surficial geology mapping program with associated thematic studies. To determine the tectonic evolution of polydeformed terrains, the deformation phases and metamorphic events must first be unravelled and defined. Two small map areas on southern Hall Peninsula with contrasting structural styles were mapped and sampled in detail in order to characterize the mineral-fabric relationships and decipher the kinematic and thermal conditions of two deformation phases. The D_1 deformation is characterized by a regionally penetrative, bedding-parallel flattening-fabric defined by sillimanite+garnet+K-feldspar+orthopyroxene, with an associated garnet+cordierite+K-feldspar+melt leucosome formation. The D_2 deformation is characterized by a variable strain gradient reflected in almost complete transposition of D_1 fabric elements on regional F_2 fold limbs, in contrast to a spaced S_2 crenulation cleavage in regional F_2 fold hinges. The thermal conditions of D_2 appear to be lower where the new fabric is defined by sillimanite+garnet+biotite±K-feldspar. The regional F_2 fold hinges are windows into the earlier deformation phase, in which S_1 is consistently oriented east-northeast, possibly reflecting the original orientation and therefore providing insight into the transport direction of the main penetrative deformation phase.

Résumé

Cette étude fait partie du Programme géoscientifique intégré de la péninsule Hall, du Bureau géoscientifique Canada-Nunavut, un programme pluriannuel de cartographie du substratum rocheux et de la géologie de surface accompagnée d'études thématiques connexes. Pour déterminer l'évolution tectonique des terrains polydéformés, il faut d'abord élucider et définir les phases de déformation et les événements métamorphiques. Deux petites zones dans le sud de la péninsule Hall présentant des styles structuraux contrastants ont été cartographiées et échantillonnées en détail dans le but de caractériser les relations minéraux-fabrique et déchiffrer les conditions cinématiques et thermiques des deux phases de déformation. La déformation D_1 est caractérisée par une fabrique à aplatissement parallèle au litage et à pénétration régionale définie par un assemblage à sillimanite+grenat+feldspath potassique+orthopyroxène, avec une formation associée de grenat+cordiérite+feldspath potassique+leucosome fondu. La déformation D_2 est caractérisée par un gradient de contrainte variable reflété dans la transposition presque complète des éléments de fabrique D_1 sur les flancs des plis F_2 régionaux, à l'opposé d'une schistosité de crénulation S_2 espacée dans les charnières des plis F_2 régionaux. Les conditions thermiques de D_2 semblent être moins élevées aux endroits où la nouvelle fabrique est définie par un assemblage à sillimanite+grenat+biotite±feldspath potassique. Les charnières des plis F_2 régionaux permettent d'observer directement les résultats de la phase de déformation précoce, dans laquelle S_1 est constamment orientée en direction est–nord-est, reflétant peut-être l'orientation initiale et donnant ainsi un aperçu de la direction du transport de la phase de déformation pénétrante principale.

This publication is also available, free of charge, as colour digital files in Adobe Acrobat® PDF format from the Canada-Nunavut Geoscience Office website: http://cngo.ca/.

Introduction

The Hall Peninsula Integrated Geoscience Program (HPIGP) is being led by the Canada-Nunavut Geoscience Office in collaboration with the Government of Nunavut, Aboriginal Affairs and Northern Development Canada, Dalhousie University, University of Alberta, Université Laval, University of Manitoba, University of Ottawa, University of Saskatchewan, Nunavut Arctic College and the Geological Survey of Canada. It is supported logistically by several local, Inuit-owned businesses. The study area comprises all or parts of six 1:250 000 scale National Topographic System map areas north and east of Iqaluit (NTS 025I, J, O, P, 026A, B).

In the summer of 2012, fieldwork was conducted in the southern half of the peninsula (NTS 025 I, J, O, P) between June 22 and August 8. Fieldwork was supported by a 20–25 person camp located approximately 130 km southeast of Iqaluit. The focus was on bedrock mapping at a scale of 1:250 000 and surficial-sediment mapping at a scale of 1:100 000. A range of thematic studies was also supported. This included Archean and Paleoproterozoic tectonics, geochronology, landscape uplift and exhumation, detailed mapping in mineralized areas, microdiamonds, sedimentary rock xenoliths and permafrost. Summaries and preliminary observations for all of these studies can be found in this volume.

Hall Peninsula, located on southeastern Baffin Island, Nunavut, represents an underexplored region of Canada's North because the current geoscience knowledge dates largely from the 1960s (Blackadar, 1967) and thematic mapping and geochronological studies in the 1990s (Scott, 1996, 1999). The Canada-Nunavut Geoscience Office undertook the first of two field seasons of regional bedrock and surficial mapping during the summer of 2012 (Machado et al., 2013; Tremblay et al., 2013). Based on this mapping, Hall Peninsula has been divided into two broad lithological domains: an eastern domain of Archean orthogneiss and a western domain of ca. 1860 Ma charnockite and Paleoproterozoic metasedimentary rocks (Figure 1; Scott, 1996, 1999; Machado et al., 2013). The earliest recognizable Paleoproterozoic deformation (D_1) is characterized by a foliation that is generally bedding parallel and accentuated with a partial melt phase. The second deformation (D_2) event transposes bedding and earlier fabrics, and controls the north-northwest-trending regional map pattern (Figure 1). This study aims to define the mineral growth–deformation fabric relationships in a 4 km^2 area on southwestern Hall Peninsula in order to characterize the kinematic and thermal conditions of D_1 and D_2. The study area straddles Newton Fiord in the central metasedimentary contact zone, where two sites with contrasting deformation styles were examined in detail (Figure 2). The northeastern and southwestern map areas are called 'Sillimanite ridge' and 'Barrow Peninsula', respectively.

Newton Fiord region

Newton Fiord is located on the southwestern edge of Hall Peninsula, within the aforementioned western domain where clastic metasedimentary rocks of inferred Paleoproterozoic age are cut by orthopyroxene-bearing monzogranite (charnockite; Figures 1, 2). The southwestern map area, Barrow Peninsula, is interpreted to lie within the hinge of a regional F_2 fold, whereas the northeastern map area, Sillimanite ridge, is interpreted to occur on the eastern limb of that fold and records strong to intense D_2 transposition (Figure 2).

Sillimanite ridge map area (Figure 3)

Rocks in the Sillimanite ridge area consist primarily of interbedded pelite and psammite (Figures 3, 4). The mineral assemblage in the pelite includes biotite, sillimanite, K-feldspar and large garnet porphyroblasts up to 8 cm in diameter (Figure 4a). The psammite is fine grained and quartz rich, with garnet porphyroblasts up to 2 cm in diameter (Figure 4b). The oldest metaplutonic unit is an orange-weathering charnockite composed of biotite, greasy green plagioclase and variable amounts of garnet. It outcrops at the western end of the Sillimanite ridge area (Figure 3a) but also occurs as minor bedding-parallel sheets within the pelite and psammite. All rocks are cut by a white-weathering leucocratic monzogranite with distinctive lilac-coloured garnet.

Particularly within the pelite, D_1 is characterized by a bedding-parallel foliation (S_1) defined by sillimanite+garnet+K-feldspar. The D_1 fabric elements are dominated by a flattening fabric (S_1) with little to no mineral lineation (L_1). The D_2 deformation is characterized by transposition of D_1 fabric elements on the limbs of tight to isoclinal F_2 folds. In the hinges of minor- and meso-scale F_2 folds, S_1 is crenulated by a weak axial-planar foliation, defined by the alignment of sillimanite and biotite parallel to the regional southeast trend of D_2 structures. The F_2 folds are isoclinal at the western boundary of the Sillimanite ridge map area and become progressively more open toward the east (Figure 3b–d). The leucosome associated with D_1 is generally bedding parallel and folded by F_2 folds (Figure 4d). It is unclear in outcrop if the sillimanite is new growth or reoriented. In some specimens, garnet overgrows early-formed sillimanite and is wrapped by later sillimanite (M_2 or reoriented M_1), in which the long axis is parallel to L_2 lineation.

Barrow Peninsula study area (Figure 5)

The Barrow Peninsula area consists of interbedded pelite, semipelite and psammite with minor calcsilicate lenses and subordinate crosscutting orthopyroxene-bearing monzogranite and leucocratic garnet-bearing monzogranite (Fig-

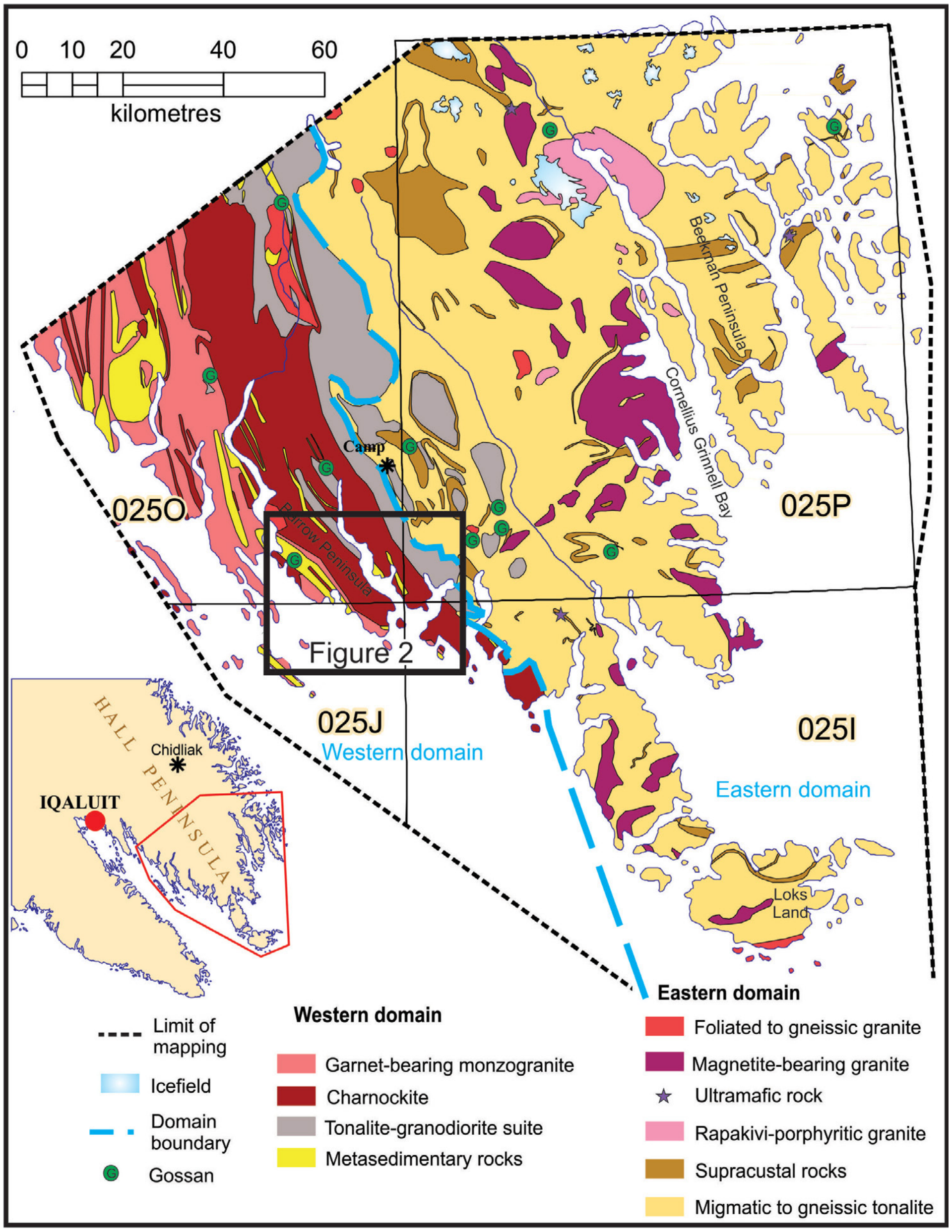

Figure 1: Preliminary simplified geology of Hall Peninsula (from Machado et al., 2013), showing the major tectonostratigraphic domains and the Newton Fiord region.

ures 5, 6). The map area is dominated by inhomogeneous diatexite hosting rafts of more refractory psammite (Figures 5d, 6a, c). The diatexite is interpreted as pelite with a high content of partial melt and consists of quartz, plagioclase, sillimanite, K-feldspar, cordierite and garnet (Figure 6a). Orange-weathering rusty semipelite is composed of graphite, biotite, orthopyroxene, K-feldspar and minor sillimanite (Figures 5b, c, 6d). Calcsilicate lenses range in size from 0.3 to 4 m and occur throughout the map area within all units; the one shown in Figure 6d is folded within the semipelite. They typically have a mineral assemblage of biotite, pyroxene, quartz and plagioclase. Two metaplutonic units are well exposed just outside the map area. The older of the two is an orthopyroxene-bearing monzogranite and is composed of biotite, greasy green plagioclase, hornblende and minor garnet. The younger unit is a leucocratic garnet monzogranite, composed of characteristically glassy grey quartz, and lilac-coloured garnet porphyroblasts.

The D_1 deformation is characterized by a well-developed bedding-parallel foliation defined by aligned garnet+ sillimanite+K-feldspar. The D_2 deformation is characterized by open to close folds associated with a spaced and variably developed axial-planar S_2 foliation and a moderately developed sillimanite-defined lineation in F_2 hinges. The spaced S_2 foliation affects S_1 and occurs in narrow (2–

3 cm) bands spaced approximately 15–20 cm apart (Figure 7). This localized S_2 planar fabric is interpreted as shear related within the hinges and on the limbs of F_2 folds. The S_1 orientation in the intervening areas between the shear-related foliation is generally east-northeast trending, which may reflect the original trend of D_1 foliation (Figure 7). In some F_2 hinges, garnet overprints early sillimanite but is also wrapped by later sillimanite.

Comparison and summary

Table 1 summarizes the fabric elements and associated mineral assemblages for the deformation phases and metamorphic events at Sillimanite ridge and Barrow Peninsula. The D_1 deformation is characterized by a strongly developed, penetrative, bedding-parallel flattening fabric and is comparable in both areas. The D_2 deformation is characterized by a variable strain gradient reflected in F_2 interlimb angles and localized S_2 development in the hinges and limbs of F_2 folds. The M_1 metamorphic event has been subdivided into M_{1A} and M_{1B} in order to reflect the relative timing, early or late, of changes in the mineral assemblages. The M_{1A} consists of sillimanite+garnet+K-feldspar+orthopyroxene and is related to the D_1 fabric-forming event that occurred at prograde granulite-facies metamorphism. The M_{1B} consists of garnet+cordierite+K-feldspar+melt in leucosome that has not recorded D_1 strain and likely reflects a change in mineral assemblage due to heat outlasting deformation. The M_2 event consists of sillimanite+garnet+biotite±K-feldspar, is related to the second fabric-forming event (D_2) and occurs at a lower temperature than M_{1A} in the biotite stability field. In summary, the mineral assemblages of all metamorphic events are well preserved in both locations; however, the textural relationships of D_1/M_{1A} are poorly preserved on the regional F_2 limb at Sillimanite ridge as a result of almost complete D_2 transposition, but D_1/M_{1A} textures are well preserved in the regional F_2 fold hinge at Barrow Peninsula, where D_2 strain is generally lower or localized. The mineral assemblage and textural relationships of D_2/M_2 are well preserved at both Sillimanite ridge and Barrow Peninsula.

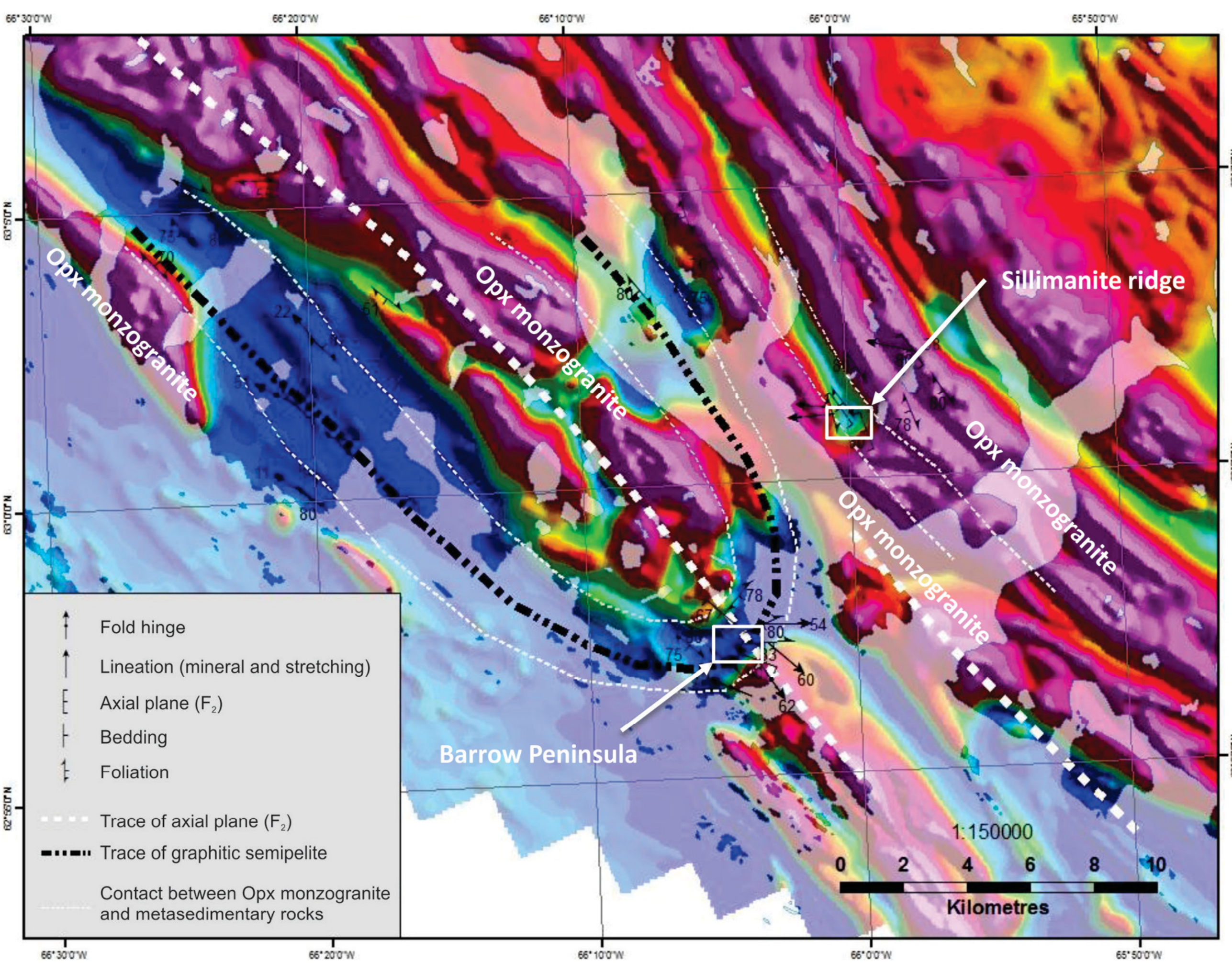

Figure 2: Annotated total field aeromagnetics of the Newton Fiord region, showing the location of the map areas (Dumont and Dostaler, 2010a–l). Abbreviation: Opx, orthopyroxene.

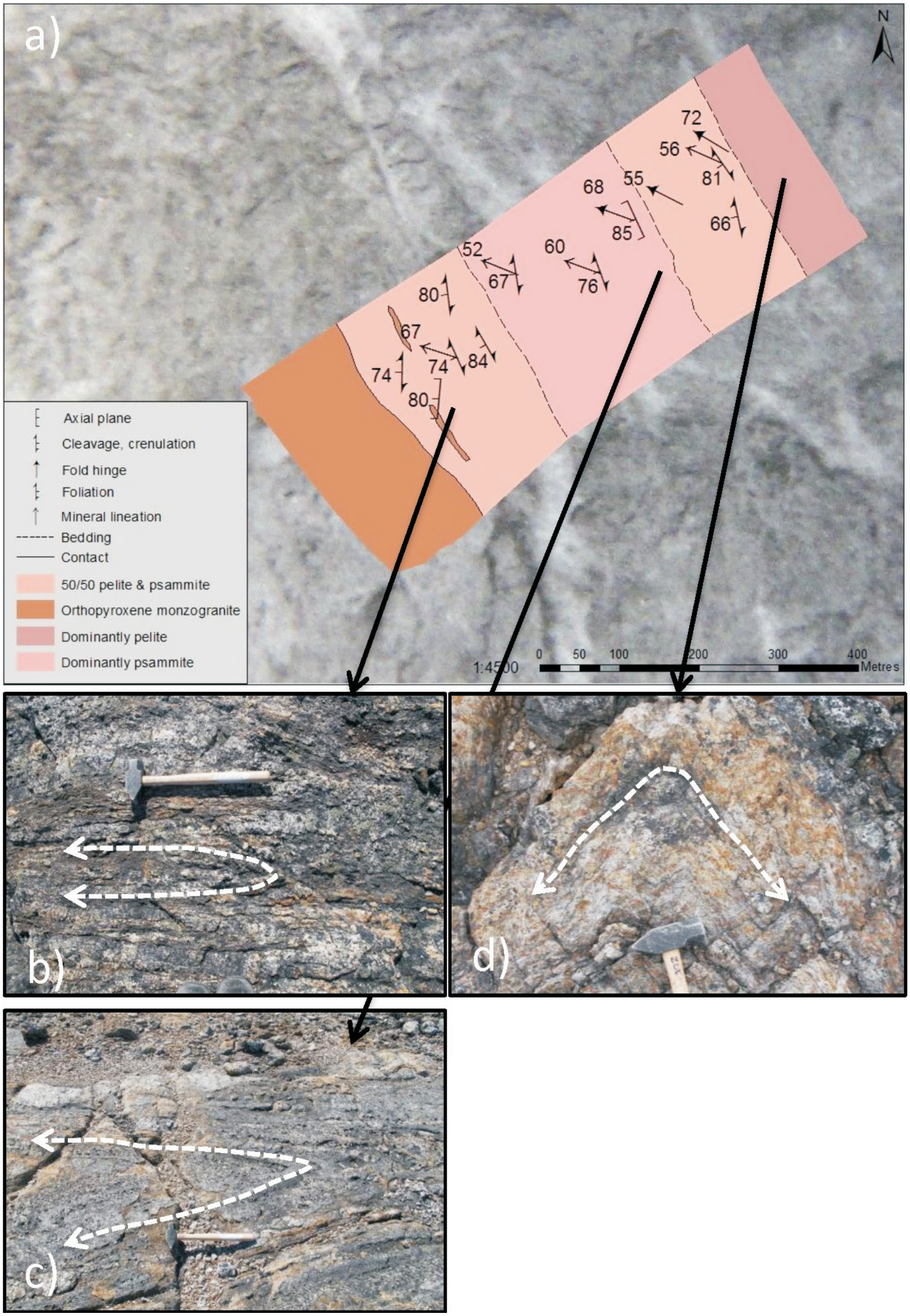

Figure 3: a) Preliminary geology of the Sillimanite ridge map area superimposed on a georeferenced airphoto. **b)**, **c)**, **d)** Field photos of F_2 folds, showing progressively tighter interlimb angles from east to west at Sillimanite ridge within interbedded pelite and psammite. Hammer is 40 cm in length.

Migmatization during D_1/M_1 has led to the separation of leucocratic material (the mobilizate) and the more refractory pelite (interpreted to be the restite). If shearing took place on a larger scale, the shearing fabric observed at Barrow Peninsula may be related to the strain gradient indicated by the progressive change in interlimb angles found at Sillimanite Ridge. In the Newton Fiord area, D_2 was not a penetrative deformation event; it alternates between high-strain zones and lower strain open fold zones that preserve D_1 fabric elements locally in their original D_1 orientations. The east-northeast-trending S_1 foliation at Barrow Peninsula may reflect the regional trend of S_1 and therefore may provide insight into the transport direction of the major fabric-forming tectonic event on Hall Peninsula.

Economic considerations and ongoing work

Deciphering the structural and metamorphic evolution of a polydeformed terrain is a crucial first step in understanding the regional metallogeny. In particular, the regional distribution of stratabound ore and industrial resources, such as carving stone, is controlled by the geometry of the deformation phases (D_1 and D_2). Although this study focuses on small map areas, the geometric relationships will be extrapolated to the entire region and will serve as first-order observations for a regional metallogenic model. This study is the basis of the first author's BSc. Honours thesis and will strive to tackle the following problems:

- Integration of outcrop observations and measurements with thin-section analysis will be carried out in order to

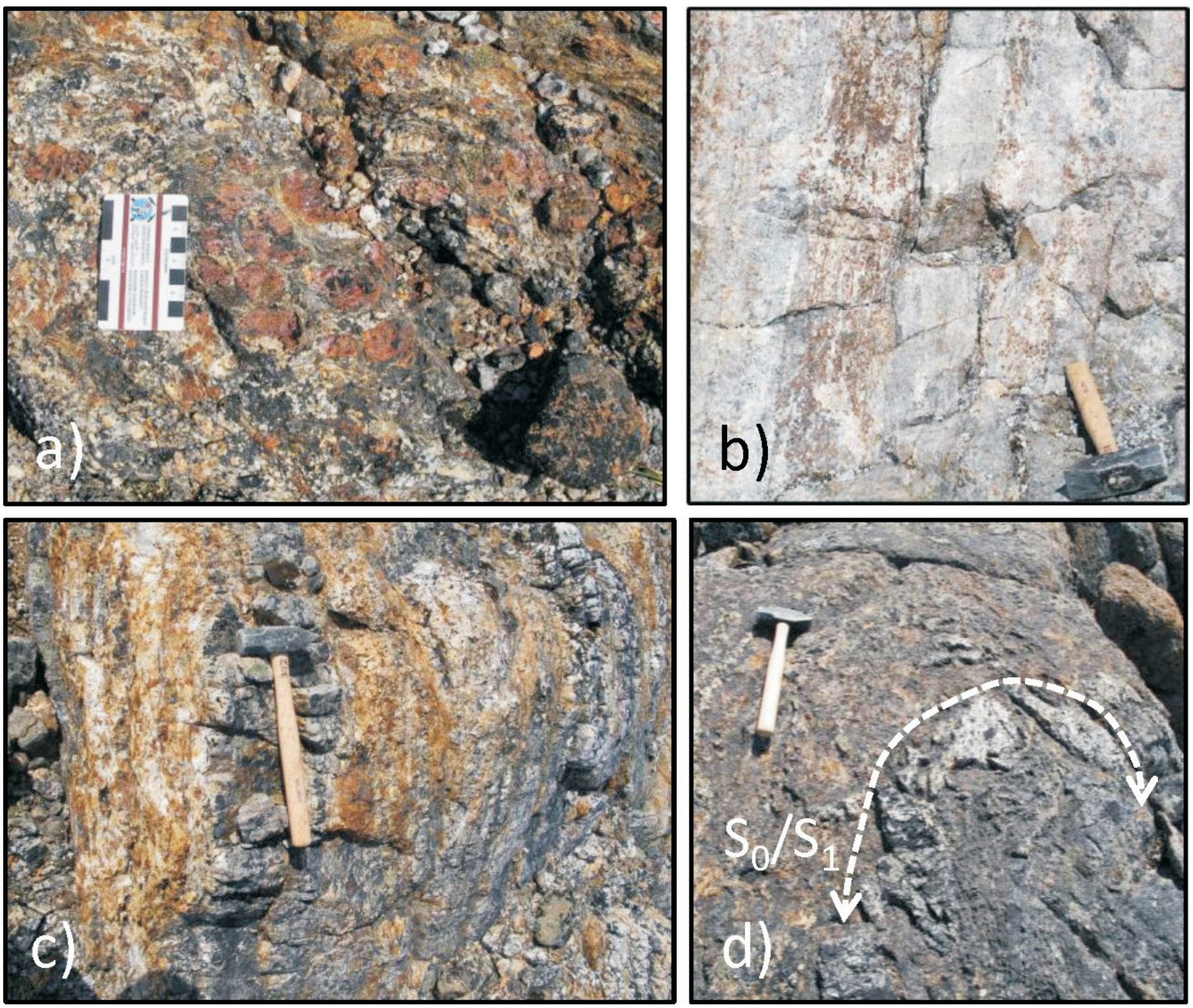

Figure 4: Field photos of rock units in the Sillimanite ridge map area: **a)** pelite with large garnet porphyroblasts; **b)** quartz-rich psammite with garnet porphyroblasts; **c)** interbedded pelite and psammite; **d)** folded D_1 partial-melt phase. Hammer is 40 cm in length.

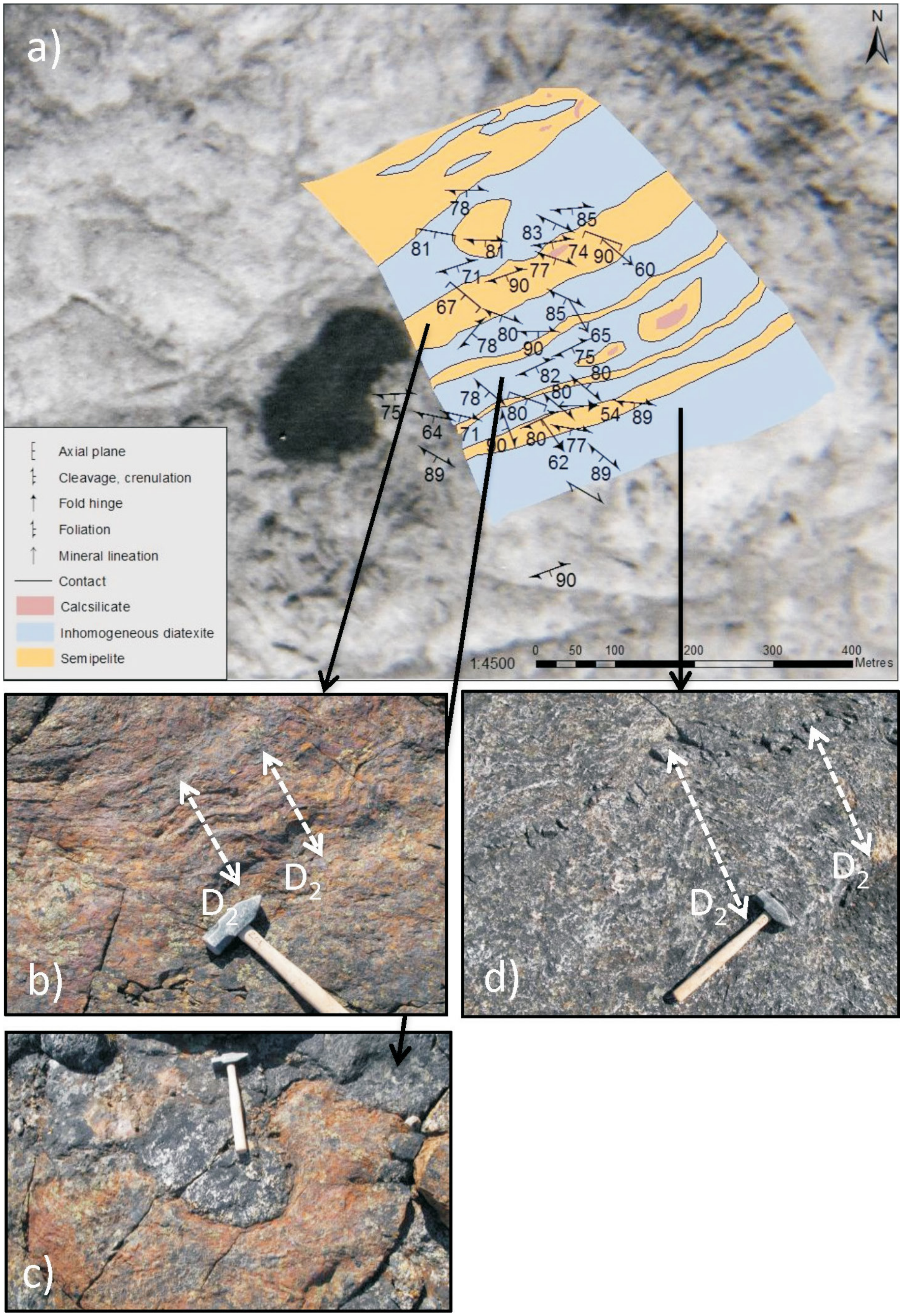

Figure 5: a) Preliminary geology of the Barrow Peninsula map area superimposed on a georeferenced airphoto. **b)** F_2 folds in graphitic semipelite with northwest-striking axial planes. **c)** Graphitic semipelite and leucocratic garnet-bearing monzogranite. **d)** F_2 folds in inhomogeneous diatexite. Hammer is 40 cm in length.

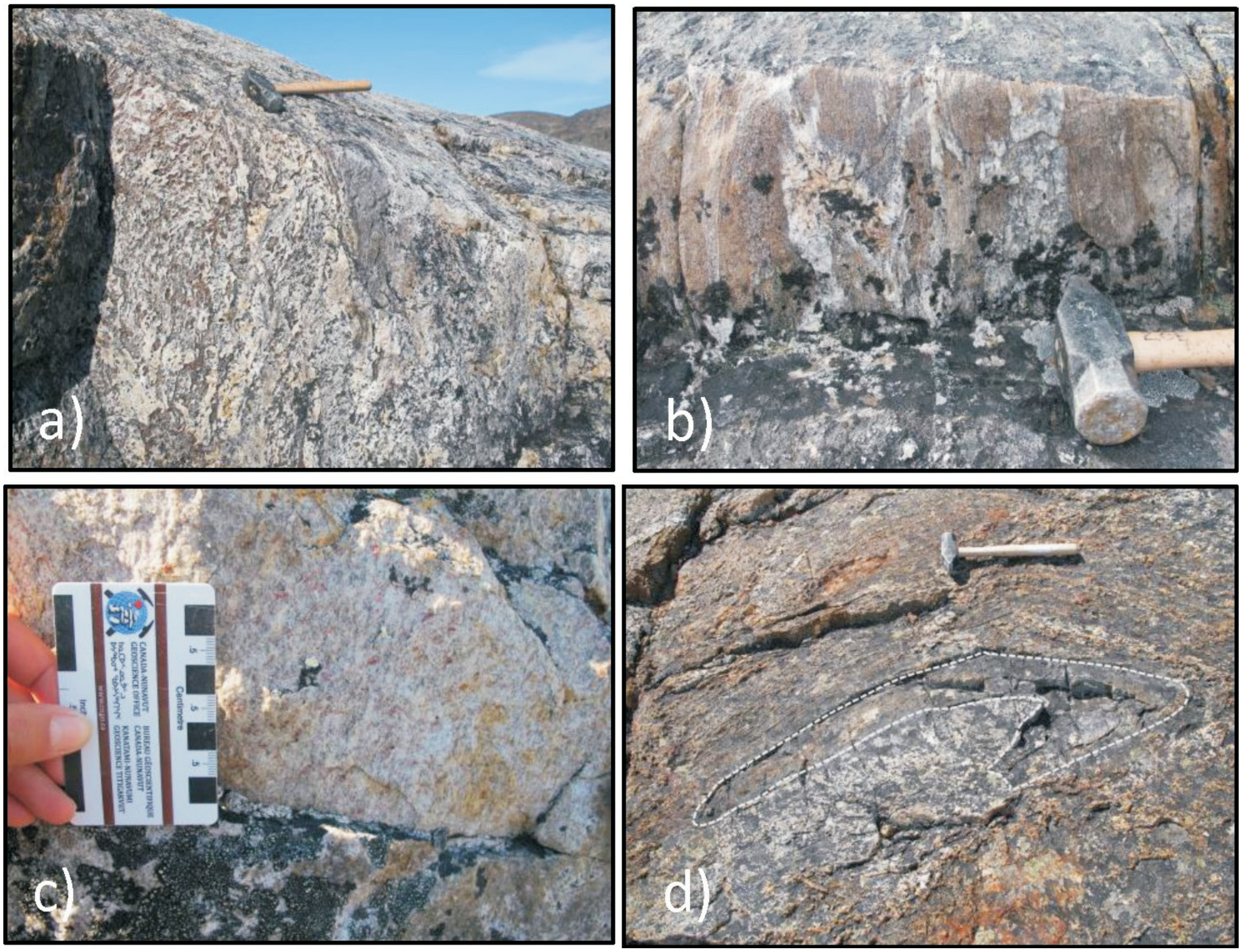

Figure 6: Field photos of rock units in the Barrow Peninsula map area: **a)** diatexite hosting psammite raft; **b)** calcsilicate and melt; **c)** psammite with garnet-biotite lineation; **d)** folded calcsilicate lens within graphitic semipelite.

improve the detailed maps that form the foundation for the microtectonic analysis (see next bullet point).

- Preliminary thin-section analysis has revealed melt rims around inclusions in garnet porphyroblasts. Further thin-section examination and microprobe analysis will be used to address whether the partial-melt phase is related to only D_1 or if there is a D_2 partial-melt phase as well. Additionally, the chemistry of the melt phases and the leucocratic garnet-bearing monzogranite will be examined to help clarify the relationship between them.
- Microprobe-derived mineral chemistry and Thermo-Calc software will be used to calculate pressure and temperature conditions of M_1 and M_2.
- Using the detailed maps, field photos, oriented samples and thin sections, an integrated evolutionary model will be constructed that will honour map-scale to thin section–scale observations, mineral-fabric textural relationships and quantitative P-T measurements.

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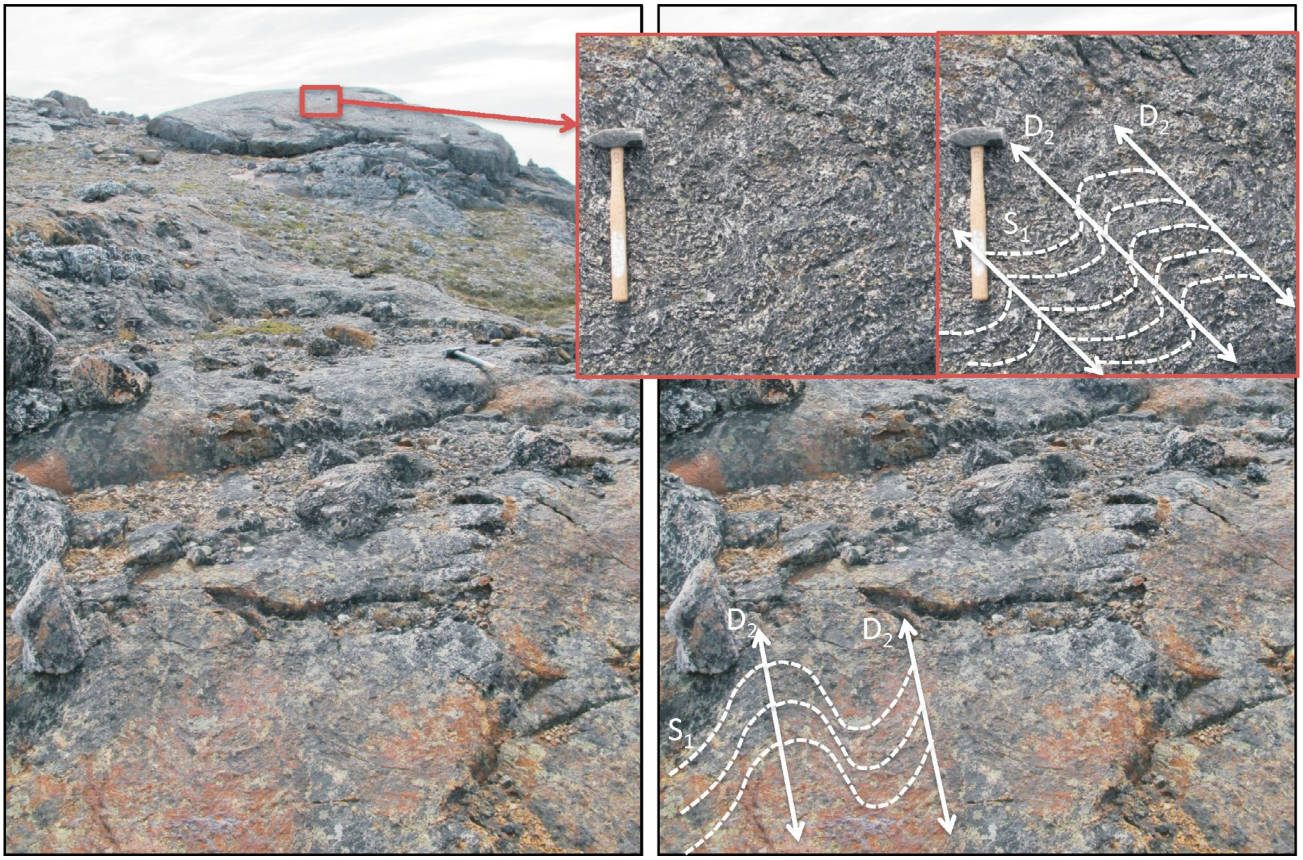

Figure 7: Annotated field photos from Barrow Peninsula with F_2 folds in graphitic semipelite and inhomogeneous diatexite showing the domainal nature of D_2. Wooden hammer handle in inset photos at top right points north and is 40 cm in length.

Table 1: Summary and comparison of D_1 and D_2 fabric elements and M_1 and M_2 metamorphic mineral assemblages at Sillimanite ridge and Barrow Peninsula.

	Sillimanite Ridge	Barrow Peninsula
Fabric elements	S_1: strong, bedding-parallel	S_1: preserved in lower strain zones, northeast-trending
	L_1: weak, not observed	S_2: spaced, shear-related foliation; south-southwest-dipping
	S_2: weak crenulation in F_2 hinges; transposition of S_1 on limbs; southwest-dipping	Lineation: locally weak to moderate and variable orientation; generation unclear
	L_2: very strong in F_2 hinges	
Transposition	Strong transposition of D_1 by D_2	Transposition of D_1 by D_2 via localized
Interlimb angles	0°–5° in the west 30°–50° in the east	Average 75°
M_{1A} mineral assemblage (defines S_1)	Garnet+sillimanite+K-feldspar± orthopyroxene	Garnet+sillimanite+K-feldspar+orthopyroxene
M_{1B} mineral assemblage (late D_1 leucosome)	Garnet+cordierite+K-feldspar+ melt	Garnet+cordierite+K-feldspar+melt
M_2 mineral assemblage (defines S_2)	Garnet+sillimanite+biotite±K-feldspar	Garnet+sillimanite+biotite±K-feldspar

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Rift flank uplift and landscape evolution of Hall Peninsula, Baffin Island, Nunavut: an exhumation model based on low-temperature thermochronology

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Abstract

This study is part of the Canada-Nunavut Geoscience Office's Hall Peninsula Integrated Geoscience Program, a multiyear bedrock and surficial geology mapping program with associated thematic studies. Baffin Island is characterized by fault-line bounded physiographic provinces that reflect lithological and structural elements inherited over the past two billion years. The northern coast of the Hall Peninsula half-horst is a rugged highland that constitutes a portion of the eastern Arctic Rim, a mountain range extending from northern Labrador to southern Ellesmere Island. Although Quaternary ice sheet and alpine glacial erosion has increased the relief of the mountain range, it appears from thermochronology and marine stratigraphy that much of the relief was generated by incision through isostatically and thermally uplifted lithosphere accompanying rifting from Greenland. In the past decade, offshore geophysical surveys have provided a firmer understanding of post-rift processes and the nature of the continental-ocean crust boundary in Baffin Bay and Davis Strait. However, many fundamental questions remain regarding the exhumation history of Hall Peninsula and adjoining provinces and the subsequent sediment fluxes to the margin: What is the timing of initial rifting along the Arctic Rim and which rifting models does this support? Is there evidence for a crustal or lithospheric root under the diamondiferous Hall Peninsula? How much rock has been denuded from Hall Peninsula and did the rate vary with climatic or tectonic controls, or both?

The purpose of this project is to determine how fast and variable Hall Peninsula rocks were exhumed. This is important because 1) it is beneficial to have onshore sediment flux rates to test and strengthen basin models of Baffin Bay and neighbouring marine sequences with petroleum potential; and 2) the exhumation history will place constraints on the timing and style of rifting in eastern Arctic Canada, as well as the total amount of erosion, which has offshore (petroleum) and onshore (diamond) economic implications. Our short term goals are to 1) use multiple methods of low-temperature thermochronometry (e.g., zircon and apatite (U-Th)/He, apatite fission track) to measure cooling histories and interpret how long it took selected rocks to cool by ascending from shallow depths; 2) combine regional stratigraphy, structural geology and thermochronometry data to establish a thermochronological model that can be used to hindcast sediment fluxes and relative differences in rock uplift on Hall Peninsula; and 3) place this into context with other available thermochronology and geological or geophysical data to improve our understanding of the long-term evolution of this region of anomalous relief in Arctic Canada.

Résumé

Cette étude fait partie du Programme géoscientifique intégré de la péninsule Hall, du Bureau géoscientifique Canada-Nunavut, un programme pluriannuel de cartographie du substratum rocheux et de la géologie de surface accompagnée d'études thématiques connexes. L'île de Baffin est caractérisée par des provinces physiographiques qui sont délimitées par des lignes de failles et qui reflètent des éléments lithologiques et structuraux hérités au cours des deux derniers milliards d'années. La côte nord du demi-horst de la péninsule Hall est un haut-pays accidenté qui constitue une partie de la bordure orientale de l'Arctique, une chaîne de montagnes qui s'étend du nord du Labrador jusqu'au sud de l'île d'Ellesmere. Bien que la nappe glaciaire du Quaternaire et l'érosion glaciaire alpine aient augmenté le relief de la chaîne de montagnes, il

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ressort des données de thermochronologie et de stratigraphie marine qu'une grande partie du relief a été incisé à travers la lithosphère soulevée par des mécanismes isostatiques et thermiques qui ont accompagné le rifting du Groenland. Au cours de la dernière décennie, les levés géophysiques au large des côtes ont permis de mieux comprendre les processus post-rift et la nature de la limite séparant les croûtes continentale et océanique dans la baie de Baffin et le détroit de Davis. Cependant, de nombreuses questions fondamentales subsistent quant à l'histoire de l'exhumation de la péninsule Hall et des provinces voisines, ainsi que des flux de sédiments subséquents vers la marge : À quel moment le rifting initial s'est-il produit le long de la bordure de l'Arctique et en fonction de quels modèles de rifting? Existe-t-il des preuves d'une racine crustale ou lithosphérique sous la péninsule Hall diamantifère? Quelle quantité de roche a été dénudée de la péninsule Hall et les facteurs climatiques ou tectoniques ont-ils eu une incidence sur le taux de dénudation?

Le but de ce projet est de déterminer à quelle vitesse et avec quelle variabilité les roches de la péninsule Hall ont été exhumées. Il s'agit d'une pièce d'information importante car : 1) il est utile de connaître la vitesse des flux de sédiments sur terre pour vérifier et renforcer les modèles de bassin pour la baie de Baffin et les séquences marines voisines ayant un potentiel pétrolier; et 2) l'histoire de l'exhumation imposera des contraintes sur la synchronisation et le style de rifting dans l'est de l'Arctique canadien, ainsi que sur la quantité totale d'érosion, processus certains d'avoir des incidences économiques au large des côtes (pétrole) et sur terre (diamant). Nos objectifs à court terme sont les suivants : 1) utiliser plusieurs méthodes de thermochronométrie à basse température (p. ex., zircon et apatite (U-Th)/He, traces de fission sur apatite) pour déterminer l'historique de refroidissement et établir le temps requis par certaines roches pour se refroidir en remontant des faibles profondeurs; 2) combiner les données de stratigraphie régionale, de géologie structurale et de thermochronométrie pour établir un modèle thermochronologique pouvant simuler de façon rétrospective les flux de sédiments et les différences relatives du soulèvement de la roche sur la péninsule Hall, et 3) mettre cette information en contexte avec d'autres données disponibles de nature thermochronologique et géologique ou géophysique afin de mieux comprendre l'évolution à long terme de cette région de l'Arctique canadien au relief anormal.

Introduction

The Hall Peninsula Integrated Geoscience Program (HPIGP) is being led by the Canada-Nunavut Geoscience Office (CNGO) in collaboration with the Government of Nunavut, Aboriginal Affairs and Northern Development Canada, Dalhousie University, University of Alberta, Université Laval, University of Manitoba, University of Ottawa, University of Saskatchewan, Nunavut Arctic College and the Geological Survey of Canada. It is supported logistically by several local, Inuit-owned businesses. The study area comprises all or parts of six 1:250 000 scale National Topographic System map areas north and east of Iqaluit (NTS 025I, J, O, P, 026A, B).

In the summer of 2012, fieldwork was conducted in the southern half of the peninsula (NTS 025 I, J, O, P) between June 22 and August 8. Fieldwork was supported by a 20–25 person camp located approximately 130 km southeast of Iqaluit. The focus was on bedrock mapping at a scale of 1:250 000 and surficial-sediment mapping at a scale of 1:100 000. A range of thematic studies was also supported. This included Archean and Paleoproterozoic tectonics, geochronology, landscape uplift and exhumation, detailed mapping in mineralized areas, microdiamonds, sedimentary rock xenoliths and permafrost. Summaries and preliminary observations for all of these studies can be found in this volume.

Hall Peninsula, Baffin Island composes part of the eastern Arctic Rim (Figure 1). Although the crystallization and metamorphism of the rocks are Precambrian in age, and they have undergone several orogenic events (Scott, 1999), the current high relief (>1000 m in places) is likely the result of rifting of Hall Peninsula from Cumberland and Baffin Island from Greenland since the Jurassic (Grist and Zentilli, 2005; Oakey, 2005; Pulvertaft and Dawes, 2011; Funck et al., 2012; Oakey and Chalmers, 2012). The high topography (up to 1000 m) along eastern Hall Peninsula is a result of vertical motions. Uplift was caused mainly by isostasy and thermal effects (van der Beek et al., 1995; Japsen et al., 2006; Schenk, 2011), and subsidence of Baffin Bay was caused by tectonic rifting, thermal and loading effects (Schenk, 2011). The erosion that generated the deep valleys and exhumed the deeply buried metamorphic rocks present at the surface today was a function of Phanerozoic fluvial processes and glacial erosion (Fortier and Morley 1956; Bornhold et al., 1976; Sugden 1976). However, the debate over which processes are most responsible for the current relief has continued (e.g., Montgomery 2002; Staiger et al., 2006; Kessler et al., 2008), and the need for more precise estimates of the rates of these processes has become a critical question here as it has in Greenland (Japsen et al., 2006) and Norway (Nielsen et al., 2009).

Hall Peninsula is situated along a rift flank system that has distinctly different physiographical, geophysical and thermochronological characteristics along its length. To the south, the Torngat Mountains represent a high relief (>2000 m in places) volcanic rift margin with geophysical and thermochronological evidence for a thick crustal root.

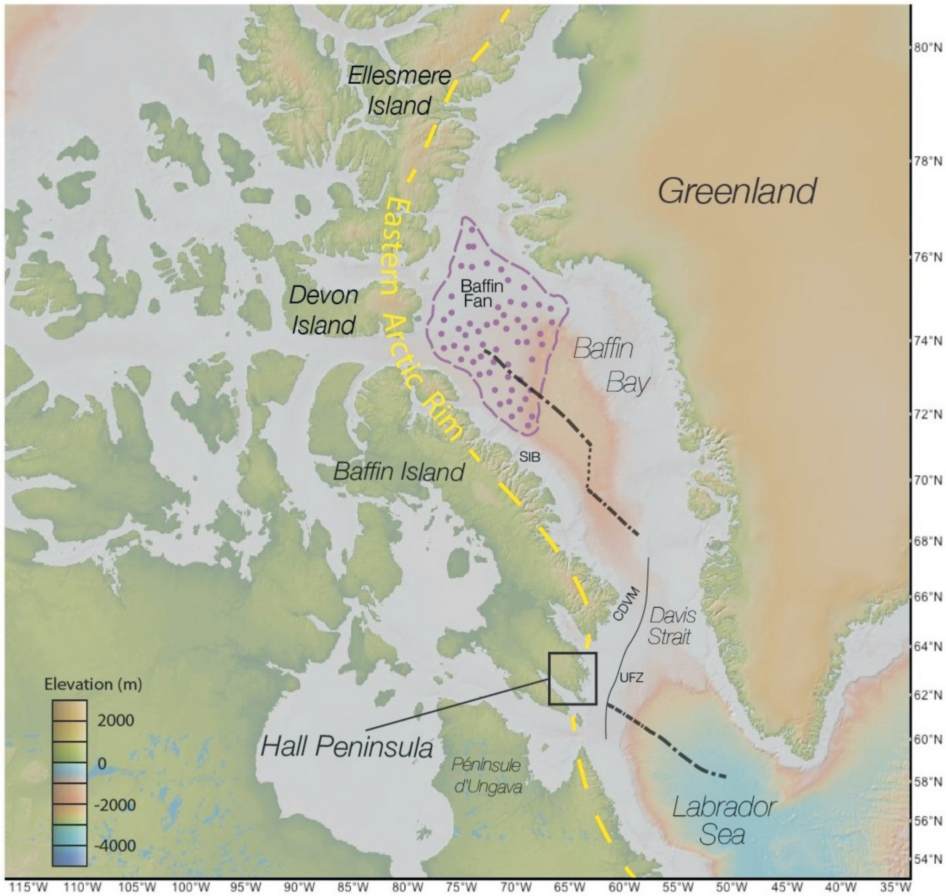

Figure 1: Map of eastern Arctic Rim (http://www.geomapapp.org, modified from Ryan et al., 2009): bold dashed line with dots is the approximate location of the extinct spreading axis of Baffin Bay and Labrador Sea; bold dotted line is the approximate location of the transform margin, from Chalmers and Pulvertaft (2001) and Oakey and Chalmers (2012); maroon dotted area is the Baffin Fan, from Harrison et al. (2011); Scott Inlet Basin (SIB), from Harrison et al. (2011); thin black line is Ungava Fault Zone (UFZ), from Chalmers and Pulvertaft (2001); Cape Dyer volcanic margin (CDVM), from Skaarup et al. (2006).

Funck and Louden (1999) discovered the presence of the ~15 km thick crustal root below the Torngat Mountains during a wide-angle seismic transect across the area. They proposed that the root was emplaced by subduction related to the Proterozoic convergence of the Nain and Superior cratons and was maintained over 1.8 b.y. due to an absence of post-orogenic magmatism. Centeno (2005) further supported the presence of a crustal root using apatite (U-Th)/He low-temperature thermochronology in a study that was aimed at quantifying the thermal history of the Torngat Mountains and also explaining the exhumation and tectonic history of the Labrador margin. Results from the study showed very rapid crustal cooling over a short time (from ~140–150 m.y.), which is attributable to the isostatic response (i.e., very rapid uplift) from the thick crustal root below the peninsula.

Northward from Hall Peninsula, the Cumberland Peninsula has similar relief but lacks thermochronological evidence for a crust root (Yaehne, 2008), and the margin transitions from a volcanic system—as defined geophysically by seaward reflecting units interpreted to be rift basalts (Skaarup et al., 2006)—to a nonvolcanic margin. Preliminary thermochronology results on Cumberland Peninsula also indicate the absence of a crustal root. The close proximity of Hall Peninsula to Cumberland Peninsula suggests a similar rift-flank exhumation history to the north-bounding provinces, but the discovery of diamond and the plausibility that the Abloviak Shear Zone extends from the Torngat Orogen through Hudson Strait opens the possibility that a small crustal or lithospheric root exists (or existed) under Hall Peninsula.

The scientific objectives of the 2012–2013 thermochronology study of Hall Peninsula are to

1) measure the cooling ages along strategically positioned vertical and horizontal transects and in random samples throughout Hall Peninsula to provide a spatial pattern of cooling ages that can be used to interpret patterns in exhumation;

2) use multiple thermochronometers (e.g., apatite-He, zircon-He and apatite fission track) in selected samples to provide a sense of the changes in cooling rates with time;
3) develop an exhumation model to interpret Hall Peninsula landscape evolution over the last 100 Ma using the new low-temperature thermochronometry data in the context of new and available geological, structural, stratigraphic and geophysical data;
4) interpret the variable rates of cooling over time as changes in exhumation rates, link those changes to regional tectonic or climate influences, and calculate the total amount of post-Jurassic exhumation; and
5) use thermochronology to better interpret the nature and style of rift flank uplift in the vicinity of Hall Peninsula, test the hypothesis of the presence of crustal or lithospheric root, and contribute to the larger understanding of the evolution of the western margin of Baffin Bay.

The results will be significant because this is the highest resolution (U-Th)/He thermochronology study to be completed on Baffin Island (spatial resolution of the samples, and number of measurements and thermochronometers used per sample), and the first to be completed on Hall Peninsula. An exhumation model will establish the geomorphic mechanisms that shaped the present-day landscape of Hall Peninsula and provide a well-constrained sediment flux history for Baffin Bay. Furthermore, the exhumation model for Hall Peninsula will contribute to other thermochronology and offshore data from around the eastern Arctic Rim to establish its post-rift evolution. This will provide critical data and tests for sedimentation models that can be employed for petroleum exploration in the area.

Methodology

Overview of (U-Th)/He thermochronometry

Thermochronology is a geological method used to determine the amount of time elapsed since a mineral cooled below a specific temperature, known as its ‘closure temperature’ (Tc). The temperature is specific to the particular isotope and mineral selected, and can depend on mineral composition, size and rate of cooling of the rock bearing the mineral. Low-temperature thermochronology is commonly used to determine the cooling history of rocks as they ascend from higher temperatures at shallow depths corresponding to Tc. However, since low-temperature thermochronometers are used to determine the cooling history of rocks through ~30 to 250°C, they are also useful for volcanic ash chronology (Westgate et al., 2012) or establishing the thermal maturation of hydrocarbon-bearing sediment (Grist et al., 1995). High-T methods can provide information about the history of metamorphism and crystal formation.

There are many low-T thermochronometry methods for a wide range of minerals (including apatite, fluorite, xenotime and zircon), and each has a specific closure temperature range that depends, for instance, on the diffusion of gas (Wolf et al., 1996), annealing of fission tracks (Arne and Zentilli, 1994), or the amount of environmental radiation affecting trapped electrons (Herman et al., 2010). For the Hall Peninsula objectives, the most appropriate thermochronometric approach is to use the apatite and zircon (U-Th-Sm)/He method, which is based on the U radioactive decay series (involving ^{238}U, ^{235}U, ^{232}Th and ^{147}Sm) and the accumulation of α particles (^{4}He gas) within the mineral’s crystal structure. Although α emission from the parent radioisotopes is constant, retention of helium within the crystal structure only occurs when the mineral grain is below a certain temperature. Thus, the longer a crystal has been below Tc, the greater the concentration of ^{4}He gas. A calculation of the parent/daughter isotope ratio (U-Th-Sm/He) within a grain can therefore be used to precisely establish the duration of time below this temperature. Apatite and zircon are particularly useful for low-T (U-Th)/He thermochronology due to their low Tc of ~75 and 180°C, respectively. For a given geothermal gradient (e.g., 25°C/km), this corresponds to the time for a rock to ascend from 3 and 7 km respectively. This is why low-T thermochronometers are well suited to provide insight into the post-Jurassic exhumation history of Hall Peninsula.

The amount of ^{4}He within a mineral is also controlled by many factors other than time since closure. Helium retention depends on the concentration of the parent radioisotopes and, because of the possibility of ejection of the α particles from the crystal, it also depends on the surface-area-to-mass ratio (crystal size), as well as the distribution of the radionuclides in the crystal. Thus, small crystal size, anhedral shape, inclusions, bubbles, radiation damage and chemical zoning can dramatically affect ^{4}He concentration. Furthermore, not all of the α particles are retained below the closure temperature. The range of temperature where ^{4}He is neither completely ejected nor entirely retained within a mineral grain is known as the helium partial retention zone (HePRZ). Within the HePRZ, increasing amounts of ^{4}He are retained as temperature decreases until all helium is completely retained. The range of the HePRZ depends mostly on cooling rate. For impact breccia and tephra (i.e., very rapid cooling) the HePRZ is ~75–70°C, but a slowly exhuming apatite crystal on Hall Peninsula the HePRZ may range from 75 to 40°C. For a more rigorous explanation of He diffusion, the HePRZ, and their importance to (U-Th)/He thermochronometry, the reader is directed to Wolf et al. (1998), Farley (2002) and Shuster et al. (2006).

Sampling strategy

Sampling was conducted during helicopter and foot traverses for bedrock and surficial mapping. Prospective sample locations were proposed by considering the physiographic geometry of the rift flank, available structural and lithological data (Scott, 1996, 1999), topography and bathymetry data (Figure 2), and the location and significance of offshore geophysical data (Suckro et al., 2012). However, exact locations were ultimately selected according to helicopter accessibility (landing surface, wind, etc.), structural simplicity, and outcrop exposure and rock type. The target was metaplutonic granitoid—specifically metatonalite—based on the observation that the largest, most euhedral crystals were obtained from orthogneisses during the previous thermochronological work on north central Baffin and Cumberland Peninsula (Yaehne, 2008).

Samples were collected in three different transects (Figure 3; Table 1). Data from a vertical transect, collected from sea level to 1000 m, will be used to determine variations in cooling history due to vertical exhumation and to test the hypothesis that a root exists (or existed) under Hall Peninsula. The analysis of data collected from a horizontal transect that trends perpendicular to the Cumberland Sound coastline will provide insight into rates and styles of rift flank exhumation (e.g., by parallel escarpment retreat or by erosion on both flanks of a pinned drainage divide around the highest peaks). Samples from a second horizontal transect running parallel to the Cumberland Sound margin will be analyzed to determine how the rift flank has tilted since rifting and if the relief and exhumation is mainly a function of west-east extension from Greenland or north-south extension from Cumberland Peninsula. Analysis of data from the latter transect will also inform about the existence of pre-Cenozoic valleys it crosses if it's found that the 75°C and lower isotherms were adequately deflected to mimic topography. Additionally, random samples were collected at various elevations throughout the peninsula which, when analyzed, and the results combined with the transect data, will constrain a 3-D heat and exhumation history for Hall Peninsula using thermodynamic modelling software (PECUBE, Braun, 2003; Braun et al., 2012).

Laboratory procedure

Apatite and zircon are isolated from other grains through standard heavy mineral separation methods, described herein, from Elhers and Farley (2003). All samples are crushed into grains less than 500 µm. The grains are separated by density through immersion in heavy liquid (e.g., lithium heteropolytungstates). Further separation is completed using a Frantz magnetic separator and ultimately by hand picking. Once isolation is complete, grain selection is based on size (generally 75–150 µm in shortest axis), euhedral shape, and lack of inclusions, fractures or evidence of zoning. The geometry of the grains is carefully measured to calculate grain volume and establish a correction for He loss to adjacent minerals. The ^{4}He abundance is measured with a He mass spectrometer on an ultrahigh vacuum (UHV) noble gas extraction line. The ^{4}He is then degassed from the apatite or zircon grain using an yttrium-aluminum-garnet (YAG) laser. After isotope dilution and column chemistry to concentrate the elements, isotopic abundances of U, Th and Sm are determined for each grain using an inductively coupled plasma–mass spectrometer (ICP-MS).

For each sample, a minimum of five apatite or zircon grains will be measured because unrecognized crystal imperfections and low abundances of the alpha parents can contribute significant total analytical uncertainty. Because apatite has a lower Tc, it is more appropriate for determining the Cenozoic exhumation history and isotherm deflections, hence it will be measured in all samples. Zircon will be measured in selected samples where the addition of data from a deeper history is valuable, and, in a few samples, apatite fission track ages will be measured to establish the pre-Jurassic thermal history and thus a useful boundary constraint for thermal modelling. At the time of submission of

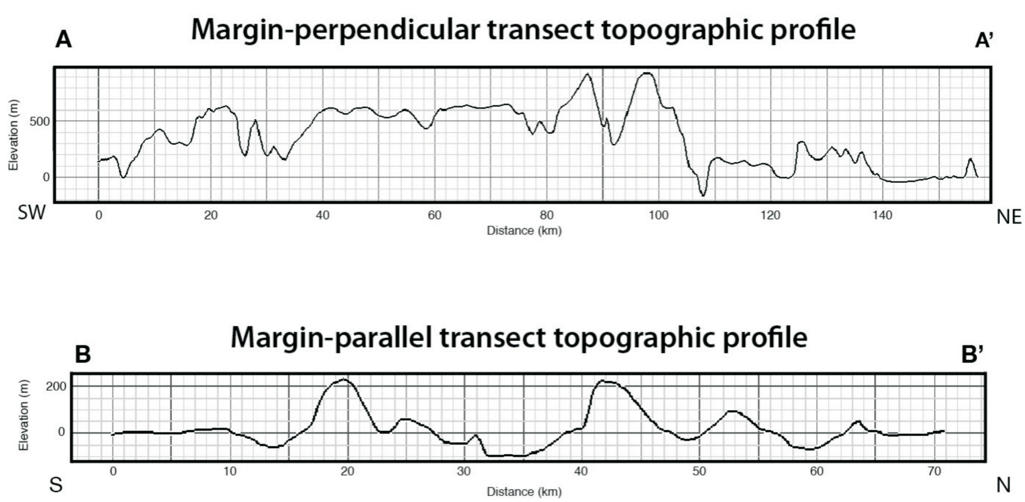

Figure 2: Topographic profiles of margin-perpendicular and margin-parallel transects of Hall Peninsula, Nunavut (modified from http://www.geomapapp.org, elevation dataset from Ryan et al., 2009).

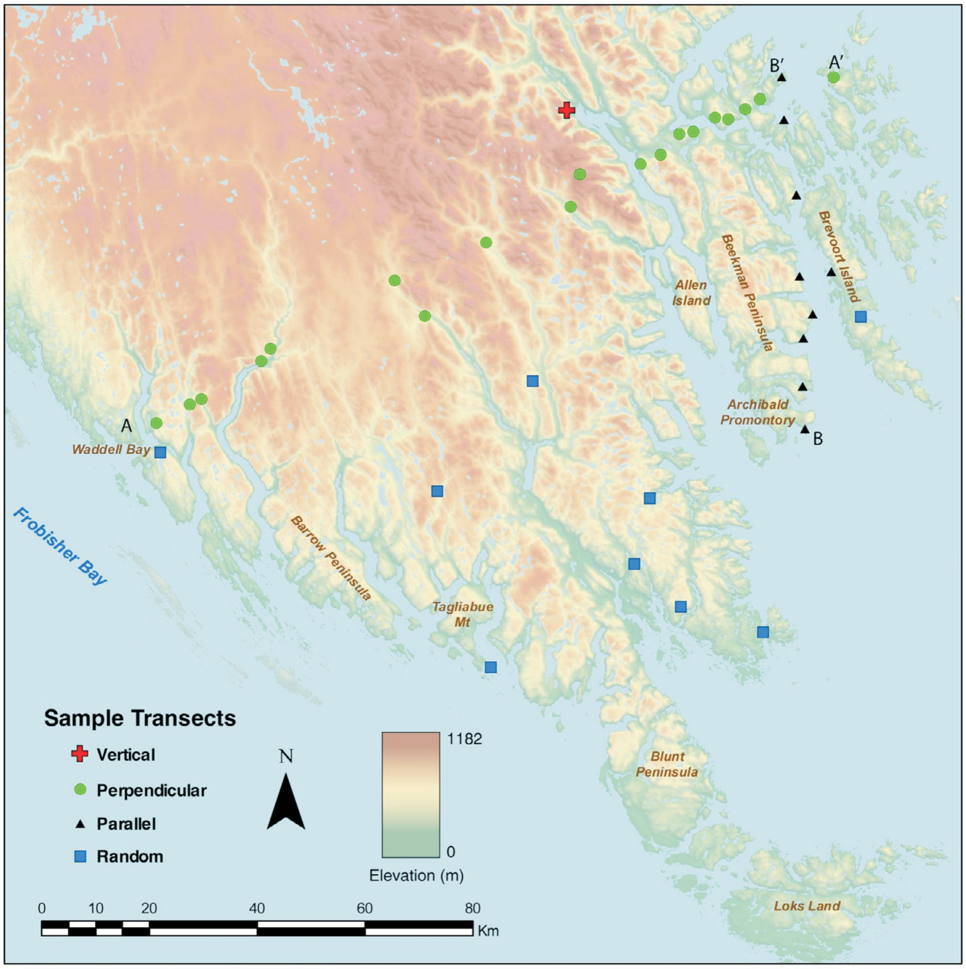

Figure 3: Map of sample sites throughout Hall Peninsula, Nunavut. Samples were collected on an opportunistic basis in co-operation with Hall Peninsula Integrated Geoscience Program bedrock mapping traverses. Red cross is vertical transect samples; 800 vertical metres (over ~950 horizontal metres), sampling every 61 m. Green circle is margin-perpendicular transect samples; 67 km at 0 m elevation, sampling every 8–10 km (varied). Black triangle is margin-parallel transect samples; 141 km at 247 m elevation, sampling every 3–10 km (varied). Blue square is random samples for PECUBE model constraints.

this article, we have demonstrated the existence of abundant suitable apatite and zircon in the tonalite on Hall Peninsula (sample 12MBC-C014A01).

Economic considerations

Understanding the history of exhumation on Hall Peninsula is critical to interpreting nearby offshore sedimentary records. It provides a means to confirm sediment provenance and establish linkages between tectonics and climate that may or may not be inferred from the marine records (Allen, 2008). The connection of onshore sediment flux histories (the byproduct of cooling histories), interpreted from 3-D thermal models for Hall Peninsula, can be used in context with other onshore data to improve the models of sediment type and accumulation rate into Baffin Bay and surrounding basins with high hydrocarbon potential (Grist et al., 1995). In particular, the results of this work are directly useful for the evaluation of petroleum potential in areas of current interest, such as the Baffin Fan, in northwestern Baffin Bay, and Scott Inlet Basin, of the northwestern Baffin Shelf. Harrison et al. (2011) speculate on the petroleum potential of the Baffin Fan. Citing many similarities in resource-related features between the Baffin Fan and Beaufort-Mackenzie Basin (e.g., dimensions, sediment type and thickness, tectonic structure, etc.), the authors suggest the possible presence of petroleum source rocks.

Hall Peninsula is in close proximity to the high relief Torngat Mountains on Ungava Peninsula to the south, where geophysical and thermochronological data indicate the presence of a crustal root. Such anomalous crustal or lithospheric depths may correlate to kimberlite pipe emplacement (Helmstaedt and Gurney, 1995). Known kimberlites on Hall Peninsula are of potential economic interest for diamond mining companies. Because the quality of dia-

Table 1: Parameters for samples collected from Hall Peninsula, Nunavut (transect, station ID, latitude, longitude, elevation and rock type).

Station ID	Latitude	Longitude[1]	Elevation (m)	Rock type
Vertical transect				
12MBC-C016	63.81690000	-65.35660000	794.2	biotite granite
12MBC-C008	63.80750000	-65.32800000	685.1	magnetite granite
12MBC-C009	63.80920000	-65.32280000	618.0	biotite granite
12MBC-C010	63.80960000	-65.31900000	561.9	biotite granite
12MBC-C011	63.81020000	-65.31700000	492.1	biotite granite
12MBC-C012	63.81150000	-65.31680000	431.1	biotite granite
12MBC-C013	63.81210000	-65.31640000	375.0	biotite granite
12MBC-C014	63.81280000	-65.31430000	311.0	biotite granite
12MBC-C015	63.81440000	-65.31260000	225.9	biotite granite
12MBC-C053	63.81450000	-65.31133000	183.5	biotite tonalite
12MBC-C068	63.80974000	-65.30544000	114.0	biotite tonalite
12MBC-C069	63.81014000	-65.30151000	35.1	biotite tonalite
Perpendicular transect				
12MBC-C001	63.69900000	-65.29080000	260.1	biotite tonalite
12MBC-C002	63.72330000	-64.98470000	243.3	biotite-magnetite granite
12MBC-C003	63.59340000	-65.65620000	326.5	biotite granite
12MBC-C004	63.47640000	-65.89860000	241.8	biotite-garnet monzogranite
12MBC-C005	63.53770000	-66.00630000	397.0	granitic pegmatite
12MBC-C006	63.43370000	-66.47810000	246.0	biotite monzogranite
12MBC-C007	63.41400000	-66.51410000	242.7	biotite monzogranite
12MBC-C018	63.31610000	-66.90960000	248.8	garnet monzogranite
12MBC-C019	63.34550000	-66.78540000	262.8	garnet monzogranite
12MBC-C020	63.35470000	-66.74150000	251.8	biotite-garnet monzogranite
12MBC-C071	63.29815330	-65.98944246	204.3	biotite-garnet monzogranite
12MBC-B098	63.83240326	-64.31572883	222.4	biotite tonalite
12MBC-B099	63.80506994	-64.59974202	252.0	biotite tonalite
12MBC-B100	63.78999827	-64.65662533	244.3	biotite-hornblende diorite
12MBC-B101	63.77476661	-64.72326863	269.9	biotite tonalite
12MBC-B102	63.77858994	-64.77428528	246.6	biotite diorite
12MBC-B103	63.75847161	-64.85916357	243.0	monzogranite
12MBC-B105	63.75529162	-64.91133354	236.0	biotite tonalite
12MBC-B106	63.70989162	-65.06324514	249.8	monzogranite
12MBC-K105	63.64591497	-65.33533835	266.9	biotite tonalite
Parallel transect				
12MBC-C022	63.32315000	-64.51551000	102.0	biotite tonalite
12MBC-C027	63.25268000	-64.51698000	0.0	biotite tonalite
12MBC-C028	63.40376000	-64.49870000	5.0	biotite tonalite
12MBC-C029	63.44227300	-64.45912000	2.0	biotite granodiorite
12MBC-C030	63.50610000	-64.49805000	0.0	metasediment
12MBC-C031	63.64214000	-64.48868000	3.0	biotite tonalite
12MBC-C032	63.76802000	-64.51345000	4.0	biotite tonalite
12MBC-C033	63.83968000	-64.51273000	18.0	biotite granite
12MBC-C034	63.51020000	-64.37807000	26.0	biotite-hematite tonalite
Random samples				
12MBC-C035	63.43046000	-64.28147000	234.0	biotite tonalite
12MBC-F095	63.35858333	-65.51034330	580.6	biotite tonalite
12MBC-K048	63.26760170	-66.90008431	320.7	garnet monzogranite
12MBC-K060	63.18395168	-65.88443647	514.6	biotite tonalite
12MBC-Y075	63.04580668	-65.17674350	255.7	biotite tonalite
12MBC-Y076	62.97026335	-65.01653692	352.9	biotite tonalite
12MBC-Y080	62.91908834	-64.72139206	12.9	magnetite monzogranite
12MBC-Y083	63.15381667	-65.10574852	265.5	biotite tonalite
12MBC-Y086	62.88777837	-65.72097326	25.9	biotite tonalite

[1] Minus sign indicates west longitude.

monds varies with depth in a diatreme, knowledge of the exhumation history of Hall Peninsula can help to focus diamond exploration in the region.

Acknowledgments

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Identification of iron-rich components in bedrock and till from multispectral satellite imaging in support of geoscience mapping of Hall Peninsula, Baffin Island, Nunavut

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Abstract

This study is part of the Canada-Nunavut Geoscience Office's Hall Peninsula Integrated Geoscience Program, a multiyear bedrock and surficial geology mapping program with associated thematic studies. RapidEye multispectral satellite data provide relatively high spatial resolution and large area coverage, making it a suitable sensor for providing information to support geological mapping at a reconnaissance scale. A preliminary analysis was performed on Hall Peninsula in order to highlight the presence of iron oxides and hydroxides commonly associated with gossans. Numerous sites of interest, ranging from a few pixels covering several tens of square metres to larger areas representing hundreds of square metres, were identified and validated by field visits. A range of geological material types was recognized. The most common were iron oxides from weathered metasedimentary units containing disseminated sulphides. Other localities correlate with localized occurrences of ultramafic rock that were previously unmapped.

Résumé

Cette étude fait partie du Programme géoscientifique intégré de la péninsule Hall, du Bureau géoscientifique Canada-Nunavut, un programme pluriannuel de cartographie du substratum rocheux et de la géologie de surface accompagnée d'études thématiques connexes. Les données multispectrales des satellites RapidEye offrent une résolution spatiale relativement élevée et une grande couverture, ce qui en font des capteurs utiles pour fournir de l'information à l'appui de la cartographie géologique à l'échelle de reconnaissance. Une analyse préliminaire a été effectuée dans la péninsule Hall afin de mettre en évidence la présence d'hydroxydes et d'oxydes de fer couramment associés à des chapeaux de fer. De nombreux sites d'intérêt, dont les dimensions varient de quelques pixels couvrant plusieurs dizaines de mètres carrés à de grandes surfaces couvrant des centaines de mètres carrés, ont été répertoriés et validés par des visites sur le terrain. On y a reconnu toute une gamme de types de matériaux géologiques. Les plus courants étaient des oxydes de fer provenant d'unités métasédimentaires météorisées qui renferment des sulfures disséminés. D'autres emplacements présentent une corrélation avec des occurrences localisées de roches ultramafiques qui n'avaient pas été cartographiées.

Introduction

The Hall Peninsula Integrated Geoscience Program (HPIGP) is being led by the Canada-Nunavut Geoscience Office in collaboration with the Government of Nunavut, Aboriginal Affairs and Northern Development Canada, Dalhousie University, University of Alberta, Université Laval, University of Manitoba, University of Ottawa, University of Saskatchewan, Nunavut Arctic College and the Geological Survey of Canada. It is supported logistically by several local, Inuit-owned businesses. The study area comprises all or parts of six 1:250 000 scale National Topographic System map areas north and east of Iqaluit (NTS 025I, J, O, P, 026A, B).

In the summer of 2012, fieldwork was conducted in the southern half of the peninsula (NTS 025 I, J, O, P) between June 22 and August 8. Fieldwork was supported by a 20–25 person camp located approximately 130 km southeast of Iqaluit. The focus was on bedrock mapping at a scale of 1:250 000 and surficial-sediment mapping at a scale of 1:100 000. A range of thematic studies was also supported.

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This included Archean and Paleoproterozoic tectonics, geochronology, landscape uplift and exhumation, detailed mapping in mineralized areas, microdiamonds, sedimentary rock xenoliths and permafrost. Summaries and preliminary observations for all of these studies can be found in this volume.

The HPIGP includes bedrock and surficial mapping that will improve the framework and conceptual knowledge of this poorly mapped and underexplored region between Cumberland and Meta Incognita peninsulas of southern Baffin Island (Machado et al., 2013). Part of this project includes incorporating remotely sensed data to support bedrock mapping and identifying prospective areas in support of exploration efforts. This paper describes some examples of recent results (Figure 1) that illustrate the application of remote sensing, or Earth observation datasets, to the identification of gossanous rocks and occurrences of ultramafic rock. The development of iron oxide from weathering of disseminated sulphides in extensive psammite and semi-

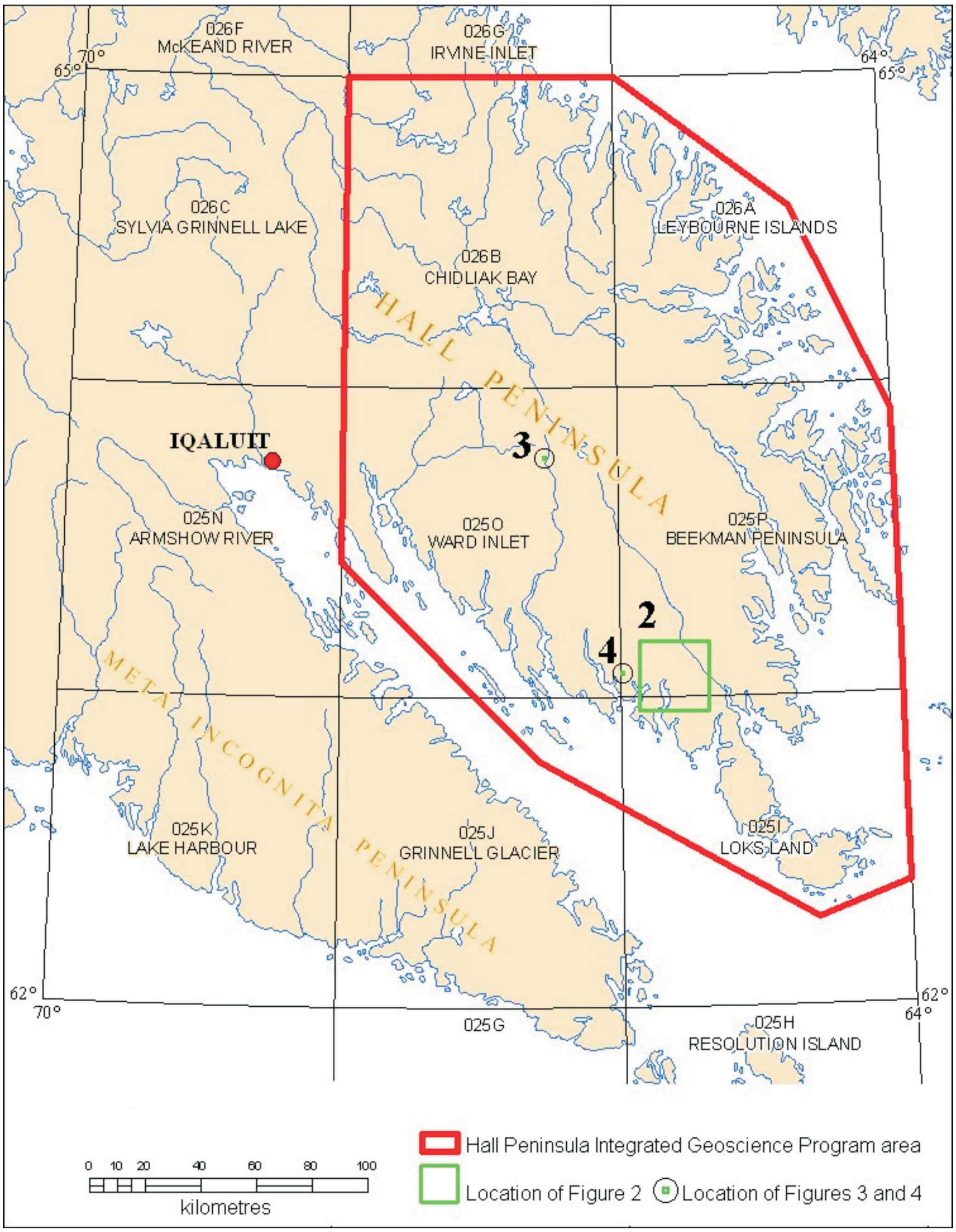

Figure 1: Area covered by the Hall Peninsula Integrated Geoscience Project and location of the RapidEye tile and sub-images discussed in this paper.

pelite units is known on southern Baffin Island. A large number of these gossans are not of economic interest; however, in some localities, reconnaissance till sediment and rock geochemistry in areas visibly enriched in iron oxides yielded anomalous gold, silver, platinum-palladium, zinc-lead or copper from indicator minerals or sediment analyses on the Cumberland (Sanborn-Barrie and Young, 2011) and Hall (Pell and Farrow, 2011) peninsulas. Some of the gossans are most likely developed from disseminated or massive sulphides within or at the contacts of intrusive mafic or ultramafic rocks. These occurrences, however, are far fewer than those associated with the rusty-weathering metasedimentary rocks of variable age. Since not all of these iron-oxide occurrences are barren of base or precious metals, there is some exploration value in searching for these exposures for further evaluation. The goal of this work is to investigate some cost-effective methods for distinguishing these occurrences from the surrounding bedrock and terrain in support of mapping efforts and mineral exploration.

Satellite data

Data-processing techniques for remotely sensed spectral data can be adapted to detect the presence of iron-oxide and -hydroxide minerals owing to their broad-band spectral properties in the visible and near-infrared (NIR) wavelengths. For these minerals, strong differences in relative reflectance exist between certain multispectral bands. Band ratios suited to enhancing contrast between iron-rich targets from all other land-cover types have been used to search for gossans in support of mineral exploration. Many of these efforts have used and continue to use publicly accessible satellite data such as Landsat or ASTER (Sabins, 1986; Abrams, 2000). Although these datasets have the advantage of covering large areas and are useful for reconnaissance work, the relatively low resolution of 30 m for Landsat and 15 m for ASTER limits their application to gossan exposures that are quite large or continuous. Since many of the economic showings are comparatively smaller, their detection would benefit from higher resolution sensors. Several commercial data providers offer multispectral data of approximately 2 m resolution; however, narrower swath and higher cost for wide-area coverage put their use beyond the scope of this work. Intermediate-resolution sensors (below 10 m resolution) have similar spectral bands, so these datasets offer a practical solution for covering wide areas with better resolution than that provided by Landsat or ASTER.

RapidEye

RapidEye was investigated for the Hall Peninsula project to evaluate the advantages and disadvantages of using data from this class of sensor (RapidEye AG, 2012). The RapidEye mission is a constellation of five satellites (RE1–5) that enables frequent revisit opportunities of once every 24 hours or less at higher latitude. The sensors on board each satellite are the same, designed to collect data in five spectral bands in the visible to NIR, from 0.4 to 0.85 µm (Naughton et al., 2011). The resolution or ground-sampling distance of RapidEye is approximately 6.5 m. The Level 3A data products acquired for this study were delivered as 25 by 25 km orthorectified tiles resampled to 5 m pixels.

Approximately 60 tiles with less than 20% cloud cover are available for the project area on Hall Peninsula. This corresponds to only about a third of the mapping area and illustrates the challenges of acquiring cloud-free coverage during the short duration of snow-free periods in the Arctic. Figure 1 is a location map of the scenes discussed and Figure 2 is an example of an image tile. Cloud cover, corresponding shadow and residual snow cover often obscure a moderate percentage of the landscape. These hidden portions of the ground are occasionally captured in other images but require retasking of the satellite for acquisition of new data.

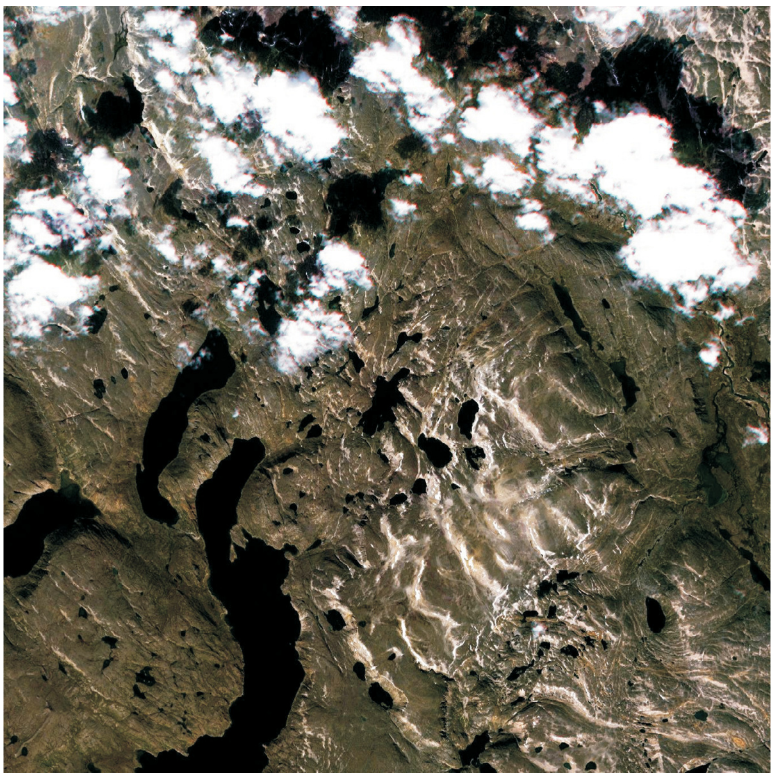

Figure 2: A RapidEye image tile (25 by 25 km) from Hall Peninsula displayed in RGB colour using bands 3, 2 and 1, respectively. Data were acquired August 30, 2011. Includes material © (2011) RapidEye AG, Germany. All rights reserved.

Data analysis and field validation

Iron ratios in multispectral data are generally dependent on high reflectance contrast between the visible red (band 3) and lower relative reflectances in the blue-green portion of the visible spectrum (bands 1 and 2; Sabins, 1986). High scatter in the atmosphere strongly affects band 1, whereas better results were obtained using band 2 in the green portion of the spectrum. A simple dark target subtraction was performed first, which helped to normalize results from scene to scene collected on different dates, under different atmospheric conditions and at various solar elevation angle and azimuth conditions. Processed data generated an iron index comprising low to high values that were scaled into classified images from blue (low) to red (high; Figures 3b, 4b). Approximately 20 representative sites with high iron indices, chosen from different image tiles, were examined in the field during a one-week period in July 2012.

Within units of garnet-bearing psammite, high iron indices correlate with zones exhibiting characteristically rusty-orange rock, usually in combination with mineral soil derived from bedrock weathering that is thought to be controlled by the breakdown of biotite or disseminated sulphides. Red iron oxides or hydroxides, such as goethite, and more yellowish to ochre limonite, are pervasive at surface (Figures 3a–c). In many localities, no primary sulphides remain; however, disseminated sulphides such as pyrite and pyrrhotite were observed at a few sites. On the colour image of Figure 3a, areas with higher or lower iron or rusty weathering are not easily identified; however, zones of greater iron concentration are more clearly discerned on the iron-index map of Figure 3b. Examined in the field, these zones exhibit weathered horizons and bedrock with higher iron oxides and hydroxides than the surrounding locations (Figure 3c).

Of note, the iron-index maps have allowed recognition of previously unknown ultramafic bodies in the map area (e.g., Figure 4a, b). Numerous ultramafic pods, some as small as only a few 5 m pixels, were often located by their very high iron-index values. Other occurrences were much larger: the largest discovered in the RapidEye data is a lens measuring about 250 by 500 m. A characteristic mustard-yellow weathering colour exhibited on exposures of these ultramafic rocks was commonly encountered in the field (Figure 4c). In almost all cases, serpentinized dunite or peridotite was the dominant rock type. The weathering of serpentinite and possibly ubiquitous iddingsite may be the source of the strong colouration of these weathered bedrock surfaces associated with high iron indices derived from the spectral data. A description of several of these ultramafic units on Hall Peninsula, and their potential as sources of carving stone, is given by Senkow (2013).

Economic and applied considerations

Earth observation data from satellite provides a means to rapidly acquire, over wide areas, current information at increasingly improved resolution and spectral depth. It offers the possibility to target smaller objects and perform better land-cover classifications for geological and other applications. This technology is becoming much more cost effective, particularly when applied in remote regions. In the case of this study, gossans and ultramafic rocks represent a very small fraction of the land surface; however, their occurrence can be reliably identified in many cases. Continuity of correlative ultramafic or gossanous units may represent regional mineralized horizons of magmatic or exhalative origin. Interest in the locations of mafic-ultramafic rocks is particularly important, as they are more prospective targets for base and precious metals such as gold, silver and zinc, or nickel–copper–platinum group elements. In conjunction with other geoscience information, remote-sensing–derived maps such as the iron-index examples described in this report may help to narrow the search for geological or exploration targets of interest.

Conclusions

For the large areas under investigation during mapping campaigns, improved remote-sensing data from newer sensors continues to assist in targeting areas of geological significance. This information can be used to determine where to invest in ‘boots on the ground’, since it is rarely possible to cover all ground during reconnaissance mapping.

The preliminary data products permitted field validation and collection of ground samples for further spectral and geochemical characterization. With these analyses and further refinements to the atmospheric correction and band processing of the multispectral data, the next stage of this work should be able to determine if improved discrimination between weathered ultramafic rock and gossanous iron-oxide–rich materials is possible from visible and near-infrared multispectral data sources. With the range of field occurrences from weak, surface iron-oxide staining to more significant deeper gossan development, future work will investigate if this gradation can also be reliably discriminated with RapidEye and other sensors, such as WorldView-2. The rudimentary iron ratio employed thus far was able to successfully identify both weathered ultramafic bodies and gossans.

The ultramafic lenses and boudins identified are relatively rare on Hall Peninsula. Their detection can be of particular importance because they appear to be isolated from one another and therefore perhaps a marker horizon that has been attenuated and boudinaged along high-strain zones. Being able to recognize their distribution throughout the peninsula may hold clues as to their significance and enable a more complete tectonic interpretation of the region.

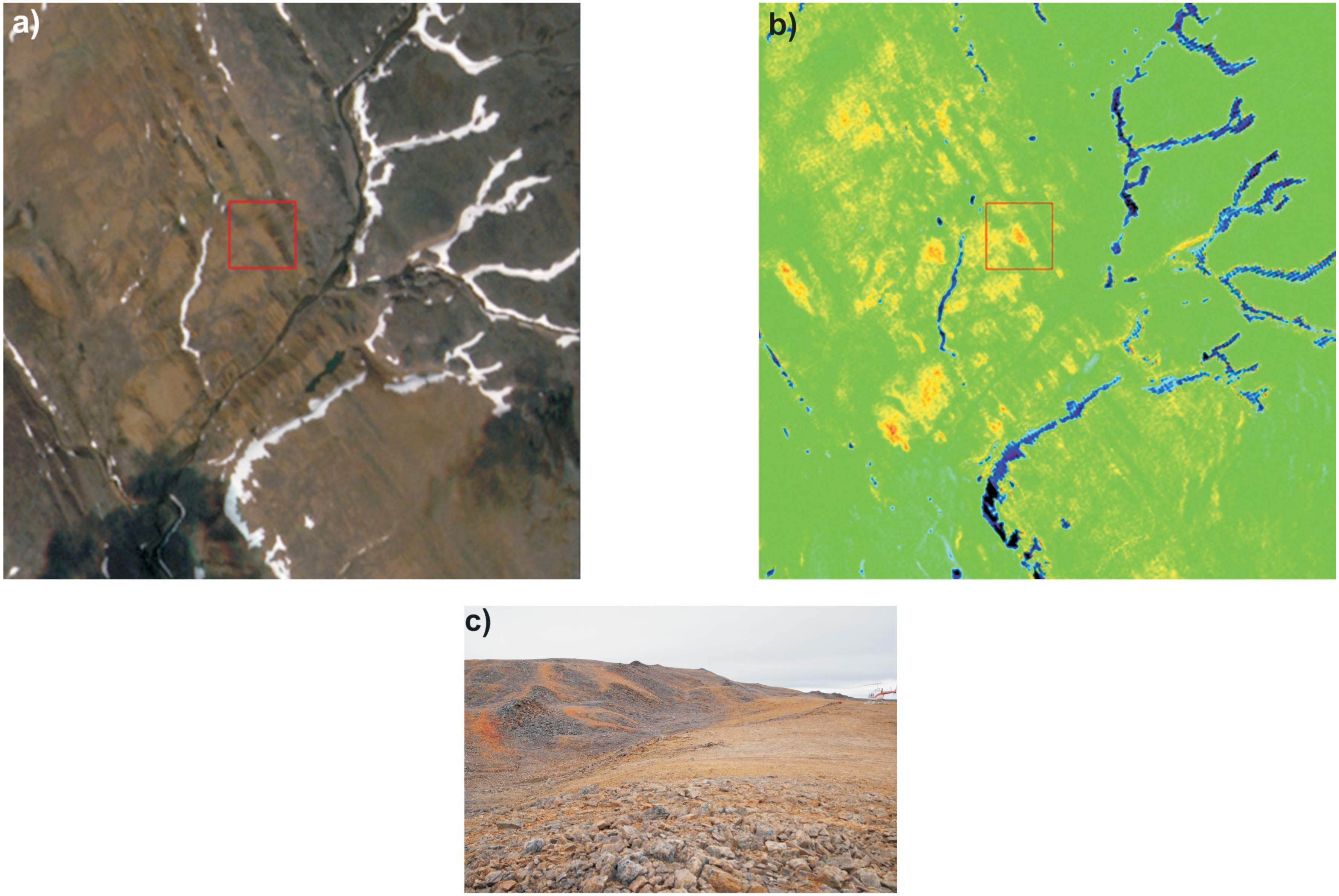

Figure 3: a) A subset area, in detail, of a RapidEye colour image (bands 3, 2 and 1) for one site visited along a broad band of supracrustal rock exposures (light brown tones). Image is 2 by 2 km. Includes material © (2011) RapidEye AG, Germany. All rights reserved. **b)** Corresponding iron-index image derived from the RapidEye multispectral data. Colour scale ranges from low values in blue to high values in red. A zone with a high iron index (outlined) was validated in the field and found to correspond to rusty weathering of the bedrock. Image is 2 by 2 km. **c)** Field photograph taken at the site outlined in the red box in (a) and (b).

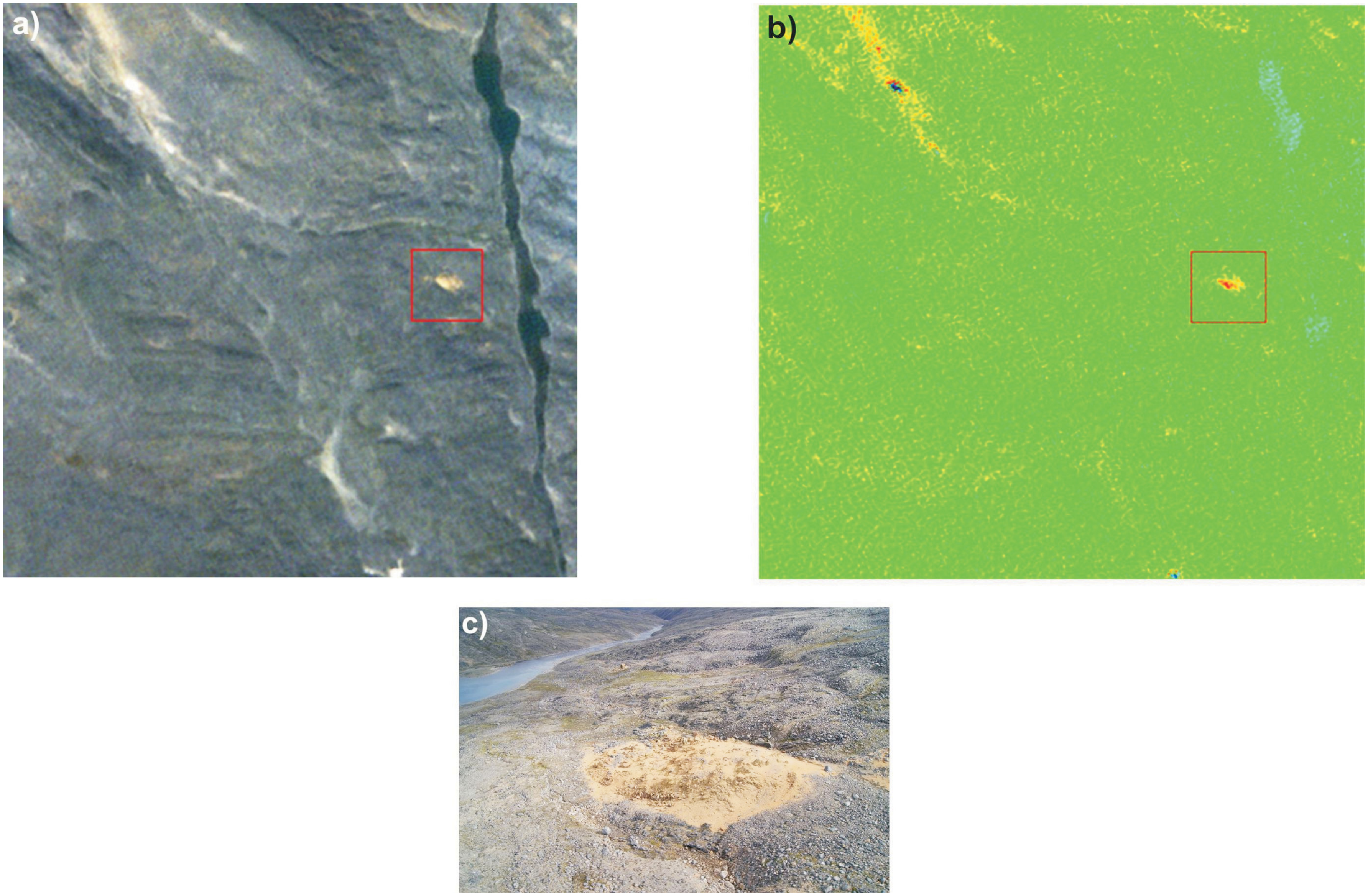

Figure 4: a) A subset area, in detail, of a RapidEye colour image (bands 3, 2 and 1) showing an isolated ultramafic pod appearing as a yellowish colour within blue- to brown-coloured supracrustal units. Includes material © (2011) RapidEye AG, Germany. All rights reserved. Image is 2 by 2 km. **b)** Corresponding iron-index image derived from the RapidEye multispectral data. Colour scale ranges from low values in blue to high values in red. The contrast between the ultramafic body and the surrounding bedrock is strongly highlighted. Image is 2 by 2 km. **c)** Aerial view photograph of the same ultramafic rock exposure, measuring about 60 by 80 m across, at the location indicated in (a) and (b).

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Surficial geology of southern Hall Peninsula, Baffin Island, Nunavut: summary of the 2012 field season

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Abstract

This study is part of the Canada-Nunavut Geoscience Office's Hall Peninsula Integrated Geoscience Program, a multiyear bedrock and surficial geology mapping program with associated thematic studies. This summary presents the surficial geology component of the program conducted during the 2012 field season, along with a summary of future work and a preliminary overview of the Quaternary geology of the area. The emphasis of this study is placed on 1:100 000 surficial geology mapping (NTS 025I, J, O, P, 026A, B), till sampling, glaciodynamic setting and ice-flow history of the area. A traditional place names geological study will aim at describing how the geological landscape is linked with Inuit traditional activities and landmarks.

Résumé

Cette étude fait partie du Programme géoscientifique intégré de la péninsule Hall, du Bureau géoscientifique Canada-Nunavut, un programme pluriannuel de cartographie du substratum rocheux et de la géologie de surface accompagnée d'études thématiques connexes. Le présent article décrit la composante « géologie de surface » du programme mené au cours de la campagne d'exploration de 2012, et résume les travaux futurs qui doivent avoir lieu, tout en présentant un aperçu préliminaire de la géologie du Quaternaire de la région. Cette étude met l'accent sur la cartographie de la géologie de surface à l'échelle de 1/100 000 (SNRC 025I, J, O, P, 026A, B), l'échantillonnage de till, le contexte glacio-dynamique et l'historique des écoulements glaciaires de la région. Une étude géologique des toponymes traditionnels cherchera à décrire la manière dont le paysage géologique est lié aux activités et aux repères traditionnels des Inuits.

Introduction

The Hall Peninsula Integrated Geoscience Program (HPIGP) is being led by the Canada-Nunavut Geoscience Office in collaboration with the Government of Nunavut, Aboriginal Affairs and Northern Development Canada, Dalhousie University, University of Alberta, Université Laval, University of Manitoba, University of Ottawa, University of Saskatchewan, Nunavut Arctic College and the Geological Survey of Canada. It is supported logistically by several local, Inuit-owned businesses. The study area comprises all or parts of six 1:250 000 scale National Topographic System map areas north and east of Iqaluit (NTS 026A, B, 025I, J, O, P; Figure 1).

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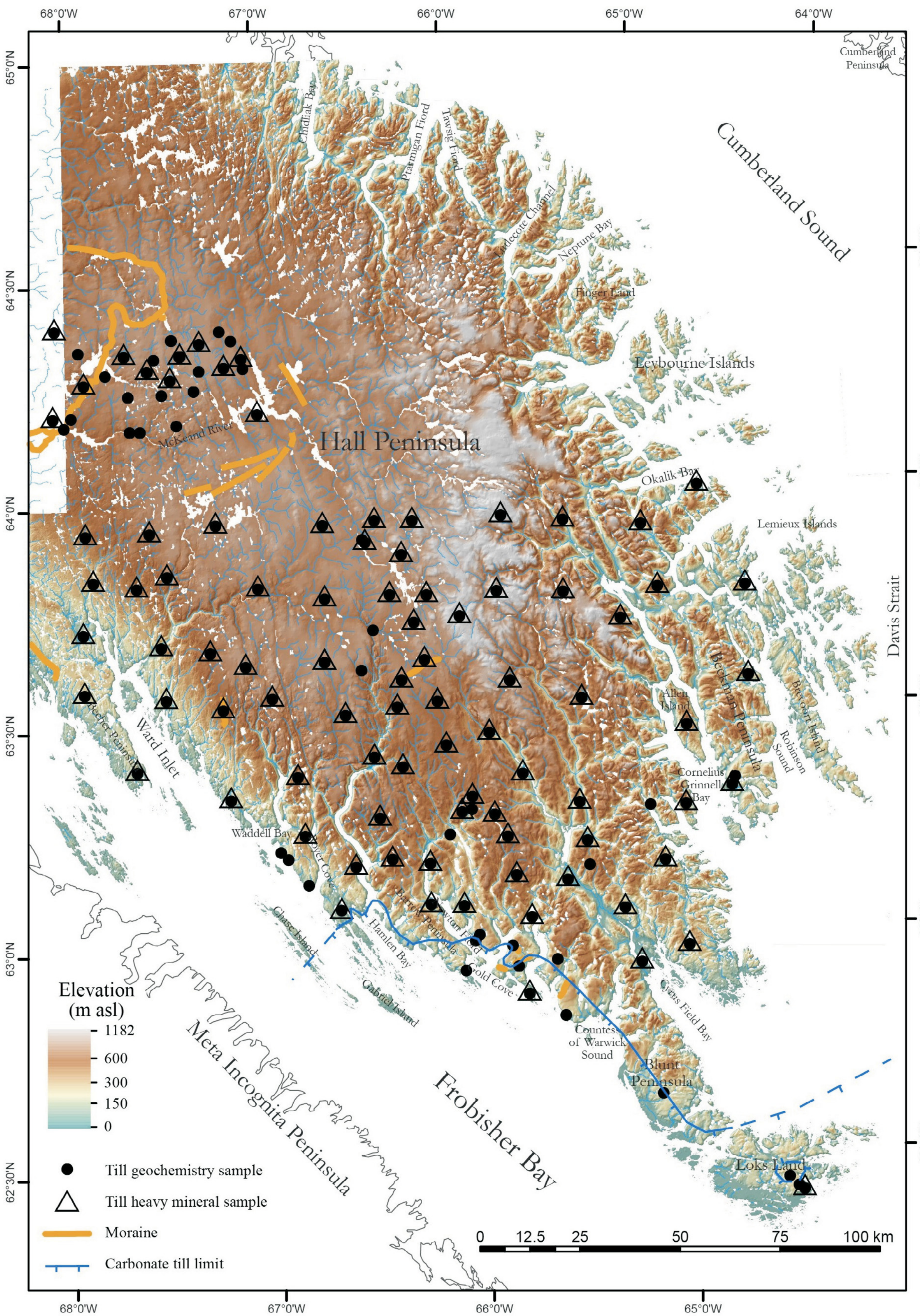

Figure 1: Location map displaying till sample locations, principal moraines and carbonate till limit, Hall Peninsula, Baffin Island, Nunavut. Digital elevation model (Gilbert, 2012) derived from CanVec 1:50 000 data (Natural Resources Canada, 2012).

In the summer of 2012, fieldwork was conducted in the southern half of the peninsula (NTS 025 I, J, O, P) between June 22 and August 8. Fieldwork was supported by a 20–25 person camp located approximately 130 km southeast of Iqaluit. The focus was on bedrock mapping at a scale of 1:250 000 and surficial-sediment mapping at a scale of 1:100 000. A range of thematic studies was also supported. This included Archean and Paleoproterozoic tectonics, geochronology, landscape uplift and exhumation, detailed mapping in mineralized areas, microdiamonds, sedimentary rock xenoliths and permafrost. Summaries and preliminary observations for all of these studies can be found in this volume.

Mineral exploration, geotechnical and aggregate resources studies require accurate surficial geology maps and glaciodynamic interpretations. Glacial geomorphology on southern Baffin Island has been the subject of much research (Andrews and Sim, 1964; Matthews, 1967; Miller, 1980; Dyke et al., 1982; Andrews et al., 1985; Stravers et al., 1992; Kaplan and Miller, 2003; Hodgson, 2005; Fréchette et al., 2006; Utting et al., 2007; Briner et al., 2009; Clements et al., 2009; Johnson et al., in press). However, there are currently no surficial geology maps for Hall Peninsula, except national-scale compilations (1:5 000 000 scale map). Ice-flow models for Hall Peninsula at a resolution suitable for drift exploration cannot be developed because publicly available databases are inadequate or nonexistent. Thus, due to limited previous research, a mixture of polythermal glacial bed conditions, and juxtaposition of alpine and ice-sheet glaciodynamics, the Quaternary geology of Hall Peninsula is complex and not completely understood.

This surficial geology mapping component of the HPIGP encompasses surficial materials characterization, ice-flow indicators, chronology and dynamics, permafrost studies, remote sensing as an aid to surficial mapping and traditional place name research. Fieldwork began in the summer of 2011 (preliminary overview of the study area), was continued in 2012 (Figure 2) and will end in 2013.

Preliminary surficial geology results

Surficial geology mapping

Surficial geology mapping at the scale of 1:100 000 commenced during the summer of 2012 with helicopter and foot traverses. Field observations, including landforms, surficial cover composition and ice-flow indicators, were compiled with ArcGIS (Esri, 2012) using the GSC-developed GanFeld application. The office-based mapping procedure included an all-digital approach combining a mosaic of airphotos in an on-screen stereoscopic view, using Summit Evolution software (DAT/EM Systems International, 2012) and ArcGIS. An extensive set of field photographs were geolocated using GPS, thus optimizing their desktop mapping usefulness. Mapping features were captured according to the new GSC surficial geology integrated legend. Landsat, RapidEye, SPOT and WorldView-2 satellite imagery and a DEM (Gilbert, 2012) from CanVec 1:50 000 data (Natural Resources Canada, 2012; Figure 1) were also used in the mapping process. The area covered in 2012 was approximately 21 000 km^2 and about 17 000 km^2 are expected to be mapped in 2013.

Surficial cover composition includes bedrock (mainly Precambrian granitoid rocks and gneiss), regolith, till, glaciofluvial sediments, glaciolacustrine and marine sediments, colluvial, alluvial and coastal deposits, and hydrological elements include streams, lakes and glaciers. Figure 1 depicts the location of the principal moraines currently mapped and the extent of carbonate till transported from Frobisher Bay towards the north (compiled from field data and Stravers et al., 1992). To improve the deglacial chronology, support the ice-flow history interpretations and establish limits on Quaternary erosion history, targeted and opportunistic samples are being collected for radiocarbon dating, optically stimulated luminescence (OSL) dating and cosmogenic nuclide dating.

Surficial material characterization (geochemistry, sedimentology, mineralogy)

A regional coverage of glacial sediments is a major component of surficial studies on Hall Peninsula. So far, 136 geochemistry samples (2 kg each; an additional 14 were sampled in 2011) have been collected from the southern half of Hall Peninsula and selected locations in the northern half, with an average spacing of 10–20 km between samples (Figure 1). The spacing is about 5–10 km in areas of elevated mineral potential (i.e., close to known deposits and volcano-sedimentary belts) and up to 20–30 km in remote islands to the northeast, underlain by metatonalite basement. Specific geotechnical studies conducted in the northern area required a higher density of geochemical samples, with a spacing around 5 km between samples. Ninety heavy mineral samples were taken (10 kg bags) to provide information on kimberlites, massive sulphides, gold, gems and many other commodities. Additionally, seven mineralized boulders containing sulphides and one soapstone boulder were sampled.

Ice-flow indicators and chronology

Ice-flow directions and chronology are being established using striations, glacial landforms, glacial sedimentology and multiple geochronological approaches (Figure 2). The occurrence of different phases of ice were observed in the field by crosscutting relationships between striations, stratigraphic relationships and ice-retreat geochronology. Interpretation of this ice-flow history is in part based on the work of previous workers (Miller, 1980; Dyke and Prest, 1987; Stravers et al., 1992; Dyke et al., 2003; Johnson et al., in press). The relative chronology of the ice-flow phases is based solely on the estimated time of the beginning of each phase and not the entire duration of the events, therefore chronological overlap is possible between phases.

Ice flow 1

Last glacial maximum(?), main recorded ice-flow direction

This important ice-flow phase radiated from an ice divide located on Hall Peninsula, possible during the last glacial maximum (LGM). During that time, Hall Peninsula was probably entirely covered by ice, as was a major part of the mountainous area of Baffin Island (Marsella et al., 2000; Staiger et al., 2006).

LGM(?), ice stream in Frobisher Bay and Cumberland Sound

Ice flows in these regions are important because they persisted for some time as high velocity zones of flows known as ice streams (Dyke and Morris, 1988), draining ice through major topographic axes in Frobisher Bay and Cumberland Sound. This ice flow may have influenced the velocity of adjacent ice.

LGM(?), radial ice flow, presumed only, no record from striation or macroforms

Sheetlike ice flow possibly occurred across the mountainous area, although no landform or glacial direction indicators in the study area directly support this theory, contrary

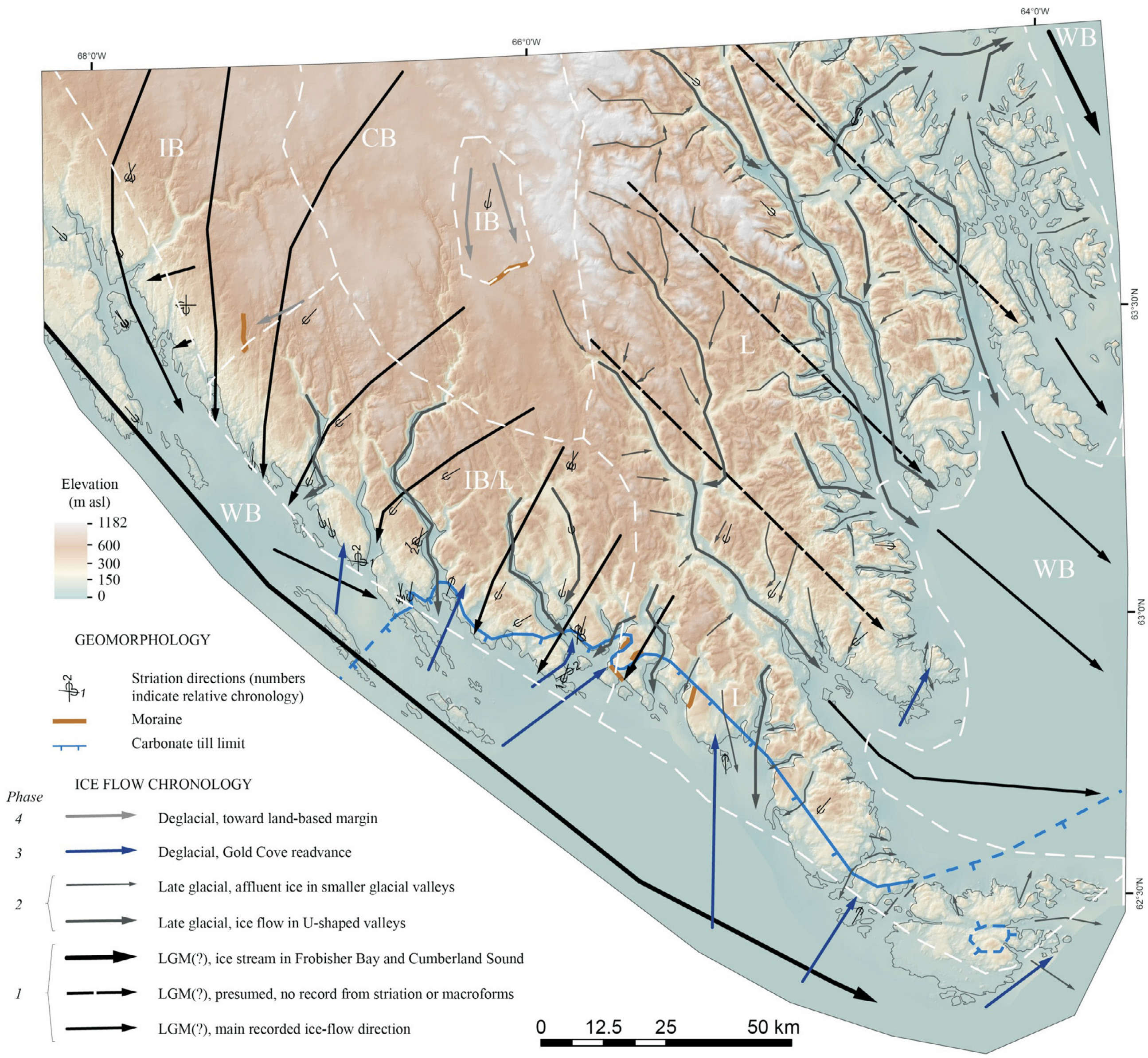

Figure 2: Preliminary ice flow and glaciodynamic setting in southern Hall Peninsula, Nunavut. Digital elevation model (Gilbert, 2012) derived from CanVec 1:50 000 data (Natural Resources Canada, 2012). Abbreviations: CB, cold-based area; IB, intermediate-based area; IB/L, mix of intermediate-based and linear selective glacial erosion areas; L, linear selective glacial erosion; WB, warm-based area.

to the northern Hall Peninsula area (as described in Johnson et al. [in press]). Alternatively, during the LGM, ice flow might also have been topographically controlled to a certain extent, especially close to the Cumberland Sound ice stream.

Ice flow 2

Late glacial, ice flow in U-shaped valleys

This ice flow phase, comprising glacial advance and retreat, occurred from the late glacial period to the Late Holocene. It is characterized by convergent patterns of ice movements that drained ice from topographic highs, including the centre of the peninsula. Glacial erosion was apparently concentrated in topographic lows (deep U-shaped valleys are evident throughout the peninsula). Fjords are commonly located at the down-ice section of the ice flows (Johnson et al., in press).

Late glacial, affluent ice in smaller glacial valleys

This ice-flow episode is directly connected to the extant mountain glaciers. Although it is possible that glacial advance and retreat occurred from the late glacial period to the present, the majority of ice flow was probably during the Holocene. Recently deglaciated, neoglacial tills and moraines are found at the margins of several modern glaciers. Similar to ice flow in U-shaped valleys, this episode is characterized by convergent patterns of ice flow draining ice from the topographic highs to offshore, but these flows are located in smaller alpine valleys and cirques in Hall Peninsula.

Ice flow 3

Deglacial, Gold Cove readvance

This flow represents a limited, northward, carbonate-bearing glacial readvance at the southern tip of Hall Peninsula. This ice flow is thought to have been influenced by ice burst episodes of the Hudson Strait and Ungava Bay ice streams (Stravers et al., 1992). This ice-flow phase was probably short-lived and appears to have occurred after ice flow 1, during a part of the longer lasting ice flow 2 phase, which was affecting the rest of Hall Peninsula.

Ice flow 4

Deglacial, toward land-based margin

This phase represents localized ice flows related to a minor standstill of the ice sheet margin or smaller alpine glaciers. The flow is best depicted by nested recessional moraines. Ice was at least slightly sliding on its base. This warm-based ice transported sediment to construct the moraines, and evidence of glacial scouring and polish is found throughout the landscape (lakes, bare outcrop and frequent fine striations on uppermost exposed bedrock surfaces).

Glaciodynamic zones

The mapping of glaciodynamic zones represents an interpretation of the geomorphological and geochemical results indicating the probable amount of glacial erosion and glacial sediment transport in a particular region (Figure 2). It may help resolve enigmatic ice-flow histories at local scales, or explain unsuccessful attempts to use glacial sediment transport as a means to establish ore sources.

The geomorphological indicators of glacial erosion are summarized as a broad classification of terrain types. The observations are primarily based on numerous field observations and interpretation of DEMs, satellite imagery and airphotos. For instance, glacial scouring as evident from the presence of numerous small lakes and glacially eroded bare outcrops is interpreted to represent erosive conditions (warm-based ice), whereas the persistence of a mix of thick nonglacial regolith, felsenmeer and till would suggest cover by predominantly weakly erosive (cold-based) ice (Sugden, 1978; Miller, 1980; Dyke, 1993; Dredge, 2000; Tremblay et al., 2011; Hodder, 2012). The dynamic character of the former ice sheet (cold- versus warm-based) can thus be inferred from this classification, and can therefore help to understand and outline the nature of glacial transport. The mapping includes methodological elements from the central Canadian Arctic (Dyke, 1993), Melville Peninsula (Dredge, 2000; Tremblay et al., 2011; Tremblay and Paulen, 2012) and from Baffin Island (Miller, 1980; Andrews et al., 1985; Johnson et al., in press). As a complement to Johnson et al.'s (in press) studies on northern Hall Peninsula, till geochemistry and cosmogenic isotopes on bedrock outcrops and tills will be used to assess the spatial distribution of glacial erosion during the Late Quaternary on Hall Peninsula.

Cold-based area (CB)

In this zone, the glacier was frozen at its base and little or no sliding occurred on the glacier bed. This area coincides with the location of the main ice divide during the LGM. The landscape is not glacially scoured (Figure 3a; this is indicated by the general absence of ice-scoured lakes and the rarity of fresh bedrock outcrops) and glacial sediments have been transported for short or negligible distances, probably as englacial load (example on Melville Peninsula [Tremblay and Paulen, 2012]). Coverage by ice sheet during the Quaternary is indicated by abundant glaciofluvial channels and the presence of rare glacial erratics, some of them intensively weathered (Miller, 1980). A few cold-based alpine glaciers are included in this area, and little or no glacial scouring is observed around them.

Intermediate-based area (IB)

The glacier was frozen at its base for long periods in this zone, and occasionally warm-based erosion occurred, but with relatively restrained intensity (example on Melville

Peninsula [Tremblay and Paulen, 2012]). Scouring of the landscape is gradually more evident compared to the cold-based area (ice-scoured lakes are present and fresh bedrock outcrops are common). This zone is often in contact with the warm-based (WB) zones. Glacial sediments were transported for short to moderate distances.

Mix of intermediate-based and linear selective glacial erosion areas (IB/L)

In this zone, glacial thermal patterns are mixed, with extensive areas of intermediate-based ice (and sparse cold-based ice areas) on plateaus, and locally linear glacial erosion in the U-shaped valleys (fjords; Sugden, 1978; Johnson et al., in press). Spatial and temporal variations in ice-flow velocity are implied by this complex glaciodynamic pattern, with warm-based ice flow in the U-shaped valleys being generally younger than the intermediate-based ice flow on the plateau (see Ice-flow indicators and chronology section).

Linear selective glacial erosion (L)

This is a landscape of patchy warm-based conditions in the numerous glacial valleys, juxtaposed with CB and IB zones on the plateaus and mountain tops (Sugden and Watts, 1977). The result is the generation of accentuated relief, caused by the deepening glacial erosion and the preservation of adjacent summit felsenmeer, where ice is kept relatively thin by the dynamic and efficient drainage through the glacial valleys. Small ice caps and valley glaciers are still present on some of the highest mountains, generally over 1000 m asl.

Warm-based area (WB)

This geomorphological landscape type reflects important glacial activity related to warm-based ice conditions, where ice is melting at the base of the glacier and sliding occurs at the bed. Glacial scouring is important and is observed by

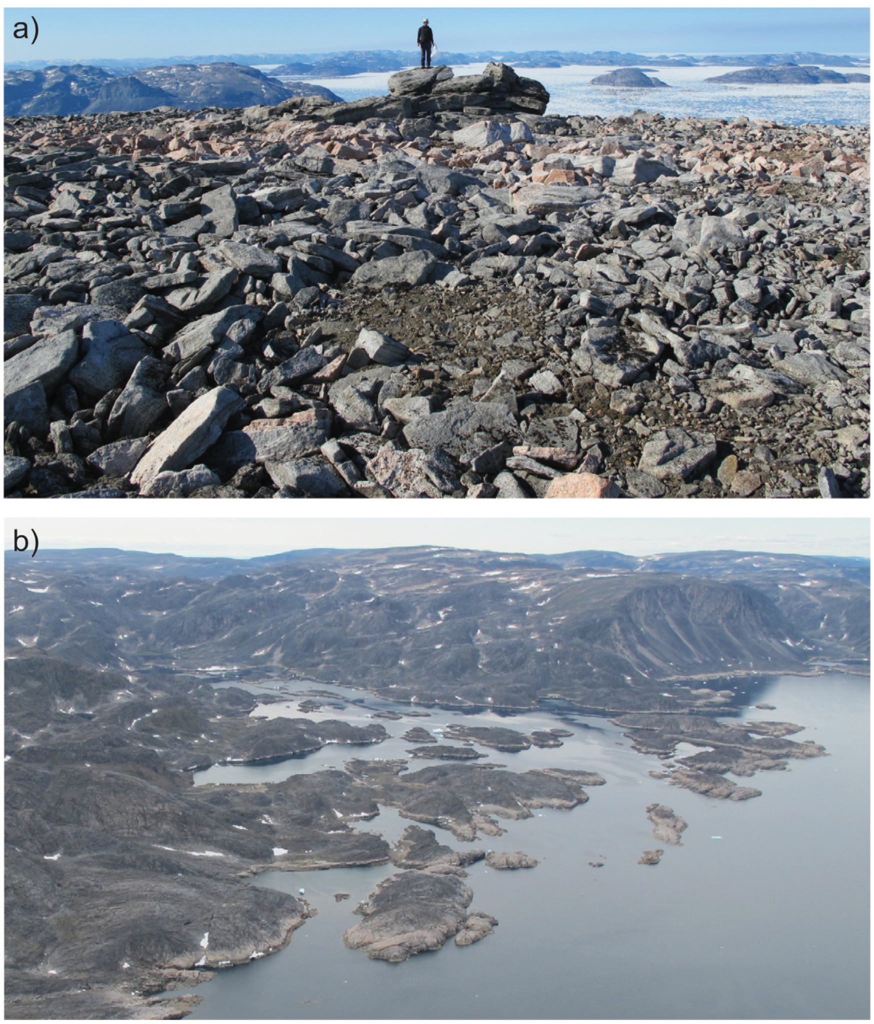

Figure 3: a) Tor on felsenmeer surface (local cold-based ice in a linear-erosion dynamic setting) at the outer edge of Lemieux Islands, Nunavut. **b)** Warm-based–ice valley and cold-based–ice plateau in a linear-erosion dynamic setting, Blunt Peninsula, Nunavut. The bay in the centre of the photo is named Isingujjuaq on the Taqulijjuaq, Nunavut place names map (Inuit Heritage Trust Inc., 2009), and was the site of a cabin where whalers stayed a long time ago.

the presence of numerous lakes, polished or striated outcrops, and streamlined depositional or erosional landforms. Glacial transport distances are generally relatively long (example on Melville Peninsula [Tremblay and Paulen, 2012]) and glacial sediment thickness is variable.

Traditional place names project

Visits were made to assemble geological information about the sites with traditional place names on Hall Peninsula (Inuit Heritage Trust Inc., 2009). These names are the original place names used by the Inuit people and transmitted through oral tradition and recently mapped from interviews with elders that lived in the specific areas.

During summer 2012, several sites located along the Hall Peninsula southern coast were photographed from the helicopter (Figure 3b). The sites were selected when their descriptive place names related to geology or geomorphology, or involved a specific activity that was controlled by the local geomorphological setting. The photographic surveys were conducted by geologists, geomorphologists and co-author, P. Peyton. Information, co-ordinates and photographs related to the sites will be compiled into a format compatible with other Inuit Heritage Trust Inc. products (notably Google Earth™-based maps).

Economic considerations

The scientific results stemming from the surficial geology studies of CNGO's HPIGP will contribute to helping Canadians make better decisions concerning the management of their natural resources. The surficial maps and geomorphological studies (glaciodynamic mapping, permafrost, satellite images and uplift history) will help to minimize risk associated with mineral exploration in glaciated terrain and optimize the design of infrastructure projects. Till geochemical and mineralogical data will contribute to more efficient mineral exploration and assessment of environmental and geotechnical characteristics of soil.

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Quaternary geology and permafrost characteristics in central Hall Peninsula, Baffin Island, Nunavut

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Abstract

This study is part of the Canada-Nunavut Geoscience Office's Hall Peninsula Integrated Geoscience Program, a multiyear bedrock and surficial geology mapping program with associated thematic studies. Hall Peninsula, southeastern Baffin Island, has a very complex record of glaciation because 1) most ice-flow indicators reflect the dynamics of the latest, topographically controlled ice; and 2) there are extensive regions that lack evidence of glacial erosion, despite the undoubted complete ice cover of the peninsula during the last glaciation. Drift prospecting in this glaciated terrain is therefore complicated due to difficulties in predicting erosion and transport distances of ore-bearing glacial drift. The objectives of this project are to map the surficial geology, improve knowledge of the glaciodynamics, and characterize the ice content and thaw properties of the permafrost in Hall Peninsula. In particular, the presence of regolith, felsenmeer and weakly eroded bedrock outcrops suggest that cold-based glaciers have covered the central part of the region during the Late Pleistocene. In summer 2012, detailed mapping, helicopter-supported and foot-traverse field surveys, and sampling were completed in a 2100 km^2 area that is representative of this surficial zone, which is found throughout the central plateau of the peninsula. The central part of the study area is surrounded by a transition zone where surficial material is composed of a mixture of regolith and glacial sediment. Field observations documented regolith with variable thickness, ranging from >3 m on the plateau to 0 m at the base of meltwater channel gorges. The regolith covers an area of approximately 50 km^2 and is characterized on satellite imagery by its white colour. The plateau is locally covered with extensive ice marginal moraines. The timing, extent and dynamics of late glacial ice and younger readvances, represented by these moraines, is presently poorly resolved. It was possible to establish that the most abundant striation set is perpendicular to the moraines and therefore correlative with their deposition. Till lithological and geochemical analyses and high resolution mapping will help in reconstructing ice-flow patterns and transportation distances of the till. Additionally, two, frozen, 1.2 m long, permafrost cores were extracted intact from the regolith cover, in the central part of the study area, to determine its particular properties. This glacial geology study supports the search for economic minerals in the region, and the permafrost characterization will be useful for land management related to infrastructure development.

Résumé

Cette étude fait partie du Programme géoscientifique intégré de la péninsule Hall, du Bureau géoscientifique Canada-Nunavut, un programme pluriannuel de cartographie du substratum rocheux et de la géologie de surface accompagnée d'études thématiques connexes. La péninsule Hall, située au sud-est de l'île de Baffin, présente une histoire de glaciation très complexe car : 1) la plupart des indicateurs d'écoulement glaciaire reflètent la dynamique de la plus récente couverture glaciaire, contrôlée par la topographie, et 2) il existe de vastes régions dénudées de traces de l'érosion glaciaire, malgré le fait que la péninsule ait manifestement été recouverte entièrement au cours de la dernière glaciation. La prospection glacio-sédimentaire dans ce terrain glaciaire est donc compliquée en raison de difficultés à prévoir les distances d'érosion et de transport des dépôts glaciaires minéralisés. Les objectifs de ce projet sont les suivants : cartographier la géologie de surface, améliorer l'état des connaissances au sujet de la glacio-dynamique et caractériser la teneur en glace et les propriétés de dégel du pergélisol de la péninsule Hall. La présence de régolite, de felsenmeer et d'affleurements rocheux faiblement érodés semble indiquer notamment que les glaciers à base froide ont recouvert la partie centrale de la région au cours du Pléistocène

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tardif. À l'été 2012, une cartographie détaillée, appuyée par des levés effectués par hélicoptère et à pied sur le terrain, ainsi que des travaux d'échantillonnage ont été réalisés sur une superficie de 2 100 km^2 qui est représentative de cette zone superficielle, que l'on retrouve partout sur le plateau central de la péninsule. La partie centrale de la zone d'étude est entourée par une zone de transition où les matériaux de surface sont composés d'un mélange de régolite et de sédiments glaciaires. Les observations sur le terrain ont documenté un régolite d'épaisseur variable, allant de > 3 m sur le plateau à 0 m à la base des gorges des chenaux d'eau de fonte. Le régolite couvre une superficie d'environ 50 km^2 et se caractérise sur l'imagerie satellitaire par sa couleur blanche. Le plateau est recouvert par endroits de moraines marginales glaciaires étendues. La cadence, l'ampleur et la dynamique de la glace de glacier tardive et des récurrences plus récentes, représentées par ces moraines, sont actuellement mal comprises. Il a été possible d'établir que l'axe de la série de stries la plus abondante est perpendiculaire aux moraines et donc corrélatif de la mise en place de ces dernières. Les analyses lithologiques et géochimiques du till et la cartographie haute résolution contribueront à la reconstitution des régimes d'écoulement glaciaire et des distances de transport du till. En outre, deux carottes congelées de pergélisol, de 1,2 m de longueur, ont été extraites intactes de la couverture de régolite dans la partie centrale de la zone d'étude en vue d'en déterminer les propriétés particulières. Cette étude de la géologie glaciaire vient appuyer la recherche de minéraux économiques dans la région et la caractérisation du pergélisol sera utile pour la gestion des terres dans le cadre du développement des infrastructures.

Introduction

The Hall Peninsula Integrated Geoscience Program (HPIGP) is being led by the Canada-Nunavut Geoscience Office in collaboration with the Government of Nunavut, Aboriginal Affairs and Northern Development Canada, Dalhousie University, University of Alberta, Université Laval, University of Manitoba, University of Ottawa, University of Saskatchewan, Nunavut Arctic College and the Geological Survey of Canada. It is supported logistically by several local, Inuit-owned businesses. The study area comprises all or parts of six 1:250 000 scale National Topographic System map areas north and east of Iqaluit (NTS 025I, J, O, P, 026A, B).

In the summer of 2012, fieldwork was conducted in the southern half of the peninsula (NTS 025 I, J, O, P) between June 22 and August 8. Fieldwork was supported by a 20–25 person camp located approximately 130 km southeast of Iqaluit. The focus was on bedrock mapping at a scale of 1:250 000 and surficial-sediment mapping at a scale of 1:100 000. A range of thematic studies was also supported. This included Archean and Paleoproterozoic tectonics, geochronology, landscape uplift and exhumation, detailed mapping in mineralized areas, microdiamonds, sedimentary rock xenoliths and permafrost. Summaries and preliminary observations for all of these studies can be found in this volume.

Research based on airphoto interpretation and fieldwork on Hall Peninsula was conducted by Andrews (1972, 1979, 1985) and Miller (1974, 1980, 1985, 2002) to reconstitute the glacial and relative sea level history of the region. Two principal moraines, Hall moraine and Frobisher Bay moraine, were mapped on the Hall Peninsula plateau by Miller (1980). The Hall moraine was dated at 9500 BP by radiocarbon analysis of shell fragments collected on glaciomarine deltas associated with the moraine (Stravers et al., 1992) and the Frobisher Bay moraine was dated at 8230 BP using radiocarbon dating on shells collected directly on the moraine (Blake, 1966). Both moraines are associated with late readvances of the Laurentide Ice Sheet and are directly in contact with proglacial lake systems, deltas and shorelines. Based on the observation of deeply weathered erratics, felsenmeer (an exposed rock surface that has been affected by freeze and thaw action causing its fracturing) and advanced soil development above elevations of 350–450 m asl on Hall Peninsula, Miller (1980) proposed the possibility that the plateau region may have been ice free during the last interstadial prior to late Wisconsinan glaciation (i.e., oxygen isotope stage 3). No fieldwork has been conducted in the central part of the peninsula to test this hypothesis.

During summer 2011, exploratory fieldwork, conducted 85 km northeast of Iqaluit (Figure 1) by the Canada-Nunavut Geoscience Office (CNGO), verified a wide, red and highly weathered regolith zone, which could be related to weakly eroding or no ice on that part of the peninsula. Regolith is a product of the weathering of underlying bedrock forming an unconsolidated soil on the surface. In temperate and warm regions, weathering is generally produced by chemical action, such as water percolation that affects the mineral composition of the rock over time, but in cold regions it can also be caused by mechanical processes, such as freeze-thaw cycles. The presence of the regolith, as well as felsenmeer and weakly eroded bedrock outcrops, suggests that cold-based glaciers could have covered this particular region of central Hall Peninsula (Sugden, 1978), providing an alternative to the previous hypothesis. The term cold-based refers to an internally flowing glacier that is frozen to its substrate. Cold-based ice is weakly (or non) erosive, so sediment will not be entrained and transported whereas warm-based ice will erode, produce evidence of ice flow (striations and till dispersion records), and provide sediment to construct ice marginal moraines. Also, dry cold-based thermal regimes tend to occur under thin ice

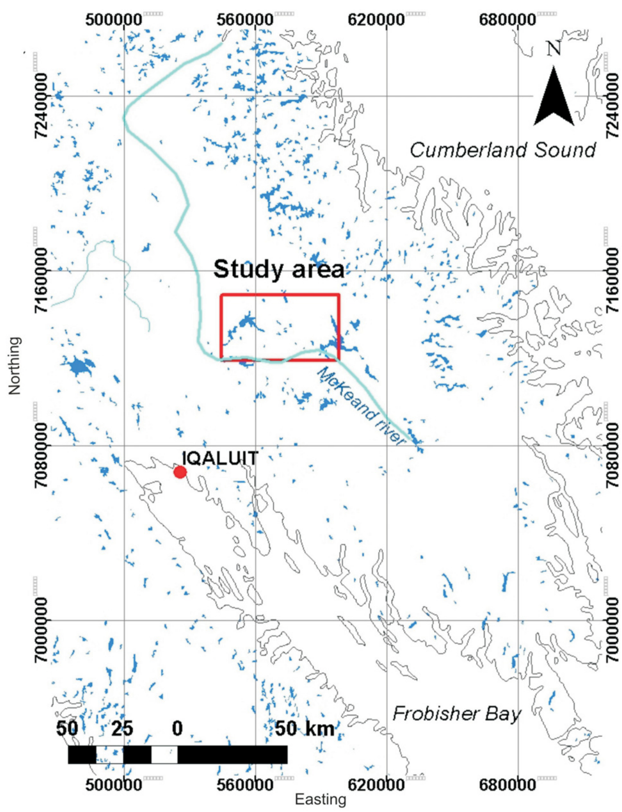

Figure 1: Location of study area, central Hall Peninsula, Baffin Island, Nunavut.

cover (allowing geothermal heat loss) or immediately under ice-flow divides or domes with there is no net ice flow, whereas wet warm-based conditions occur under thick ice or where ice is converging or where ice flow is significantly fast to contribute subglacial frictional heating.

In July 2012, based on this exploratory work, a detailed study of a 60 by 35 km area within this relatively highly weathered plateau zone was completed. This paper presents the main objectives and preliminary results of this study.

Objectives

This research has two main objectives. The first one is to better understand the glaciodynamic history of the region by mapping the surficial geology, determining the main directions of ice flow and identifying the regional limits between the cold- and warm-based regimes of the ice sheet over the region. This objective will help test the two hypotheses. The second objective is to explore the characteristics of permafrost in highly weathered bedrock. The purpose of this work is to support mining exploration by improving knowledge about glacial transport of sediments during the last glaciation and to better understand issues associated with infrastructure development, such as the construction of transportation routes in central Hall Peninsula.

Preliminary results

Sample collection

Surficial mapping, from interpretation of remotely sensed imagery and airphotos, as well as helicopter-supported and foot-traverse field observations were completed in summer 2012. In total, 35 sediment samples were collected in the study area (Figure 2). Grain-size analysis on different types of sediment samples will determine the size distribution and sorting of the different deposits, such as till, glaciolacustrine, glaciofluvial and more recent deposits. Heavy mineral analyses on 16 till samples will help identify the composition of the bedrock up ice. Ten bedrock samples were also taken for heavy mineral analysis. Geochemical analyses will be done on all 16 till and 11 regolith samples and will consist of iron and aluminum extraction by leaching. The composition of the regolith will be compared with the mineral composition of samples collected from the bedrock, which will indicate whether the regolith has been transported from an external source or if it comes from in situ alteration. Electronic scanning microscope (ESM) imaging of sand grains from till samples will be performed to verify the presence of shock marks on glacially transported material; similarly ESM imaging on the iron oxidized fraction of the regolith samples shall verify the presence of traces of chemical weathering on mineral grains. Finally, X-ray diffractometry on the oxidized ferric clay portion of the regolith samples will provide information on the crystal structure of the altered mineral. Two permafrost cores were also extracted from the regolith for analysis, such as ice content, active layer thickness and liquidity and plasticity limits.

Moraine

On the west side of the study area, there is a moraine ridge that averages 15 m high and 150 m wide (Figure 2). It represents a part of the Frobisher Bay moraine which, based on Blake's mapping (Blake, 1966), extends 150 km from Frobisher Bay to the head of Cumberland Sound. This moraine was formed during a minor readvance of the Laurentide Ice Sheet (Miller, 1985) around 8230 BP. An important concentration of lakes at the surface of the terrain and the presence of deltas almost directly in contact with the moraine was noted during 2012 fieldwork. The concentration of lakes around the moraine is an indicator of the thermal regime beneath the glacier, which in this case was a zone of transition between cold-based and warm-based glacier beds (Sugden, 1978). The deltas, reaching heights of 25 m, reflect the fast rate of deglaciation in the region. The dip direction of the foreset beds in the deltas provides information about the direction of meltwater flow draining into Cumberland Sound, as was predicted by Miller (1985). The presence of glaciolacustrine deposits next to the deltas and the moraine could be explained by the presence of a proglacial lake.

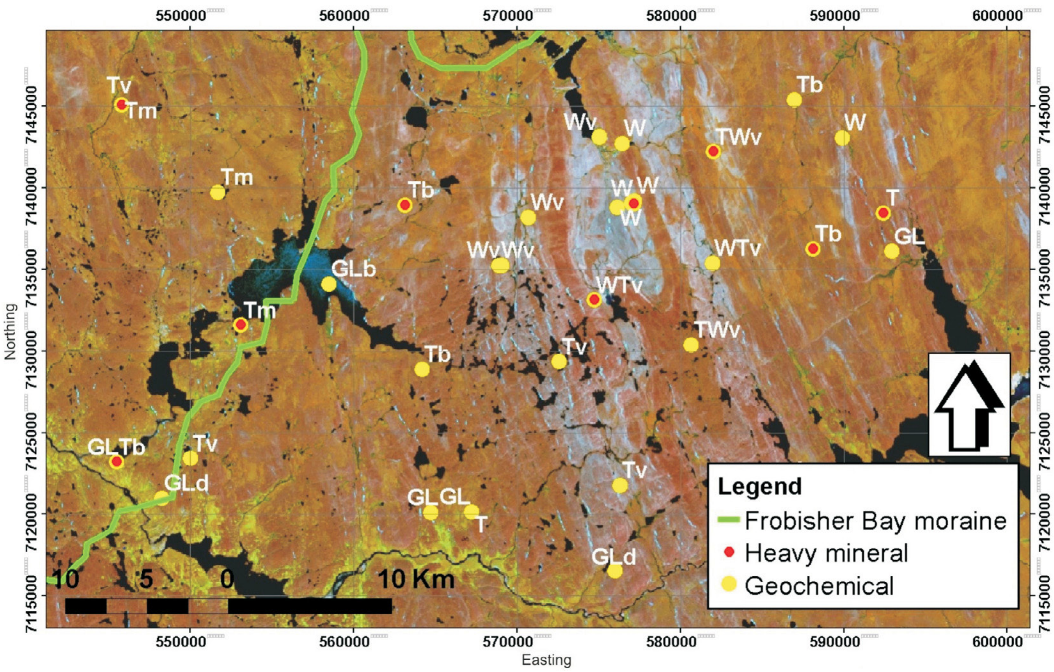

Figure 2: Location of sediment samples, central Hall Peninsula, Baffin Island, Nunavut.

Ice-flow directions

In the study area, glacial striations were observed in only five locations (Figure 3), owing to the dominance of weathered and weakly polished bedrock surfaces. Based on preliminary interpretations, the striations correspond to the ice-flow directions during ice-retreat phases. Most polished and striated outcrops were found outside the regolith zone on the shores of rivers and lakes where fresh bedrock surfaces are present. The area seems to have been affected by two, possibly three, different ice flows. The striations collected are mostly directed toward the east and southeast, generally perpendicular to the moraine located south of McKeand River (Hall moraine) and to the nearby portion of the Frobisher Bay moraine.

Regolith

The central part of the study area is covered by 1–3 m of regolith forming a wide plateau with low relief. This regolith zone is readily distinguished on imagery and from the air by its light colour (Figures 2, 3) and is interpreted to be related to a region that has not been covered by actively eroding ice during the last (Wisconsinan) glaciation. This regolith is red, primarily due to geochemical alteration. Deep weathering of bedrock likely occurred under warmer climate conditions, during interglacial periods or even before. However, the presence of rare erratic boulders on the surface of the regolith and the large size of the ice sheet, as deduced from its offshore extension (Miller, 2002), indicate that the whole region was covered during the last glaciation. A glaciofluvial channel shows how water carved into this in situ material, eroding the regolith to bedrock (Figure 4). This can be viewed as evidence that chemical alteration preceded the Wisconsinan glaciation on Hall Peninsula. The regolith areas were thus recently covered by cold-based, noneroding ice. The central regolith zone is surrounded by an outer zone covered by a mixture of regolith and till, which represents a transition between regions of actively eroding ice and regions of nonactively eroding ice. This transition is further correlated with the presence of a progression from rare, periglacially affected bedrock outcrops (felsenmeer) to progressively more abundant, glacially scoured and/or polished bedrock outcrops. Those two characteristics, the importance of the bedrock erosion and the proportion of regolith and till can represent a gradual transition between cold-based and warm-based basal thermal regimes under the last ice sheet.

Permafrost

Two, 1.2 m long, permafrost cores were extracted from the regolith cover in the central part of the study area (Figure 5). During the extraction at the end of July 2012, the thaw front was reached at approximately 1.1 m below surface in both excavations. Continuous frozen cores were extracted down to an average depth of 2.3 m below surface in what seems to be a transition zone where the bedrock gradually becomes less weathered. This suggests that, as proposed, the regolith material originates from in situ weathered bedrock and was not eroded or transported by glacial ice, thus supporting the cold-based ice hypothesis. Permafrost analyses, such as ice content, active layer thickness and liquidity and plasticity limits, will be completed in order to assess soil behaviour in areas of permafrost thawing. This information will support possible future infrastructure

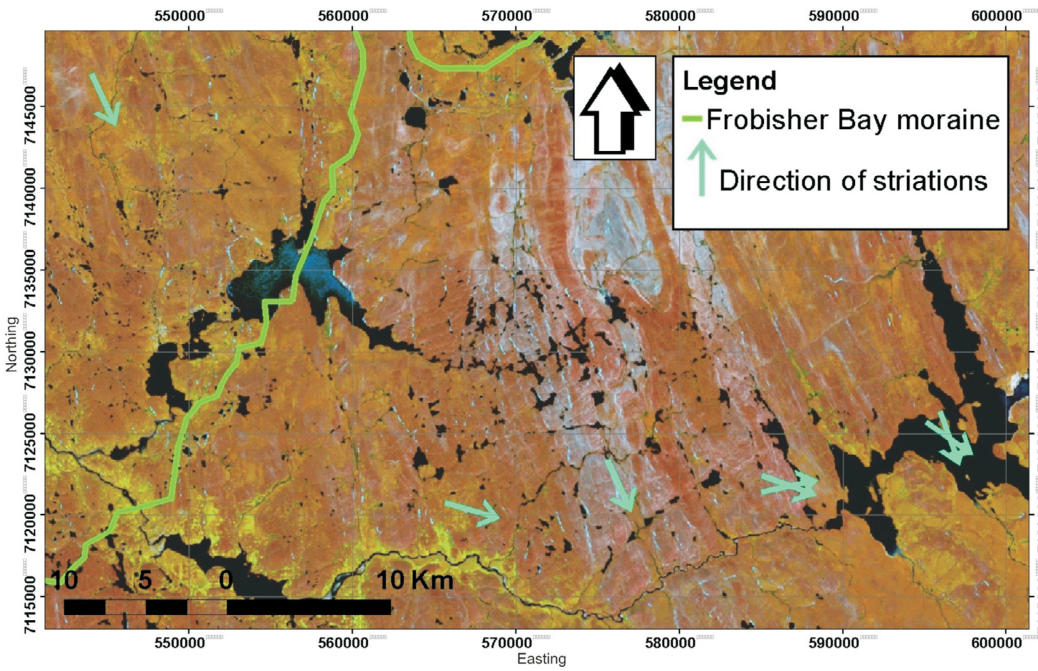

Figure 3: Measured striation directions, central Hall Peninsula, Baffin Island, Nunavut.

construction due to mining industry expansion in the region.

Future studies

This work shall help to better define the transitions between weathered and glacially affected zones, i.e., to establish the boundaries between regions dominated by cold-based and warm-based glacial ice covers. Using the findings of this field study, it may be possible to reliably map these zones from satellite and airborne imagery. More fieldwork will be necessary to either confirm or to further improve the preliminary glaciodynamic model.

The geochemical and heavy mineral analysis that will be

done on till and regolith samples will help clarify preliminary interpretations. The regolith so far remains a poorly studied type of permafrost material.

Conclusion and economic considerations

This project will result in an improved, more detailed, 1:20 000 surficial geology map and a better understanding of the Pleistocene ice dynamics on Hall Peninsula. Properties of the permafrost, such as water content, thickness of active layer and liquidity and plasticity limits, in the regolith of central Hall Peninsula, north of Iqaluit, will be better known. Therefore, it will be possible to evaluate the impacts of possible thawing caused by climate change or engineered works. Fieldwork done during summer 2012 has led the authors to postulate that the central part of the study area was locally covered by cold-based ice during the last glacial advance. This implies that the material covered by cold-based ice in the central part of the peninsula was not transported during glaciation. In these cold-based ice regions, the minerals found in till come from in situ alteration of the underlying bedrock rather than from a source up ice. Drift prospecting in this glaciated terrain is therefore complicated due to difficulties in predicting erosion and transport distances of ore-bearing glacial drift. Knowing the exact limits of cold-based ice will facilitate drift prospecting. The results of this research shall provide a better understanding of the glaciodynamic settings that have affected Baffin Island during the Quaternary. This glacial geology study supports the search for economic minerals in the region and permafrost characterization will be useful for land management related to future infrastructure development by mining companies.

Figure 5: Portion of permafrost core extracted in central Hall Peninsula, Baffin Island, Nunavut. Scale in centimetres.

Acknowledgments

This project is funded and organized by the Canada-Nunavut Geoscience Office (CNGO) based in Iqaluit, with support from the Centre d'études nordiques (CEN), the ArcticNet (Networks of Centres of Excellence of Canada program) and the Geological Survey of Canada (GSC), Ottawa. E. L'Hérault (CEN), W. Sladen (GSC) and G. Oldenborger (GSC) are thanked for their technical contribution to the drilling and geophysical field operations. D. Mate, Chief Geologist of the CNGO, provided camp facilities and logistics. J. Gosse, A-M. LeBlanc and D. Mate helped with the revision of this paper.

Natural Resources Canada, Earth Sciences Sector contribution 20120345

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Study of sedimentary rock xenoliths from kimberlites on Hall Peninsula, Baffin Island, Nunavut

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Zhang, S. and Pell, J. 2013: Study of sedimentary rock xenoliths from kimberlites on Hall Peninsula, Baffin Island, Nunavut; *in* Summary of Activities 2012, Canada-Nunavut Geoscience Office, p. 107–112.

Abstract

This study is part of the Canada-Nunavut Geoscience Office's Hall Peninsula Integrated Geoscience Program, a multiyear bedrock and surficial geology mapping program with associated thematic studies. Hall Peninsula, located on southeastern Baffin Island, Nunavut, hosts the newly discovered Chidliak kimberlite province. Presently, this area lacks Phanerozoic sedimentary cover; however, Late Ordovician and Early Silurian microfossils (conodonts) have been recovered from carbonate xenoliths preserved in the Upper Jurassic–Lower Cretaceous kimberlites. The well-preserved conodont faunas provide reliable evidence for estimating 1) the thickness of Lower Paleozoic sedimentary cover prior to the intrusion of the kimberlites; and 2) the variations in temperature recorded by conodonts preserved in sedimentary rock xenoliths within the same kimberlite, and among the different kimberlites.

The project activities include 1) collecting sedimentary rock xenoliths from the drillholes intersecting kimberlites in the Chidliak-Qilaq area; 2) processing the carbonate xenoliths for conodonts; 3) estimating the total thickness of Lower Paleozoic sedimentary cover and the degree to which the xenoliths were heated by the kimberlites, using the conodonts' age and colours; and 4) obtaining information about the Paleozoic petroleum system in the nearby Baffin Bay area by studying sedimentary rock types and collecting Rock-Eval 6 data.

Résumé

Cette étude fait partie du Programme géoscientifique intégré de la péninsule Hall, du Bureau géoscientifique Canada-Nunavut, un programme pluriannuel de cartographie du substratum rocheux et de la géologie de surface accompagnée d'études thématiques connexes. La péninsule Hall, située dans le sud-est de l'île de Baffin (Nunavut) renferme la nouvelle province kimberlitique de Chidliak, récemment découverte. À l'heure actuelle, cette région n'a pas de couverture sédimentaire du Phanérozoïque, mais des microfossiles (conodontes) de l'Ordovicien tardif et du Silurien précoce ont été récupérés de xénolites carbonatés préservés dans les kimberlites du Jurassique supérieur et du Crétacé inférieur. Les faunes de conodontes bien conservées fournissent des preuves fiables pour estimer 1) l'épaisseur de la couverture sédimentaire du Paléozoïque inférieur avant l'intrusion des kimberlites et 2) les variations de température enregistrées par les conodontes préservés dans les xénolites des roches sédimentaires au sein de ces mêmes kimberlites et dans des kimberlites différentes.

Les activités du projet comprennent : 1) la collecte de xénolites de roches sédimentaires dans les forages recoupant les kimberlites dans la région de Chidliak–Qilaq; 2) le traitement des xénolites carbonatés pour déceler la présence de conodontes; 3) l'estimation de l'épaisseur totale de la couverture sédimentaire du Paléozoïque inférieur et l'évaluation, en fonction de l'âge et de la couleur des conodontes, de la mesure dans laquelle les xénolites ont été chauffés par les kimberlites; et 4) l'obtention d'information sur le système d'hydrocarbures du Paléozoïque dans la région environnante de la baie de Baffin grâce à l'étude des types de roches sédimentaires et à la collecte de données Rock-Eval 6.

Introduction

The Hall Peninsula Integrated Geoscience Program (HPIGP) is being led by the Canada-Nunavut Geoscience Office in collaboration with the Government of Nunavut, Aboriginal Affairs and Northern Development Canada, Dalhousie University, University of Alberta, Université Laval, University of Manitoba, University of Ottawa, University of Saskatchewan, Nunavut Arctic College and the Geological Survey of Canada. It is supported logistically by several local, Inuit-owned businesses. The study area comprises all or parts of six 1:250 000 scale National Topographic System

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(NTS) map areas north and east of Iqaluit (NTS 025I, J, O, P, 026A, B).

In the summer of 2012, fieldwork was conducted in the southern half of the peninsula (NTS 025 I, J, O, P) between June 22 and August 8. Fieldwork was supported by a 20–25 person camp located approximately 130 km southeast of Iqaluit. The focus was on bedrock mapping at a scale of 1:250 000 and surficial-sediment mapping at a scale of 1:100 000. A range of thematic studies was also supported. This included Archean and Paleoproterozoic tectonics, geochronology, landscape uplift and exhumation, detailed mapping in mineralized areas, microdiamonds, sedimentary rock xenoliths and permafrost. Summaries and preliminary observations for all of these studies can be found in this volume.

The southern half of Baffin Island, Nunavut, including Hall Peninsula, was targeted for greenfields diamond exploration by BHP Billiton and Peregrine Diamonds Ltd. in 2005. Since that time, focused exploration for primary diamond sources on Hall Peninsula has resulted in the discovery of 61 kimberlites on the Chidliak project and three more kimberlites on the adjacent Qilaq project. Together, these 64 bodies form the completely new Chidliak kimberlite province, which covers a 40 × 70 km area (Figure 1; Pell et al., 2012). These Late Jurassic–Early Cretaceous (139.1–156.7 Ma) kimberlites (Heaman et al., 2012) intruded dominantly 2.92–2.80 Ga orthogneiss of the Hall Peninsula Block (Figure 2; Whalen et al., 2010).

At present, the Chidliak-Qilaq area lacks Phanerozoic sedimentary cover, except for unconsolidated glacial deposits. However, the Lower Paleozoic carbonate xenoliths that have been recovered from the kimberlites prove that this part of the Hall Peninsula was overlain by Lower Paleozoic sedimentary rocks before and during the Late Jurassic and Early Cretaceous (i.e., the time of kimberlite emplacement).

This study reports the preliminary results on the conodonts that were recovered from carbonate xenoliths preserved in the kimberlite pipes, and estimates the total thickness of Lower Paleozoic sedimentary cover and the degree to which the xenoliths were heated by the kimberlites, using the conodonts' age and Colour Alteration Index (CAI). In addition to the carbonate xenoliths, a black-shale xenolith was also found in one of the pipes in the Chidliak kimberlite province; this research is ongoing.

Conodonts and materials

Conodonts are common marine microfossils; they first appeared in the Cambrian and became extinct by the end of the Triassic. The fossils themselves are believed to be the

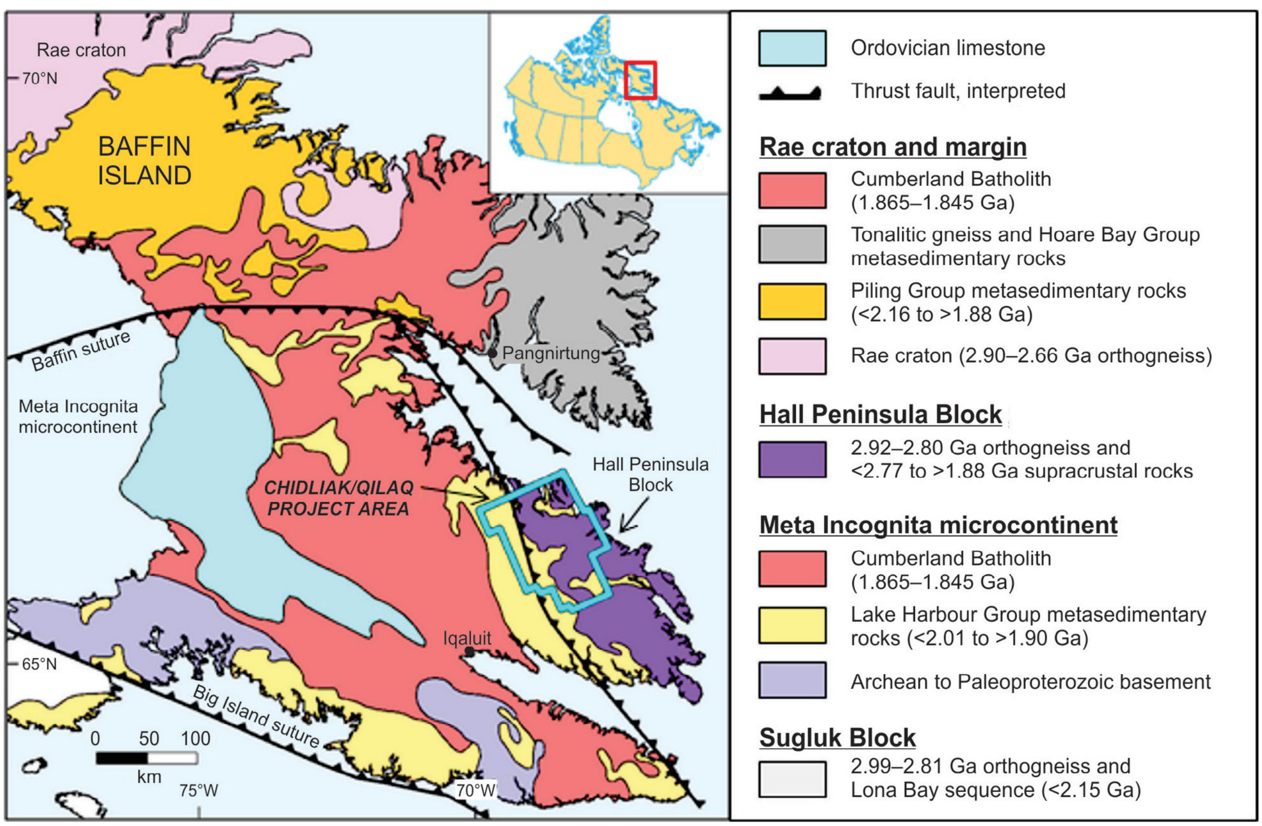

Figure 1. Simplified geology of southern Baffin Island, showing major tectonostratigraphic assemblages, bounding crustal structures (adapted from Pell et al., 2012) and the Chidliak/Qilaq project area (greenish-blue polygon).

skeletal elements of conodont animals' feeding apparatus. Conodonts are normally preserved in carbonate rocks; dissolving the carbonates in 10–12% acetic acid is the common method of isolating the fossil conodonts.

Conodonts have many important characteristics that are useful in different geological applications. The following characteristics are employed in this study:

- Most of the conodont species have shorter temporal ranges than most other fossil groups; therefore, they are commonly the first choice for dating Paleozoic and Triassic marine sedimentary rocks. The biostratigraphic information derived from conodonts can be used to estimate the thickness of Paleozoic cover that has been lost to erosion from the Chidliak kimberlite province.
- Conodont colour changes with increasing temperature under burial conditions. Unweathered and unheated conodonts are pale yellow; with increasing temperature, their colour alters to light to dark brown, black, grey, opaque white or crystal clear. A well-established method, the Conodont Colour Alteration Index (CAI) that relates these colour changes to temperature, was developed by Epstein et al. (1977) and Rejebian et al. (1987). The CAI scale of 1–8 covers a temperature range from less than 50°C to more than 600°C. This scale is employed in this study to estimate the variations in temperature recorded by the conodonts preserved in carbonate xenoliths within the kimberlites.

In total, 109 carbonate-xenolith samples were collected from 19 drillholes in the Chidliak-Qilaq kimberlites (Table 1). Because of the random sizes of the xenoliths, the sample sizes range between 0.5 kg and 5 kg. Of the 109 samples, 95 samples from 16 drillholes have been processed (14 samples from CH1-554-11-DD01, CH1-192-11-DD01 and CH1-400-11-DD01 are still being processed); 69 of these were productive, with a total of 1022 identifiable conodont specimens with numerous fragments being recovered.

Age of conodonts and inferred thickness of Paleozoic strata eroded from the Chidliak kimberlite province

Among the 1022 conodont specimens, 33 species were recognized, with ages ranging from Late Ordovician to Early Silurian. This confirms that, during the Late Ordovician and Early Silurian, the Chidliak-Qilaq area was covered by a shallow tropical sea.

Ordovician carbonate rocks presently crop out on southwestern Baffin Island, some 150–280 km west of Chidliak-Qilaq area. There, the exposed rock units include the Frobisher Bay, Amadjuak and lower Akpatok formations, with a total thickness about 100 m (Zhang, 2012). Conodonts recovered from the sedimentary xenoliths within the kimberlites, such as *Appalachignathus delicatulus* (Figure 3A), *Belodina confluens* (Figure 3C), *Oulodus velicuspis* (Figure 3E) and many other species, are also known from the Frobisher Bay, Amadjuak and lower Akpatok formations on southwestern Baffin Island (McCracken, 2000). In turn, this suggests that these formations must also have been present in the Chidliak-Qilaq area prior to kimberlite emplacement but were erosionally removed from the study area sometime between the Early Cretaceous and the present.

Other conodont species, such as the late Late Ordovician *Rhipidognathus symmetricus* (Figure 3D), Early Silurian *Ozarkodina elibata* (Figure 3B) and many others of the same age, have not been reported from southwestern Baffin Island (McCracken, 2000) but occur in strata in Hudson Bay and on Southampton Island (Zhang and Barnes, 2007; Zhang, 2011). The former species is from the Upper Ordovician Red Head Rapids Formation that is 26–98 m thick in Hudson Bay (Zhang and Barnes, 2007) and about 40 m thick on Southampton Island (Zhang, 2011); the latter is from the Lower Silurian Severn River Formation that is 223–252 m thick in Hudson Bay (Zhang and Barnes, 2007), but the *O. elibata* Zone is restricted to the lower 40–100 m of the Severn River Formation. The discovery of these conodonts suggests that at least another 66–198 m of strata younger than the Frobisher Bay, Amadjuak and lower Akpatok formations must have been present in the Chidliak-Qilaq area when the kimberlites were emplaced, and that these younger strata were also likely present on southwestern Baffin Island, where the Ordovician sedimentary cover remains preserved. Therefore, it is estimated that a total of about 165–300 m of Upper Ordovician and Lower Silurian strata have been lost to erosion in the Chidliak-Qilaq area.

The above interpretation regarding the age of the xenoliths and the inferred thickness of Paleozoic strata is based on the 95 processed samples. Owing to the 14 unfinished samples from drillholes CH1-554-11-DD01, CH1-192-11-DD01 and CH1-400-11-DD01, any conodonts additional to the 33 recognized species would change the inferred thickness of Paleozoic strata lost to erosion in the Chidliak-Qilaq area.

Conodont CAI and temperature variation among the kimberlites in the Chidliak kimberlite province

As noted earlier, 1022 identifiable conodont elements have been recovered from 69 productive samples from 16 drillholes intersecting kimberlite in the Chidliak-Qilaq area. Although some of the conodont species have a relatively long stratigraphic range and are not useful in dating the xenoliths, each element has its specific colour and provides a reliable CAI value. The conodont elements in the kimberlites from the Chidliak kimberlite province have a wide CAI range, from 1.5 to 8. The CAI data can be used to determine the temperatures to which the sedimentary xenoliths were heated, which provides an independent estimate for the minimum temperature of emplacement of the various types of pipe infill found within the Chidliak-Qilaq kimberlites. The temperatures recorded within these xenoliths range from 50°C to more than 600°C. The sedimentary xenoliths occur in kimberlites that have either pyroclastic or apparently coherent kimberlite infill (Pell et. al., in press); work is ongoing to relate the temperatures these xenoliths attained to pipe-infill types.

Xenoliths of black shale, and dolostone or dolomitic-limestone breccia from the Chidliak kimberlite province

A 10 cm long black-shale xenolith was collected from a drillhole (CH1-482-10-DD01) into kimberlite. The following work has been completed on it:

- Three samples from this black-shale xenolith were sent for Rock-Eval 6 analysis. The analysis provided some reasonably reliable values of total organic carbon (TOC) and T_{max} (a parameter of thermal maturation for petroleum source rock), which could be an indication of potential petroleum source rocks in the Baffin Bay area, if the age of the sample was known.
- Two samples from this black-shale xenolith were sent for palynology and chitinozoan processing to obtain biostratigraphic data. Residue of abundant, blackish-brown, degraded organic debris was found, but no identifiable palynomorphs were observed (Sweet, 2011) and no chitinozoans were found (E. Asselin, pers. comm., 2011); therefore, the age of this xenolith remains unknown.
- In a further attempt to get an age for this black-shale xenolith, the sample has been sent to Tracer Isotope Lab at the University of Alberta for isotope dating. The results are pending.

Numerous xenoliths of dolostone or dolomitic-limestone breccia (Figure 4) were collected from four drillholes (CH1-258-11-DD07, CH1-258-11-DD08, CH1-050-11-DD16, CH1-050-11-DD19) into kimberlite. This rock type does not outcrop on southwestern Baffin Island (McCracken, 2000; Zhang, 2012). This kind of dolostone and dolomitic limestone breccia was first reported from the Upper Ordovician Red Head Rapids Formation on Southampton Island (Zhang, 2008) and was interpreted as hydrothermal dolomite, which can be a significant conventional reservoir for oil and gas (Lavoie et al., 2011).

The petroleum system in the nearby Baffin Bay area is poorly understood. The xenoliths of black shale, and dolostone or dolomitic-limestone breccia discovered in the Chidliak kimberlite province are valuable in understanding the Paleozoic source rock and reservoir rock in the area.

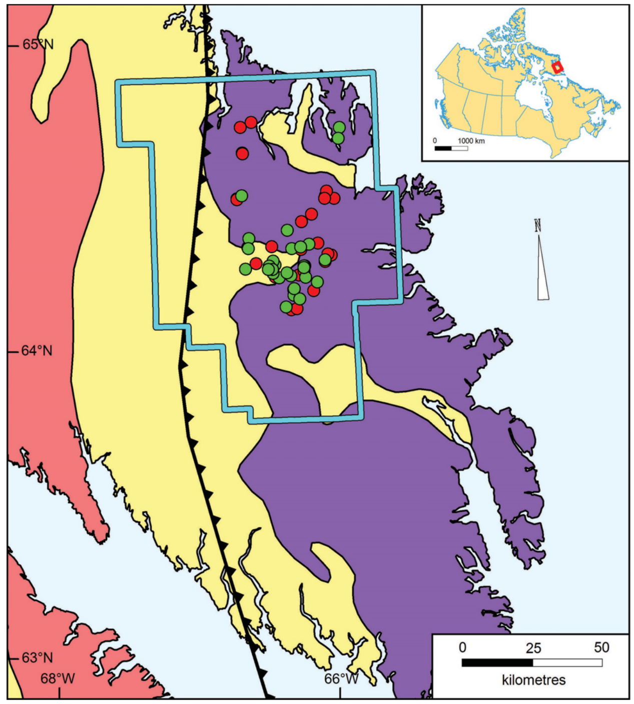

Figure 2. Distribution of kimberlite intrusions, Hall Peninsula, southern Baffin Island (adapted from Heaman et al., 2012). The Chidliak/Qilaq project area is marked by a greenish-blue polygon; red and green dots (with dates in Heaman et al., 2012) represent the locations of kimberlites.

Table 1. Summary of sedimentary xenolith samples from Chidliak-Qilaq kimberlites, Hall Peninsula, southern Baffin Island.

Location	Depth (m)	No. of samples	Basic lithology
CH1-050-11-DD16	80.1 88.6	3	Carbonate rocks
CH1-050-11-DD19	79.25 80.12	1	
CH1-101-11-DD02	13.5 68.07	2	
CH1-101-11-DD03	32.38 37.03	4	
CH1-101-11-DD04	35 52.47	4	
CH1-166-11-DD02	68.5 68.9	1	
CH1-192-11-DD01	102.2 165	6	
CH1-251-10-DD05	120.66 120.86	1	
CH1-251-11-DD08	146.75 148.2	1	
CH1-251-11-DD14	38.4 219	4	
CH1-258-11-DD05	58.1 104.9	2	
CH1-258-11-DD06	63.9 118.1	2	
CH1-258-11-DD07	11.2 41	2	
CH1-258-11-DD08	11 94.3	8	
CH1-400-11-DD01	39.8 144.4	3	
CH1-482-10-DD01	13.84 407	46	
CH1-488-11-DD02	128.95 151.05	2	
CH1-554-11-DD01	84.2 152.35	5	
CH1-557-11-DD02	77.8 181.4	12	
CH1-482-10-DD01	295.5 305.5	1	Black shale

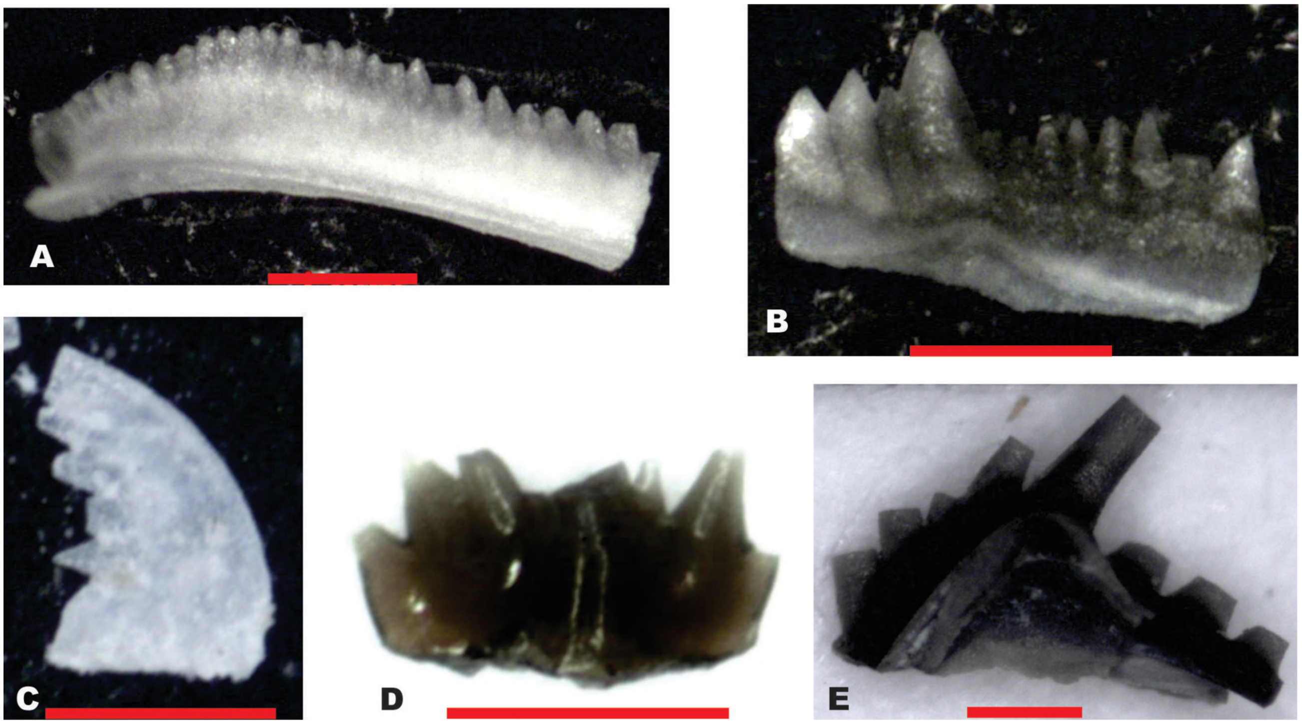

Figure 3. Representative conodont species recovered from carbonate xenoliths preserved in the Chidliak-Qilaq kimberlites: **A)** *Appalachignathus delicatulus*, lateral view of Pa element (CAI 7), sample SZ12-01-09 (drillhole CH1-050-11-DD19); **B)** *Ozarkodina elibata*, lateral view of Pa element (CAI 6.5–7), sample SZ12-01-08 (drillhole CH1-050-11-DD16); **C)** *Belodina confluens*, lateral view of compressiform element (CAI 8), sample SZ11-21-14 (drillhole CH1-258-DD05); **D)** *Rhipidognathus symmetricus*, posterior view of Pb3 element (CAI 3–4), sample SZ11-01-43 (drillhole CH1482-10-DD01); **E)** *Oulodus velicuspis*, inner lateral view of Pb element (CAI 5–6), sample SZ11-01-34 (drillhole CH1482-10-DD01). Red bar below each image is 0.25 mm.

Economic or applied considerations

The Paleozoic xenoliths in the Chidliak kimberlite pipes provide evidence that will help in understanding these kimberlites and their emplacement processes. The estimate of the thickness of eroded strata (165–300 m) is a minimum estimate of the postemplacement erosion in the area, which is consistent with having the uppermost parts of the craters removed but does not suggest that the pipes were deeply eroded. The presence of large kimberlites in this area is therefore possible. The conodonts recovered from xenoliths in the kimberlites have a wide CAI range of 1.5 to 8, which corresponds to temperatures ranging from 50°C to more than 600°C. Understanding the temperatures to which the sedimentary xenoliths were heated provides an independent estimate for the minimum temperature of emplacement of the various types of pipe infill, which will further the understanding of emplacement processes.

In addition to the significance of Paleozoic xenoliths and microfossil conodonts in the Chidliak kimberlite study, the xenoliths of black shale, and dolostone or dolomitic-limestone breccia discovered in the kimberlite pipes provide rare information that will help in understanding the potential Paleozoic petroleum source rock and reservoir rocks in the nearby Baffin Bay area.

Acknowledgments

This project is part of the Hall Peninsula Integrated Geoscience Project of the Canada-Nunavut Geoscience Office (CNGO). Financial support from CNGO is greatly appreciated. Thanks go to Peregrine Diamonds Ltd. for giving permission to the first author to collect xenolith samples.

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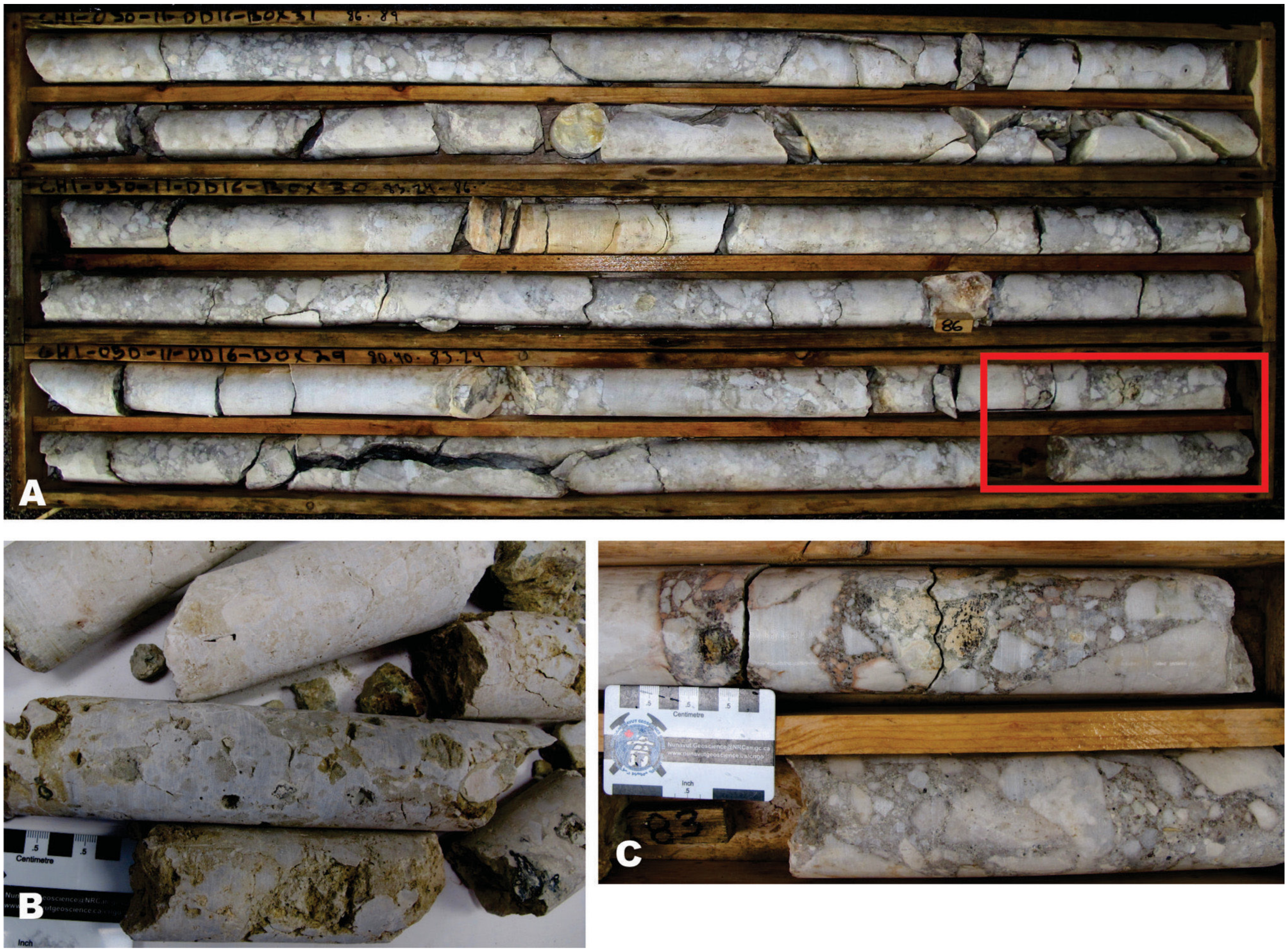

Figure 4: A) and **B)** Xenoliths of dolostone or dolomitic-limestone breccia from drillholes Ch1-050-11-DD16 and CH1-258-11-DD08, respectively. **C)** Enlargement of red rectangle in (A).

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Diamond sources beneath the Hall Peninsula, Baffin Island, Nunavut: preliminary assessment based on microdiamonds

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Abstract

This study is part of the Canada-Nunavut Geoscience Office's Hall Peninsula Integrated Geoscience Program, a multiyear bedrock and surficial geology mapping program with associated thematic studies. The Chidliak kimberlites, located 120 km northeast of Iqaluit, on the Hall Peninsula, southern Baffin Island, tap mantle source regions of unknown paragenesis, age and history; the recently discovered kimberlites have proven to be diamondiferous. Of the 44 kimberlites (out of 62) tested for diamonds, 41% of the kimberlites contained commercial-sized diamonds. Approximately 740 microdiamonds (≤600 μm) have been provided by Peregrine Diamonds Ltd. for this study, of which 102, within the size range of 210 to 600 μm, are presented in this paper. Microdiamonds were separated from the kimberlite by SRC Geoanalytical Laboratories of Saskatoon, Saskatchewan, using crushing techniques and caustic fusion. The microdiamonds were then sorted into sieve sizes (600 μm, 425 μm, 300 μm, 210 μm, 150 μm, 106 μm).

This project will focus on microdiamond characteristics, such as morphology, colour, carbon isotopic composition, nitrogen concentration and nitrogen aggregate states, to constrain the upper-mantle source, the microdiamond residence time in the mantle and the conditions of diamond formation. After the physical description of the microdiamonds, the principle focus for this study will be to fingerprint their possible mantle source regions. This will be done by determining the nitrogen characteristics and carbon isotope compositions of the microdiamond samples using spatially highly resolved (15 μm spot size) analyses obtained via the state-of-the-art Cameca IMS1280 ion microprobe. Here we report preliminary findings on the microdiamonds from two kimberlite samples (P5500 and P6807) on the Hall Peninsula.

Résumé

Cette étude fait partie du Programme géoscientifique intégré de la péninsule Hall, du Bureau géoscientifique Canada-Nunavut, un programme pluriannuel de cartographie du substratum rocheux et de la géologie de surface accompagnée d'études thématiques connexes. Les kimberlites de Chidliak, situées à 120 km au nord-est d'Iqaluit, sur la péninsule Hall dans le sud de l'île de Baffin, puisent dans des régions d'origine mantellique dont on ignore la paragenèse, l'âge et l'histoire; les kimberlites récemment découvertes se sont avérées diamantifères. Des 44 kimberlites (sur 62) soumises à l'essai pour les diamants, 41 % contenaient des diamants de taille commerciale. Environ 740 microdiamants (= 600 ìm) ont été fournis par la Peregrine Diamonds Ltd., aux fins de cette étude, dont 102, dans la plage de taille de 210 à 600 ìm, font l'objet du présent article. Les microdiamants ont été séparés de la kimberlite aux SRC Geoanalytical Laboratories de Saskatoon (Saskatchewan) au moyen de techniques de broyage et de fusion caustique; les microdiamants ont ensuite été classés au tamis (600 ìm, 425 ìm, 300 ìm, 210 ìm, 150 ìm, 106 ìm).

Ce projet mettra l'accent sur les caractéristiques des microdiamants, notamment la morphologie, la couleur, la composition isotopique du carbone, la concentration en azote et les états d'agrégation des ions d'azote, en vue de circonscrire la source du manteau supérieur, le temps de séjour des microdiamants dans le manteau et leurs conditions de formation. Une fois la description physique des microdiamants établie, cette étude cherchera à localiser leurs éventuelles régions d'origine

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mantellique. Pour ce faire, il s'agira de déterminer les caractéristiques de l'azote et la composition isotopique du carbone dans les échantillons de microdiamants en utilisant les analyses d'images à haute résolution spatiale (taille du point : 15 ìm) réalisées à l'aide d'une microsonde ionique perfectionnée de marque Cameca IMS1280. Nous présentons ici les résultats préliminaires pour les microdiamants provenant de deux échantillons de kimberlite (P5500 et P6807) provenant de la péninsule Hall.

Introduction

The Hall Peninsula Integrated Geoscience Program (HPIGP) is being led by the Canada-Nunavut Geoscience Office in collaboration with the Government of Nunavut, Aboriginal Affairs and Northern Development Canada, Dalhousie University, University of Alberta, Université Laval, University of Manitoba, University of Ottawa, University of Saskatchewan, Nunavut Arctic College and the Geological Survey of Canada. It is supported logistically by several local, Inuit-owned businesses. The study area comprises all or parts of six 1:250 000 scale National Topographic System map areas north and east of Iqaluit (NTS 025I, J, O, P, 026A, B).

In the summer of 2012, fieldwork was conducted in the southern half of the peninsula (NTS 025 I, J, O, P) between June 22 and August 8. Fieldwork was supported by a 20–25 person camp located approximately 130 km southeast of Iqaluit. The focus was on bedrock mapping at a scale of 1:250 000 and surficial-sediment mapping at a scale of 1:100 000. A range of thematic studies was also supported. This included Archean and Paleoproterozoic tectonics, geochronology, landscape uplift and exhumation, detailed mapping in mineralized areas, microdiamonds, sedimentary rock xenoliths and permafrost. Summaries and preliminary observations for all of these studies can be found in this volume.

Starting in 2005, extensive work on the Hall Peninsula resulted in the discovery of the diamondiferous Chidliak kimberlite field. At Chidliak micro- and macrodiamonds were recovered during initial kimberlite sampling. Chidliak microdiamonds were sorted into 600 µm, 425 µm, 300 µm, 210 µm, 150 µm and 106 µm size classes; for the purpose of this study, a microdiamond is defined as ≤600 µm in size, because there is no 500 µm size class. Microdiamond studies are a powerful tool to characterize the mantle sources of cratonic roots and to gain insights into conditions of diamond formation and preservation beneath the Hall Peninsula. The Canada-Nunavut Geoscience Office (CNGO) is leading research in Canada's north; the Chidliak project is currently the largest diamond exploration project in Nunavut, and the Hall Peninsula is a new diamond district (Pell et al., 2012).

Diamond may crystallize in two primary forms: the octahedron and the related macle (spinel twin), and the cube and re-entrant cube (e.g., Robinson 1978; Reutsky and Zedgenizov 2007). Octahedral and cubic diamonds may show both growth-related primary surface features and secondary surface features. Diamond may experience resorption during mantle residence and kimberlite ascent; the extent of resorption can be identified through characteristic morphologies and surface features: octahedral and cubic diamonds gradually convert to dodecahedral morphologies (Robinson et al., 1989).

Diamond is one allotrope of carbon, in which the carbon atoms are bonded by strong covalent bonds in the diamond lattice. Molecular impurities present in the diamond lattice include nitrogen and, less commonly, boron. Fourier-transform infrared spectroscopy (FTIR) is employed to determine nitrogen concentrations and aggregation states of Chidliak microdiamonds. This will be used to constrain their residence history and time-averaged mantle residence temperature. Subsequently, spatially highly resolved (15 µm spot size) analyses of nitrogen concentrations and carbon isotope compositions via secondary-ion mass spectrometry (SIMS) will be conducted to fingerprint the possible mantle source regions of these microdiamonds.

The focus of this study will be lithospheric microdiamonds from Chidliak; lithospheric diamonds form in the subcontinental lithospheric mantle (SCLM) and are associated with mantle peridotite, eclogite and sometimes pyroxenite (Gurney et al., 2010). Microdiamond characteristics, carbon isotopes, nitrogen concentrations and nitrogen aggregate states will be used to constrain the upper-mantle source, the microdiamond residence time in the mantle and the conditions of formation. The benefits of this study lie in providing a first order assessment as to what the likely mantle sources of these diamonds are and how they are situated in a worldwide context. It will provide the first direct constraints on diamond sources in the deep lithosphere beneath the Hall Peninsula.

Geological background

The microdiamonds used for this study come from kimberlites from the Chidliak Project area (Figure 1), 120 km northeast of Iqaluit, located on the Hall Peninsula, southern Baffin Island (Pell, 2008; Pell and Farrow, 2012). Specifically, this study will focus on microdiamonds from two kimberlites, CH-7 (sample P5500) and CH-6 (sample P6807). Kimberlite bodies were identified after a suite of kimberlite indicator minerals (KIMs) were discovered during the 2005 field season; subsequently, in 2008, a helicop-

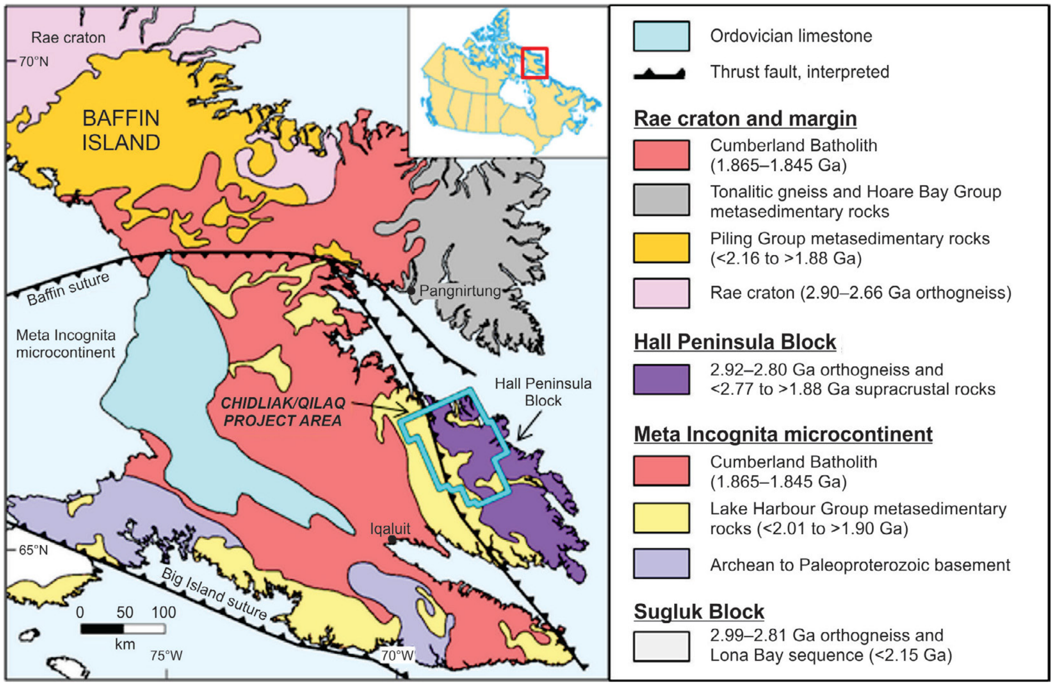

Figure 1: Simplified regional geological map of southern Baffin Island (after St-Onge et. al., 2006; Whalen et. al., 2010), showing the location of the Hall Peninsula Block (purple) and the Chidliak project area (light blue box; Pell et al., 2012).

ter-borne magnetic/electromagnetic survey was flown, totalling 11 700 line-kilometres, leading to the discovery of kimberlite bodies (Pell, 2009).

The Hall Peninsula may be a microcontinent that was accreted during a three-way collision between the Superior, Rae and North Atlantic cratons, although there are other speculations for its origins, including the possibility that it is part of the Nain/North Atlantic craton or reworked Archean gneisses of the Nagssugtoqidian Orogen of Greenland (Scott, 1996; Snyder, 2010; Pell, et al., 2012). The Hall Peninsula is separated from northern Baffin Island by the Baffin suture; it also contains the eastern edge of the Paleoproterozoic Cumberland Batholith, which is in contact with Paleoproterozoic supracrustal rocks to the east (St. Onge, 2001; Pell and Farrow, 2012). After completion of the 2012 field season, the total number of kimberlites identified was 64 (61 at Chidliak; 3 at the neighbouring Qilaq project), of which 7 have proven to be distinctly diamondiferous with characteristics that are consistent with economic Arctic diamond deposits (Pell, et al., 2012). Based on U-Pb perovskite age-determinations from 29 kimberlites, Heaman et al. (2012) demonstrated that kimberlite emplacement took place from 156 to 138 Ma, spanning approximately 18 m.y.

Physical descriptions

State of knowledge

Microdiamond physical characterization is carried out using a binocular microscope, following the guidelines and terminology of McCandless et al. (1994) and Robinson (1979), while adhering to rules from Harris et al. (1975). Microdiamonds are characterized based on morphology, surface features, colour, breakage and extent of resorption. In Harris et al. (1975), rules are applied to aid in classifying diamond into primary divisions. These rules state that if 50% of the diamond remains it will be classified based on the observed shape, if <50% of the diamond remains it will be classified as broken or irregular (Harris et al., 1975). Other diamond classification schemes and observations were considered, (e.g., Orlov, 1977; Gurney, 1989; Tappert and Tappert, 2011), but not utilized for this study.

Diamond growth can be complex; growth layers may be stepped, and the edges may be stepped or kinked. Changes in the environment during crystal growth can also cause complex shapes and features (Wilks and Wilks, 1991). If the diamond has grown in a spiral growth mode as a regular lattice of atoms, the crystals often have sharp edges and flat faces (Wilks and Wilks 1991). The final morphology of a diamond will be determined by the planes which grow outward most slowly, because the quickest growing faces will eventually disappear (Wilks and Wilks, 1991). Based on observations made during high pressure, high temperature synthesis of diamond, it appears that octahedral diamonds form at higher temperatures than cubes (Gurney, 1989).

Primary surface features found on octahedral diamonds include smooth octahedral surfaces, triangular plates (single and imbricated) and shield-shaped laminae (Robinson, 1979). Secondary surface features include negative trigons, positive trigons, hexagonal pits and serrate laminae (Robinson, 1979; McCandless et al., 1994). These features are not all seen on every octahedral diamond, nor are they always seen together. For cube diamonds, secondary surface features include negatively and positively oriented tetragonal pits, crescentic steps and pointed plates (Robinson, 1979).

Dodecahedral diamonds are a product of resorption of the primary forms of diamond; any primary features observed would therefore have to be internal growth features or growth features due to regrowth after resorption (Robinson, 1979). Secondary surface features observed due to resorption are terraces, hillocks, corrosion sculpture, shallow depressions, micro-disk patterns and patterns of micro-pits (Robinson, 1979). There are also surface features that are not restricted to any particular diamond form. These features include lamination lines, ruts, inclusion cavities, knob-like asperities, pitted disks, frosting and graphite coatings (Robinson, 1979). It is also possible to determine subpopulations of microdiamonds based on the identified surface features and morphologies.

Fragmental diamonds are identified based on how much of the original crystal remains; if <50% of the original diamond remains, it is classified as a fragment based on dominant surface features observed on the crystals primary surfaces (e.g., octahedral fragment; McCandless et al., 1994). If the diamond has been broken, and no features are visible on a primary surface, it is classified as a fragment; whereas diamonds with complex shapes showing no dominant primary surface features are classified as irregular. Breakage is also noted, especially whether the breakage surface has been resorbed or not. This is important because it will enable us to identify the extent of diamond breakage due to processing procedures, and will also aid in a rough assessment of conditions during mantle residence and ascent.

Chidliak diamonds

Currently the physical descriptions show that irregular is the most abundant microdiamond shape at Chidliak, followed by octahedral fragments and partially resorbed microdiamonds (>50% of the shape is characteristic of the dodecahedral morphology); two stones show pseudohemimorphic resorption (‘half resorbed’). At Chidliak, the number of broken microdiamonds with resorption features (i.e., broken prior to emplacement) is almost equivalent to the number of microdiamonds that show breakage, but are not resorbed. The majority of the microdiamonds are colourless, although colour can be difficult to identify in microdiamonds due to their thinness. For a summary of the identified characteristics, see Table 1 and Figure 2.

A JEOL 6301F scanning electron microscope (SEM) was used to capture an image of a representative sample set of microdiamonds at high resolution to aid in identification of surface features and to provide insight into features unidentifiable using a binocular microscope. The characteristics identified using an SEM confirm those seen with the binocular microscope. Figure 3 shows an example of one of the

Table 1: Summary table of the identified physical characteristics of 102 Chidliak microdiamonds from kimberlite samples P5500 and P6807.

Shape	P5500[1] (CH-7)[2]	P6807[1] (CH-6)[2]	Total	Colour	P5500[1] (CH-7)[2]	P6807[1] (CH-6)[2]	Total
Octahedra	3	2	5	Colourless	19	29	48
Octahedral fragment	12	3	15	Very light brown	3	0	3
Octahedral aggregate	4	1	5	Brown	4	2	6
Cube	0	4	4	Light brown	7	4	11
Cubic fragment	0	2	2	Very light yellow	0	1	1
Cubic aggregate	1	0	1	Light yellow	2	3	5
Macle	1	1	2	Yellow	0	4	4
Dodecahedral macle	0	1	1	Bright yellow	1	1	2
>50% Octahedra	4	2	6	Dark yellow	1	3	4
Dodecahedral	0	6	6	Green-yellow	0	1	1
>50% Dodecahedral	5	10	15	Light grey	6	0	6
Irregular	15	16	31	Grey	2	1	3
Fragment	6	2	8	Opaque/cloudy	0	2	2
Tetrahexahedroid	0	1	1	White	1	0	1
Total			**102**	Brown/grey	2	0	2
Broken no resorption	8	22	30	Brown/pink	1	0	1
Broken with resorption	20	7	27	Light pink	2	0	2
Total			**57**	**Total**			**102**

[1] Kimberlite sample number

[2] Kimberlite name

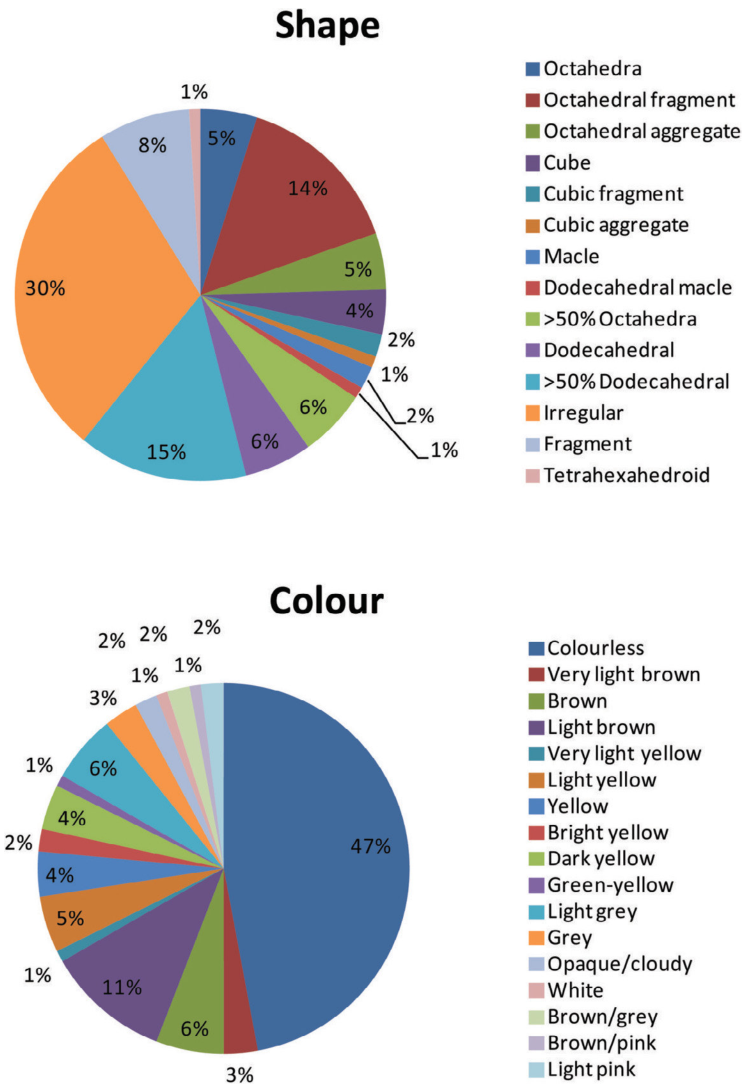

Figure 2: Pie charts showing the shape and colour distribution described in Table 1.

images obtained of microdiamond CH6-18 from kimberlite sample P6807.

Nitrogen characteristics and carbon isotopes

Currently, Fourier-transform infrared spectroscopy (FTIR) has been completed for 102 microdiamonds. Determination of nitrogen concentrations and aggregation states were carried out using a Thermo Scientific Nicolet FT-IR spectrometer. Spectra were collected for 200s, after subtraction of a 1 cm pure Type II diamond spectrum, the spectra were converted into absorption coefficients. The spectra were deconvoluted into A, B and D components using software provided by D. Fisher (The Diamond Trading Company).

Since carbon and nitrogen have a similar ionic radius, nitrogen substitutes and bonds very strongly with carbon in the crystal structure (Cartigny, 2005), which is why nitrogen is by far the most abundant substitutional impurity (and elemental impurity) in diamond, with values as high as 0.55% (Sellschop et al. 1980). Nitrogen concentrations can be used to obtain broad constraints on possible upper-mantle diamond sources since the median nitrogen content for a peridotitic source is only 70 atomic ppm and for an eclogitic source it is 370 atomic ppm (Stachel et al., 2009). Diamond can be classified into different types based on the presence and aggregation state of nitrogen impurities; on the basis of infrared (IR) absorption spectroscopy, two main types of natural diamond have been recognized, Type I and Type II (Harris, 1987). Type I has nitrogen present and Type II has no detectable nitrogen (Harris, 1987). Type I diamonds can be further subdivided based on whether the nitrogen is single substitutional (Type Ib), or if it has aggregated within the carbon lattice (Type Ia; Evans and Qi, 1982; Harris, 1987). Nitrogen enters the crystal lattice as single substitutional atoms, but during mantle residence these single nitrogen atoms aggregate into pairs of nitrogen atoms (A cen-

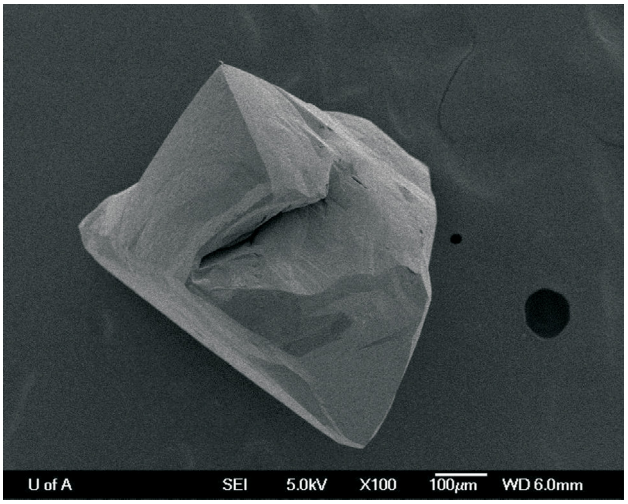

Figure 3: An SEM photograph of microdiamond CH6-18 from a pseudohemimorphic (half-resorbed) octahedral microdiamond.

tre), then into groups of 4 atoms surrounding a vacancy (B centre). The aggregation state of nitrogen found in the diamond crystal lattice is directly related to the residence temperature in the Earth's mantle (Harris, 1987). The process of nitrogen aggregation stops once diamond emplacement in the Earth's crust occurs (Allen and Evans, 1981; Evans and Qi, 1982; Stachel, 2007). Diamonds with >90% of the total nitrogen in the A centre are classified as Type IaA. Intermediate diamonds with 10–90% of their total nitrogen content in the B centre are categorized as Type IaAB. Diamonds with >90% of the total nitrogen in the B centre are Type IaB, and are completely aggregated.

Chidliak microdiamonds have nitrogen contents ranging from no detectable nitrogen to 3356 atomic ppm, with an average nitrogen concentration of 1237 atomic ppm. Two analyses were carried out for each of the microdiamonds. The microdiamonds from kimberlite sample P6807 show an approximate 50/50 split between Type IaAB and Type IaA diamonds; there are ~5% of Type II diamonds. The microdiamonds from kimberlite sample P5500 are predominantly Type IaA, with ~10% Type II diamonds. The percentage of Type II Chidliak microdiamonds observed is less than that of the worldwide database for lithospheric diamonds (20%; Stachel, 2007). None of the analyzed microdiamonds are fully aggregated Type IaB.

Using an assumed mantle residence time (e.g., 3 or 1 b.y.), it is possible to use the measured nitrogen abundance and aggregation to identify time-averaged mantle residence temperatures (Figure 4; Taylor et al., 1990; Leahy and Taylor, 1997). The Chidliak microdiamonds show a range in temperature from ~960 to 1260°C. Only high quality spectra are used to determine temperature; for microdiamonds that are pure Type IaA (0% nitrogen in the B centre), an assumed value of 0.5% B was used for the temperature calculations

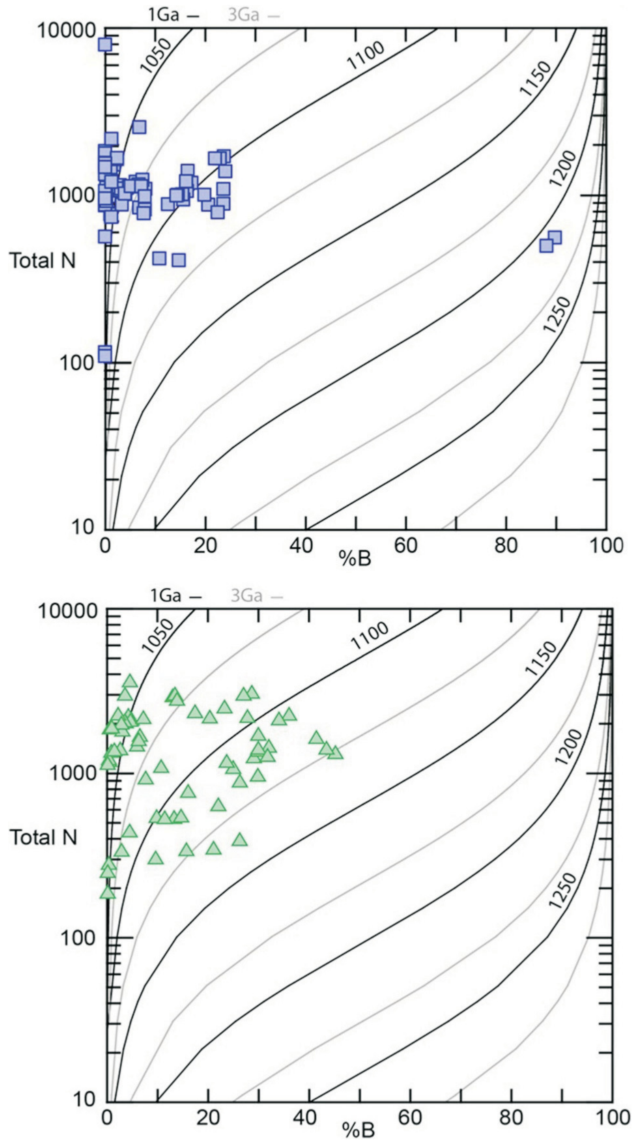

Figure 4: Time-averaged mantle-residence temperatures for microdiamonds from kimberlite samples P5500 (blue squares)and P6807 (green triangles), isotherms are calculated using assumed mantle residence times of 3 and 1 b.y., after Taylor et al., 1990 and Leahy and Taylor, 1997. Total N is in atomic ppm, nitrogen aggregation is expressed as %B, i.e., the relative proportion of nitrogen in the B centre.

(i.e., calculated temperatures for these diamonds represent a maximum value).

Later this year, the carbon isotopic composition of 100 Chidliak microdiamonds will be analyzed using SIMS at high-spatial resolution, thus removing the need for conventional analysis of carbon isotopes. Conventional analysis involves the combustion of diamonds, thereby averaging isotopic heterogeneities. The nitrogen content has to be measured again during SIMS analyses (in addition to previous FTIR work) to obtain it at the exact same location where carbon isotopes are measured, as this will allow the investigation of co-variations between the two parameters.

A Zeiss EVO 15 scanning electron microscope will be used to characterize the samples through cathodoluminescence (CL) imaging, which will reveal the internal structure of the microdiamonds prior to ion-probe analysis. Mounting of the microdiamonds includes sorting them according to weight and size and placing them on double-sided thermal tape, then mounting them in epoxy pucks and subsequently polishing the pucks.

Economic considerations

The conclusions of this study will provide valuable initial information to constrain the upper-mantle source, the time-averaged mantle residence temperature, the conditions of formation, and the preservation of microdiamonds found on the Hall Peninsula, in Nunavut's largest diamond exploration project. This preliminary study on microdiamonds, part of a new CNGO led regional geosciences initiative on the Hall Peninsula, will provide a first order assessment of the Chidliak diamonds, and how they are placed in a worldwide context. Research will aid in the modern interpretation and understanding of the diamond mantle sources beneath the Hall Peninsula, and ultimately contributes to the economic development of Nunavut's mineral resources.

Acknowledgments

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Studies of Paleozoic stratigraphy and petroleum potential in the Hudson Bay and Foxe basins, Nunavut

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Abstract

This is the last year of the Hudson Bay–Foxe Basin Project under the 2008–2013 Geo-Mapping for Energy and Minerals (GEM) program; the aim of the project is to evaluate the hydrocarbon potential in the Hudson Bay and Foxe basins. Onshore, the sedimentary succession that is exposed in Nunavut—on Southampton Island, northeastern Melville Peninsula and southern Baffin Island—records key elements that can be used to assess the petroleum potential of the two basins. The onshore succession is also exposed in northeastern Manitoba and northern Ontario, although most of the basin succession is concealed beneath the waters of Hudson Bay and Foxe Basin.

The project activities at the Canada-Nunavut Geoscience Office include 1) field studies during three field seasons on Southampton Island, northeastern Melville Peninsula and southern Baffin Island that focused on Paleozoic stratigraphy and the stratigraphic and geographic distribution of Ordovician oil-shale intervals; 2) re-evaluation and new studies of the well materials from 1960–1980 drilling in offshore areas of Hudson Bay and the Hudson Bay Lowlands, including both well cuttings and gamma-ray logs; 3) Rock-Eval 6 analyses and organic geochemistry of Ordovician oil shale and extracts; 4) a conodont biostratigraphic study based on nearly one thousand samples from both field outcrops and well cuttings; and 5) the organization of a 2010 field trip, with national and international participants, that focused on the Ordovician stratigraphy of Southampton Island.

Résumé

Il s’agit de la dernière année du projet Bassins sédimentaires d’Hudson/ Foxe qui s’inscrit dans le cadre du Programme de géocartographie de l’énergie et des minéraux (GEM) pour 2008–2013; l’objectif du projet est d’évaluer le potentiel en hydrocarbures dans les bassins de la baie d’Hudson et de Foxe. Sur terre, la succession sédimentaire qui est exposée au Nunavut (île Southampton, nord-est de la presqu’île Melville et sud de l’île de Baffin) renferme des renseignements clés pouvant servir à évaluer le potentiel pétrolier des deux bassins. La succession sur terre est également exposée dans le nord-est du Manitoba et le nord de l’Ontario, bien que la majeure partie de la succession du bassin soit cachée sous les eaux de la baie d’Hudson et du bassin de Foxe.

Les activités liées au projet relevant du Bureau géoscientifique Canada-Nunavut comprennent : 1) des études sur le terrain au cours de trois campagnes, réalisées dans l’île Southampton, le nord-est de la presqu’île Melville et le sud de l’île de Baffin, qui mettaient l’accent sur la stratigraphie du Paléozoïque et la répartition stratigraphique et géographique des intervalles de schiste bitumineux de l’Ordovicien; 2) une réévaluation et de nouvelles études axées sur les matériaux extraits lors des forages réalisés dans les années 1960 à 1980 au large des côtes de la baie d’Hudson et dans les basses terres de la baie d’Hudson, y compris les déblais de forage et les diagraphies de rayons gamma; 3) des analyses Rock-Eval 6 et la géochimie organique des schistes bitumineux et des extraits de l’Ordovicien; 4) une étude biostratigraphique des conodontes basée sur près d’un millier d’échantillons d’affleurement prélevés sur le terrain et de déblais de forage; et 5) l’organisation en 2010 d’une expédition sur le terrain portant sur la stratigraphie de l’Ordovicien de l’île Southampton et à laquelle ont participé des chercheurs Canadiens et étrangers.

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Introduction

Hudson Bay (~1 200 000 km^2) and Foxe Basin (~136 568 km^2) are two large water bodies in northern Canada that together cover more than 10% of Canada's surface (9 985 000 km^2). The Hudson Bay and Foxe basins are two related Phanerozoic sedimentary basins for which the petroleum potential is poorly understood, although basins of similar age in the central United States are major hydrocarbon producers. Within Nunavut, the stratigraphic succession of the Hudson Bay Basin crops out on Southampton Island, and exposures of the Foxe Basin are found on northeastern Melville Peninsula and southern Baffin Island (Figure 1).

Most of the two basins are covered by the water of Hudson Bay and Foxe Basin. Therefore, study of the Paleozoic stratigraphy and identification of Ordovician source rocks on Southampton Island, northeastern Melville Peninsula and

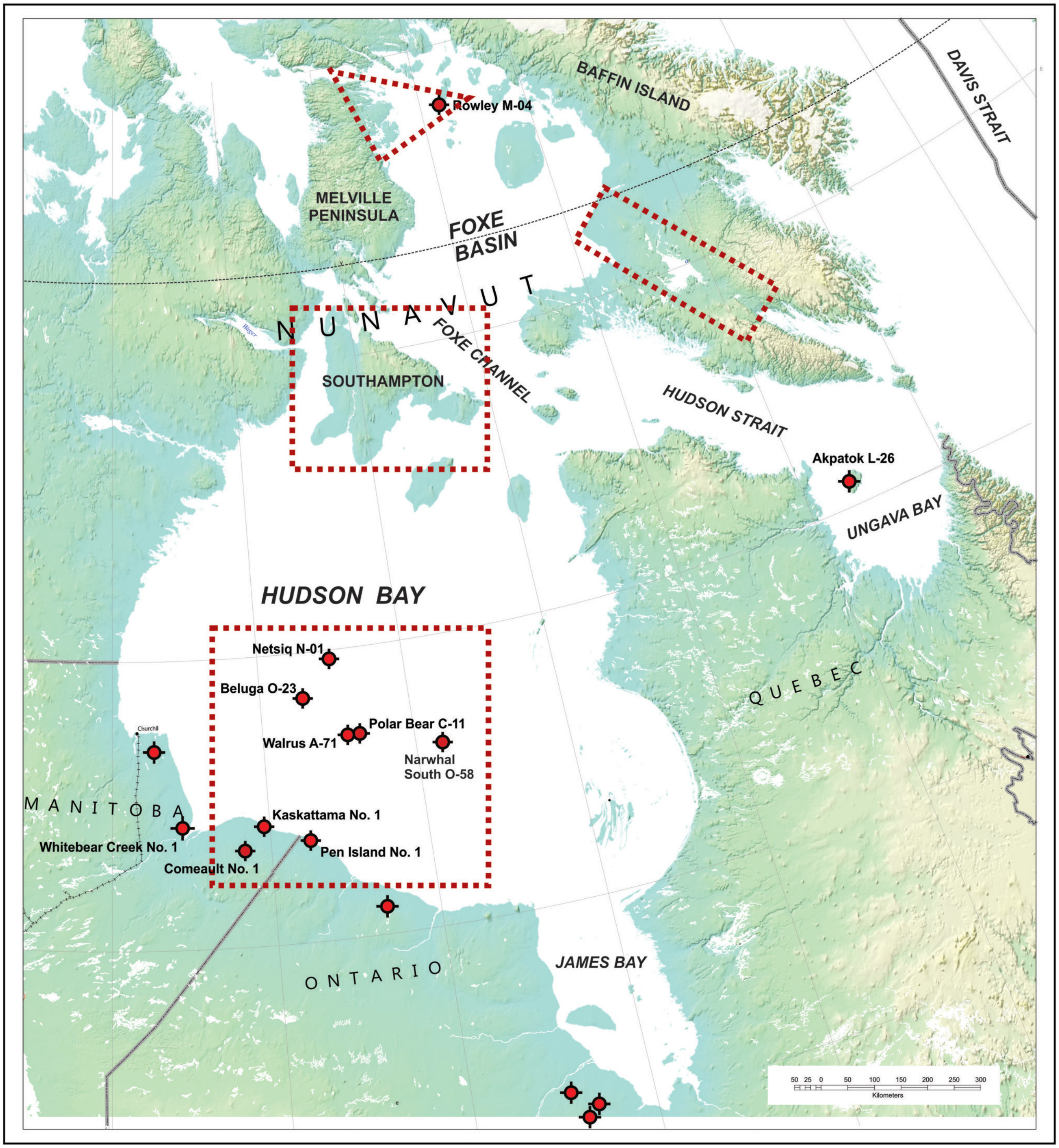

Figure 1. Hudson Bay and Foxe basins, showing study areas as red polygons. Red dots represent well locations.

southern Baffin Island, and re-evaluation of the 1960s–1980s offshore well materials are keys to a better understanding of the petroleum potential in both basins. Based on these facts, the Canada-Nunavut Geoscience Office (CNGO) initiated a Nunavut Energy Project in 2007; since then, the project has focused on the Paleozoic stratigraphy and petroleum potential in the Hudson Bay Basin. In 2009, this project was merged with the Hudson Bay–Foxe Basin Project of Natural Resources Canada's GEM program, a joint endeavour of the Geological Survey of Canada (GSC), the Manitoba and Ontario geological surveys and CNGO. This report summarizes CNGO research activities and major outcomes since the project was initiated in 2007.

Field studies on Southampton Island, northeastern Melville Peninsula and southern Baffin Island

Southampton Island

During the Paleozoic, Southampton Island was located near the northern margin of the Hudson Bay Basin. The 1:1 000 000 geological map from Heywood and Sanford (1976) served as a base map for the Paleozoic stratigraphy.

The fieldwork on Southampton Island was carried out by the first author during July and August of 2007. The survey focused on the Upper Ordovician Bad Cache Rapids and Churchill River groups and Red Head Rapids Formation, as well as the lowest part of the Lower Silurian Severn River Formation.

These units range from 180 to 300 m in thickness, and are dominated by carbonate, with subordinate thin shale intervals informally named 'Boas River shale' (Sanford *in* Heywood and Sanford, 1976) and 'Sixteen Mile Brook shale' (Nelson and Johnson, 1966, 1976; Nelson, 1981). Despite the fact that these shale intervals were identified on Southampton Island about 40 years ago, their stratigraphy and hydrocarbon potential were poorly understood. There has been considerable debate regarding these oil-shale intervals, which focused on fundamental stratigraphic issues, including the number of distinct shale intervals (from one to three) within the Ordovician succession, their precise stratigraphic positions, their potential extension into the Hudson Bay offshore area and their hydrocarbon potential. The field study was designed to generate data and answers pertinent for the stratigraphic debate.

Ordovician oil-shale stratigraphy

The stratigraphic issues were solved with detailed field observations of the Upper Ordovician and lowest Silurian strata at Cape Donovan on Southampton Island. At that locality, three oil-shale intervals were unequivocally mapped and stratigraphically assigned to the lower Red Head Rapids Formation (Zhang, 2008). Precise lithostratigraphic and biostratigraphic data led the author to conclude that the Cape Donovan lower and middle/upper oil-shale intervals can be stratigraphically correlated with the 'Boas River shale' and 'Sixteen Mile Brook shale', respectively (Figure 2; Zhang, 2008, Figure 2).

Rock-Eval 6 data for Ordovician oil shale

Rock-Eval 6 data from 40 samples of the three oil-shale intervals in the Cape Donovan sections led to the recognition of immature Type I–Type II kerogen and much higher yield and total organic carbon (TOC) values than previously reported (Macauley, 1986). Nineteen samples from the middle and upper oil-shale intervals have average and maximum yields of 136.5 and 230 kg hydrocarbons (HC)/tonne, and average and maximum TOC of 20 and 34%; 21 samples from the lower oil-shale interval have average and maximum yields of 58.5 and 112.5 kg HC/tonne, and average and maximum TOC of 9.8 and 17.3% (Zhang, 2008, Figures 11–14). Some advanced geochemical work was also done on six samples from the three oil-shale intervals (Zhang, 2011b).

Ordovician conodont biostratigraphy

Approximately 15 000 conodont elements from 269 samples at 14 localities enabled the establishment of four interval zones throughout the Upper Ordovician succession on Southampton Island (Figure 2; Zhang, 2011a, Figure 1). These zones are the *Belodina confluens* and *Pseudobelodina v. vulgaris* zones in the Bad Cache Rapids Group, correlative with the upper Edenian–lowest Richmondian Stage; the *Amorphognathus ordovicicus* Zone from the uppermost Bad Cache Rapids Group to the top of Churchill River Group, correlative with the lower Richmondian Stage; and the *Rhipidognathus symmetricus* Zone in the Red Head Rapids Formation, correlative with the upper Richmondian Stage. The oil-shale intervals in the lower Red Head Rapids Formation exposed at Cape Donavan, Sixteen Mile Brook and Boas River on Southampton Island are correlated with the lower *R. symmetricus* Zone of the upper Richmondian Stage (Figure 2), not with the Maysvillian–Richmondian Stage as previous interpreted (McCracken and Nowlan, 1989). The 'Boas River shale' and 'Sixteen Mile Brook shale' biostratigraphically correlate with the Cape Donovan lower and middle oil-shale intervals, respectively (Figure 2; Zhang, 2011a, Figure 3), and obviously the upper oil-shale interval is younger than the 'Boas River shale' and 'Sixteen Mile Brook shale'. The conodont data and continuous sections across the boundaries between the different lithostratigraphic units have documented the presence of Maysvillian strata on Southampton Island, contrary to previous belief (McCracken and Nowlan, 1989).

Field trip on Southampton Island

Based on the new stratigraphic breakthrough and interpretation, a field trip on Southampton Island was conducted

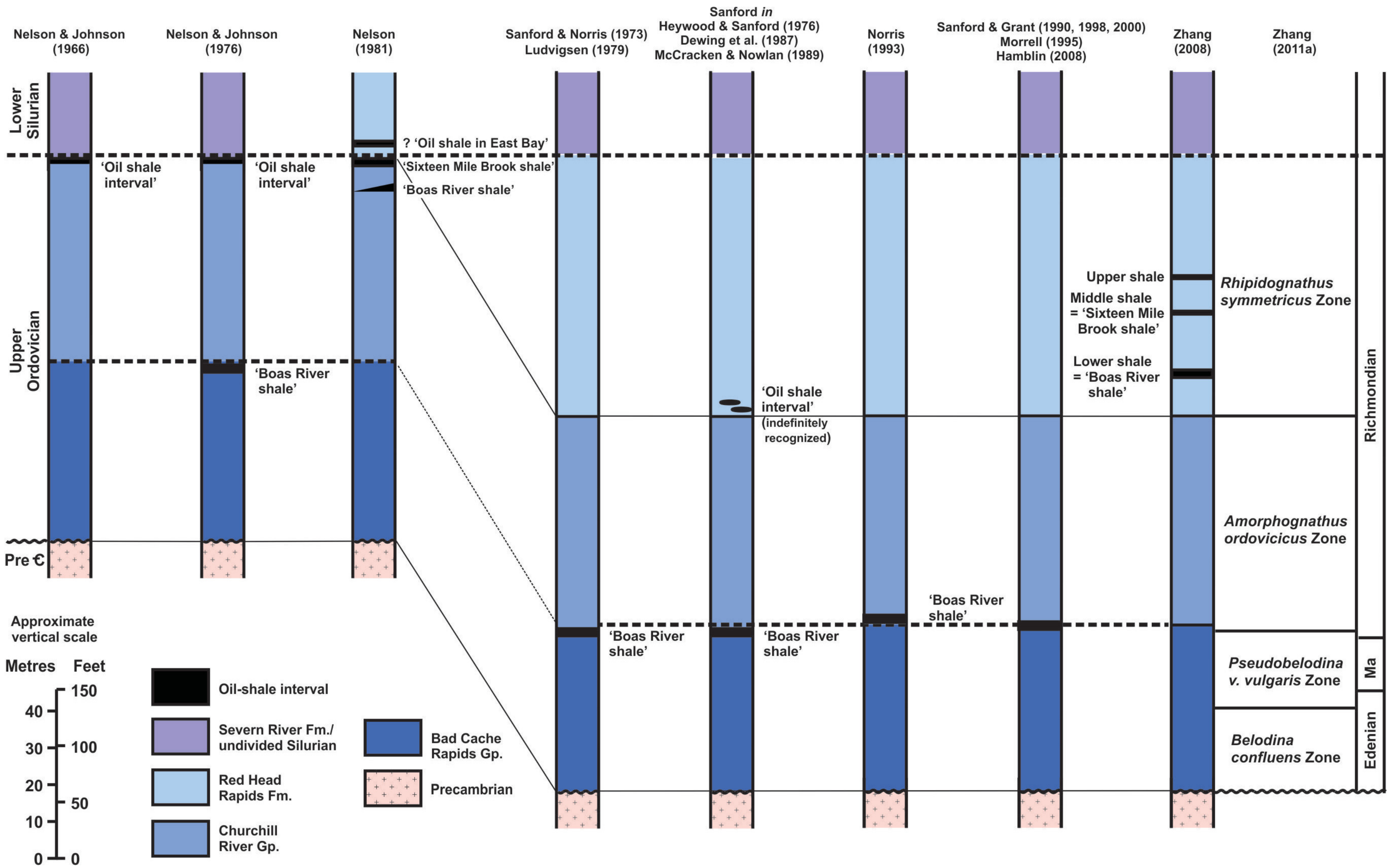

Figure 2. Historical review of interpretations of the number of oil-shale intervals and their stratigraphic positions within the Ordovician sequence on Southampton Island (modified from Zhang, 2008, 2011a). Abbreviation: Ma, Maysvillian.

under the GEM Hudson Bay–Foxe Basin Project and co-led by the authors (Zhang, 2010). This field trip attracted national and international participants, including geologists from the GSC, the Ontario and Manitoba Geological Surveys, Shell International Exploration and Production Company (Houston) and Cairn Energy PLC.

Northeastern Melville Peninsula

The Paleozoic succession that outcrops on northeastern Melville Peninsula belongs to the Foxe Basin. The 1:250 000 geological map of northeastern Melville Peninsula by Trettin (1975) served as a base map for the stratigraphic and paleontological studies of Sanford (1977) and others. Sanford and Grant (2000) formally divided the Paleozoic strata into the Lower Ordovician Ship Point Formation, the Middle Ordovician Frobisher Bay Formation and the Upper Ordovician Amadjuak, Boas River (an organic-rich unit), Akpatok and Forster Bay formations on northeastern Melville Peninsula, although no outcrops of Boas River and Akpatok strata have been found.

The fieldwork on northeastern Melville Peninsula was carried out by the first author in July 2009. The survey concentrated on some of the localities visited by Trettin (1975) and Sanford (1977), stratigraphically covering the Lower Ordovician Ship Point Formation and the Upper Ordovician Frobisher Bay (the age is redefined), Amadjuak, Akpatok and Forster Bay formations. The aims of this field study were to 1) explore the entire Paleozoic sequence; 2) determine if there is any Ordovician oil shale on northeastern Melville Peninsula; and 3) if the oil shale is present, address its lithostratigraphic and biostratigraphic position and its precise relationship with the oil-shale intervals on Southampton Island.

Methods of fieldwork

The Paleozoic strata are poorly exposed on northeastern Melville Peninsula; in particular, there is no outcrop of the upper Amadjuak, Akpatok and lower Forster Bay formations. To address the stratigraphic issues over such a large area (67°45'–69°30'N, 81°15'–83°15'W), the following methods were used:

- Detailed sampling for microfossils (conodonts) was carried out on outcrops of some stratigraphic units.
- In order to fill the biostratigraphic gap in areas without outcrops that seem to have been affected relatively little by glacial erosion (carbonate rocks of the upper Amadjuak, Akpatok and lower Forster Bay formations), rubble samples were collected from two transects (each about 15 km long) oriented roughly perpendicular to the regional strike of strata.
- Because of the nearly horizontal distribution of Paleozoic strata, an estimation of the most likely thickness of eroded Paleozoic strata was based on the precise location (GIS and Google Earth™) of sample localities with identified specific conodont fauna.

Primary outcomes of the field studies

Samples were collected from 62 of the 75 localities examined. One hundred and twenty-two conodont samples were taken from 24 outcrops and 38 rubble localities. The following preliminary results are based on the new conodont data:

- Identification of the diagnostic conodont species from units 2–4 of the Ship Point Formation indicates a late Early Ordovician age.
- Identification of the characteristic conodont species from the Frobisher Bay Formation suggests an earliest Late Ordovician age.
- The typical conodont species identified from the outcrops of the lower Amadjuak Formation, from rubble assumed to correlate with the upper Amadjuak, Akpatok and lower Forster Bay formations and from outcrops of the upper Forster Bay Formation support a stratigraphic correlation of these formations with the Upper Ordovician Bad Cache Rapids and Churchill River groups and the Red Head Rapids Formation in the Hudson Bay Basin.
- By combining the new conodont data with the GIS and Google Earth technology, the total thickness of Paleozoic strata on northeastern Melville Peninsula was estimated to be no more than 180 m.

Neither outcrops with black oil shale nor any black oil-shale rubble was found during the field study. The lack of black oil shale on northeastern Melville Peninsula is interpreted as the result of facies change and a thinner stratigraphic succession in this area compared to other outcrop domains of the Foxe Basin (Figure 3).

The detailed data and new interpretation regarding the Paleozoic stratigraphy and petroleum potential on northeastern Melville Peninsula have been prepared by the first author (Zhang, work in progress).

Southern Baffin Island

The Paleozoic succession on southern Baffin Island belongs to the Foxe Basin. With the notable exception of the Lower Ordovician Ship Point Formation, the stratigraphic units on southern Baffin Island are much thicker than their correlatives on northeastern Melville Peninsula (Figure 3). As such, and even if currently relatively little studied, the succession on southern Baffin Island should preserve a more complete record of the stratigraphy and hydrocarbon potential of the Ordovician succession in the Foxe Basin. Macauley (1987) succinctly reported the presence of black oil-shale intervals on southern Baffin Island, although without precise stratigraphic and lithological contexts.

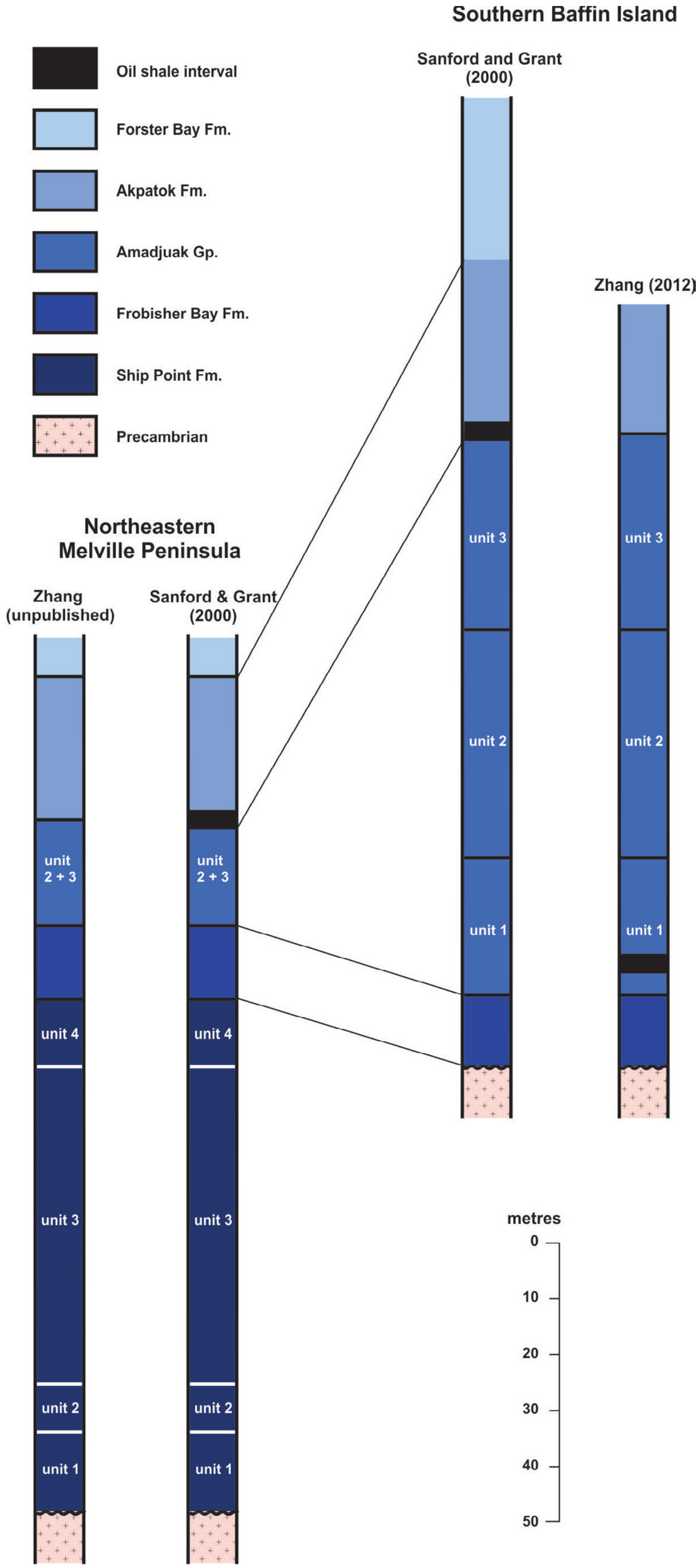

Figure 3. Correlation at the formation level of the Ordovician stratigraphy on southern Baffin Island and northeastern Melville Peninsula, and the significance for oil-shale stratigraphic distribution.

Field studies

Field studies by the first author on southern Baffin Island (Figure 1) in 2011 were designed to evaluate the stratigraphic position, geographic distribution and petroleum potential of the Ordovician oil shale on southern Baffin Island. A total of 39 localities was examined throughout the Paleozoic outcrop area on southern Baffin Island; 130 samples were collected from selected sections for conodont biostratigraphic study (processing currently underway) and 46 shale samples were collected from representative sections and rubble for Rock-Eval 6 analyses.

Stratigraphic position and geographic distribution of Ordovician oil shale

An oil-shale interval roughly 2 m thick outcrops in a large Paleozoic outlier in the vicinity of the Jordan River (Zhang, 2012, Figure 14). The new stratigraphic interpretation suggests that the oil-shale interval belongs to the lower Amadjuak Formation (Figure 3). This contrasts with its previous assignment at the contact between the Amadjuak and Akpatok formations of Sanford and Grant (2000). At the Jordan River locality, this oil-shale interval gradually changes upward from black, laminated, papery oil shale at the bottom to grey mudstone. Laterally, the black oil shale changes to a grey non–oil-shale zone on the western shore of Amadjuak Lake (Zhang, 2012, Figure 12).

The 130 samples for conodont study were collected with a focus on the sections of the Amadjuak Formation at the Jordan River and the western shore of Amadjuak Lake. It is anticipated that the biostratigraphic information will provide important information regarding the lateral facies change from oil to sterile shale in the lower Amadjuak Formation.

Rock-Eval 6 data for Ordovician oil shale

The preliminary Rock-Eval 6 data indicate that (Zhang, 2012, Table 2): 1) 15 samples from an outcrop of the lower Amadjuak Formation at Jordan River have TOC values of 1.68–12.97%, with an average of 7.79%; 2) 17 black, laminated, papery oil-shale rubble samples from various locations and lithologically similar to the outcrop samples yielded TOC values of 8.83–14.91%, with an average of 12.68%; 3) 9 grey shale and mudstone samples from a 2–3 m thick outcrop of the lower Amadjuak Formation on the western shore of Amadjuak Lake have lower TOC values of 0.31–0.76%; 4) 5 samples of brown, flaggy, argillaceous limestone rubble, from various locations, that lies scattered on outcrops of the Amadjuak or Akpatok formation have TOC values of 2.82–5.13%, with an average of 4.21%; these 5 samples are interpreted as belonging to the Forster Bay Formation, which has been eroded off the island; and 5) based on T_{max} (the temperature at which the maximum release of hydrocarbons from cracking of kerogen occurs during pyrolysis) and HI (hydrogen index) values, all samples with TOC content greater than 1.68% consist of immature Type I–Type II kerogen (Zhang, 2012, Figure 4).

Primary conclusions of the field studies

The 2011 field study on southern Baffin Island led to the following conclusions:

- The stratigraphic position of the black oil-shale interval is in the lower part of the Upper Ordovician Amadjuak Formation (Figure 3).
- The black oil shale laterally changes into grey non-oil shale.
- Another interval of low hydrocarbon yield occurred higher in the stratigraphy but has been eroded from the study area.
- The previously mapped Forster Bay Formation, which overlies the Akpatok Formation, does not outcrop on southern Baffin Island, most likely due to the deeper erosional level in that area (Figure 3; Zhang 2012, Figure 1B).

Restudying the 1960s–1980s onshore and offshore well materials from Hudson Bay

Hudson Bay was explored for hydrocarbon resources, at a reconnaissance scale, during the late 1960s to early 1980s, although the exploration potential remains largely untested. Five wells were drilled in the central part of Hudson Bay, although four of them were designed only to test a specific fault-hydrocarbon play. The onshore and offshore drilling activities indicated that the lower part of the basin succession comprises approximately 600–1040 m of Upper Ordovician Bad Cache Rapids and Churchill River groups and Red Head Rapids Formation, and Lower Silurian Severn River, Ekwan River, Attawapiskat and Kenogami River formations. These formations comprise mainly carbonate rocks, specifically alternating fossiliferous and reefal limestone, evaporite, dolostone and minor shale. The well materials, including well cuttings and well logs, from these formations are valuable for understanding the Paleozoic stratigraphy and petroleum potential in the Hudson Bay Basin. The top part of the succession consists of Lower Devonian carbonate, evaporite and minor clastic rocks. A major unconformity is present at the Silurian–Devonian contact, with the Upper Silurian (Ludlovian and Pridolian) and Lower Devonian (Lochkovian and Pragian) missing through either erosion or nondeposition (Hu et al., 2011; Pinet et al., work in progress). A maximum thickness of 2500 m of preserved sediments is present in Hudson Bay.

Microfossil conodonts from continuous cores and well cuttings

More than 4500 conodonts were examined and described from 390 conodont-bearing samples taken from continuous core and well cuttings from six exploration wells (Comeault No. 1, Kaskattama No. 1, Pen Island No. 1, Walrus A-

71, Polar Bear C-11 and Narwhal O-58; Figure 1) in the Hudson Bay Lowlands and offshore area. Based on the conodont data, seven conodont zones were established for the Upper Ordovician–Lower Silurian interval, leading for the first time to a precise biostratigraphic control for the different formations and to their correlation between wells (Zhang and Barnes, 2007, Figure 9).

Conodont Colour Alteration Index (CAI) values were evaluated for all wells in the Hudson Bay Lowlands and offshore area. The CAI values from the Upper Ordovician and Lower Silurian strata are all approximately 1. This suggests that the majority of rocks in Hudson Bay area might not have reached the window for petroleum generation. However, a slightly different conodont CAI was revealed when comparing the same kind of very thin conodont elements from 4470 ft. at Polar Bear C-11 and 550 ft. at Comeault No. 1; the former is slightly darker than the latter. This may be an indication that the rocks in the deep offshore area were within the window for petroleum generation (Zhang and Barnes, 2007).

Rock-Eval 6 data collected from well cuttings

Two hundred and forty-six samples, randomly picked from the carbonate well cuttings of four wells (Polar Bear C-11 and Narwhal South O-58 in the Hudson Bay offshore area, Comeault No. 1 in the Hudson Bay Lowlands and Rowley M-04 in the Foxe Basin), were analyzed using the Rock-Eval 6 pyrolysis technique. The results show that the TOC is uniformly very low (Zhang and Dewing, 2008).

Fifty-five cutting samples were collected from the interval 4625–4355 ft. in Polar Bear C-11, and another 55 cutting samples from the interval 3645–3375 ft. in Narwhal O-58. These samples were almost pure limestone/dolostone; they were carefully washed and the possible organic-rich fragments were preferentially picked from the cuttings under a stereo microscope. A small number of possible organic-rich fragments occur in almost all cutting samples from Polar Bear C-11 (Zhang, 2008, Figure 17). The possible organic-rich fragments from 23 samples from the interval 4590–4430 ft. in Polar Bear C-11 were analyzed by Rock-Eval 6 pyrolysis. Total organic carbon values of 2.23–5.73% occur in five samples at three levels, but T_{max} values are lower than 435°C in almost all samples (Zhang 2008, Figure 18).

Under a stereo microscope, 28 samples of black-shale fragments were picked from the cuttings from the interval 875–630 m (Devonian) in the Beluga O-23 well. These samples have been sent to the Rock Eval lab at GSC-Calgary for data collection.

Re-examining the well logs

The gamma-ray logs from offshore exploration wells Netsiq N-01, Beluga O-23, Polar Bear C-11 and Narwhal South O-58 were carefully re-examined. Three positive kicks in the lower–middle Red Head Rapids Formation were identified in the four wells (Zhang, 2008, Figure 15). The three positive gamma ray kicks are prominent, with their position mimicking the three oil-shale intervals on Southampton Island and correlating with the intervals where cutting fragments with TOC values of 2.23–5.73% were hand-picked (Zhang, 2008, Figure 18). This suggests the presence of the three oil-shale intervals in the offshore area.

Economic considerations

The aim of the project was to evaluate the presence of favourable hydrocarbon-system elements (source rocks, maturation, reservoirs) and link these in new hydrocarbon plays for the Hudson Bay and Foxe Basin region. The extensive fieldwork and post-field studies of Paleozoic stratigraphy in the Hudson Bay and Foxe basins during the past six years have contributed significant new data and led to a better understanding of the petroleum potential of the sedimentary basins. Specifically,

- the age and stratigraphic position of Ordovician oil-shale intervals vary from the Hudson Bay Basin to the Foxe Basin, so potential source rocks in the vast area of the Hudson Bay and Foxe basins should be targeted at different stratigraphic levels in different basins.
- the Hudson Bay Basin has seemingly a more significant hydrocarbon potential compared to the Foxe Basin, although little information is available for the marine domain of the latter area.

These contributions have significantly increased the understanding of regional petroleum systems, which could eventually help in focusing future exploration activities. Such exploration activities could result in economic hydrocarbon discoveries, the production of which would add a significant new element to the economic growth in Nunavut and benefit the northern communities.

Future study at CNGO

This is the last year of the Hudson Bay–Foxe Basin Project under the 2008–2013 GEM Program; however, some studies have not been finished at CNGO. In the near future, the first author will

1) continue to study the materials collected from southern Baffin Island, including conodont biostratigraphy and facies changes that affected the distribution of Late Ordovician oil shale;
2) conduct data interpretation for the 28 samples of black-shale fragments preferentially picked from the cuttings from the 875–630 m interval (Devonian) in the Beluga O-23 well; and
3) conduct a field study on Akpatok Island, when funding becomes available, to better understand the Paleozoic

stratigraphy and petroleum potential in both Hudson platform and southeast Arctic platform.

The reason for proposing a field study on Akpatok Island is that the island occupies a strategic position in the Ungava Bay and Hudson Strait; preliminary interpretation suggests that the sedimentary succession in Hudson Strait (Pinet et al., work in progress) is significantly thicker than the one preserved around the Foxe Basin and comparable to the maximum thickness documented in the Hudson Bay Basin; based on lateral facies variation in the oil-shale intervals on southern Baffin Island, a thicker Ordovician black-shale interval is expected in that eastern domain of the Hudson Strait.

Acknowledgments

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Permafrost characterization at the Iqaluit International Airport, Nunavut, in support of decision-making and planning

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Abstract

The Iqaluit International Airport is a key and strategic infrastructure on which the well-being of eastern Canadian Arctic residents depend. Increased passenger traffic and mineral exploration and development in the Arctic have put pressure on improving this key regional facility. Proposed renovation and expansion of the Iqaluit International Airport must address existing thaw settlement and frost cracking problems that are affecting the pavement and foundations of the runway and taxiways. Climate warming will also necessitate additional improvements in engineering design in order to adapt to changing terrain and environmental conditions. In order to support informed decision-making and reduce risk to public investments in northern transportation infrastructure and resource development, a joint Canada-Nunavut Geoscience Office, Natural Resources Canada and Université Laval study on the sensitivity of permafrost and terrain conditions at the airport began in 2010. In 2012, geophysical investigations, including electromagnetic and electrical resistivity surveys, were used to enhance permafrost characterization and monitor spatial and seasonal changes in unfrozen water content in sensitive areas. RADARSAT-2 image acquisition was also completed in summer 2012 and provided the second year of ground surface movement information by interferometric synthetic aperture radar mapping. Results based on one year of ground temperature records from under the runway, and interpretation of geophysical surveys and remote sensing data indicate that 1) permafrost temperature is slightly warmer and active layer thickness is slightly thicker under the runway than the surrounding undeveloped ground; 2) the thawing front under the runway penetrates through the existing embankment into the underlying, largely glaciomarine deltaic sediments and therefore settlement due to melting ice wedges will probably continue; 3) electrical conductivity anomalies present below taxiway A and under at least one section of the runway are associated with localized settlement problems; and 4) interferometric synthetic aperture radar data on ground surface motion related to frost heave and thaw settlement provide a good correlation with underlying surficial geology.

Résumé

L'aéroport international d'Iqaluit est une infrastructure stratégique de grande importance au bien-être des résidents de l'Est de l'Arctique canadien. Avec l'augmentation du trafic passagers et des activités d'exploration et de mise en valeur minière dans l'Arctique, il devient impératif d'améliorer cette importante installation régionale. Les travaux proposés de rénovation et d'agrandissement de l'aéroport international d'Iqaluit doivent tenir compte des problèmes actuels de tassement dû au dégel et de fissuration gélivale qui touchent le revêtement et l'assise de la piste et des voies de circulation. Le réchauffement climatique rendra également nécessaire la mise en place d'améliorations additionnelles à la conception technique en vue de permettre l'adaptation aux conditions changeantes touchant le terrain et l'environnement. Afin d'éclairer la prise de

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décisions et de réduire les risques auxquels doivent faire face les investissements publics dans les infrastructures de transport et le développement des ressources dans le Nord, le Bureau géoscientifique Canada-Nunavut, Ressources naturelles Canada et l'Université Laval ont entrepris en 2010 une étude conjointe sur la sensibilité du pergélisol et les conditions du terrain de l'aéroport. En 2012, des études géophysiques, y compris des levés de résistivité électromagnétique et électrique, ont été réalisées pour mieux caractériser le pergélisol et suivre l'évolution spatiale et saisonnière de la teneur en eau non gelée dans les zones sensibles. L'acquisition d'images RADARSAT-2 a également été achevée à l'été 2012 et a fourni pour une deuxième année des données sur les mouvements de la surface du sol au moyen de la cartographie par interférométrie radar à synthèse d'ouverture. Les résultats d'une année de données sur la température du sol sous la piste et l'interprétation des levés géophysiques et des données de télédétection indiquent ce qui suit :1) la température du pergélisol est légèrement plus chaude et la couche active est légèrement plus épaisse sous la piste que dans le sol environnant non aménagé; 2) le front de dégel sous la piste traverse le remblai existant vers les sédiments sous-jacents, en grande partie deltaïques et de nature glaciomarine, et, ainsi, le tassement dû à la fonte des coins de glace va probablement se poursuivre; 3) les anomalies de la conductivité électrique sous la voie de circulation A et sous au moins une section de la piste sont associées à des problèmes de tassement localisé; et 4) les données obtenues par interférométrie radar à synthèse d'ouverture sur le mouvement de la surface dû au travail du gel et du dégel présentent un haut degré de corrélation avec la géologie de surface sous-jacente.

Introduction

The city of Iqaluit is growing rapidly. Its airport is the gateway hub for the eastern Canadian Arctic and is also an international airport. This airport is not only vital for maintaining year-round links between southern cities and remote communities, but is essential to support active mineral and resource development, particularly in the Qikiqtaaluk Region. Since its construction by the United States Army during the Second World War, the history of the Iqaluit International Airport has been punctuated with noticeable stability problems (Eno, 2003). Because the underlying permafrost is now experiencing warming and degradation, decision-makers are facing new challenges in order to maintain the existing infrastructure and plan future expansion. In order to support the Government of Nunavut in ensuring growth, safety, informed decision-making and reduced risk to infrastructure investment, and therefore, to investments in northern resource development, a joint Canada-Nunavut Geoscience Office (CNGO), Natural Resources Canada (NRCan; Geological Survey of Canada [GSC] and Canada Centre for Remote Sensing) and Université Laval (Centre d'études nordiques) study on permafrost sensitivity and terrain conditions within the Iqaluit International Airport area was initiated in 2010. Several field studies have been conducted. Remote sensing data were used in support of mapping and for spatially determining terrain surface motion utilizing interferometric synthetic aperture radar (InSAR) technology. A major component of the project was the development of a multidisciplinary earth sciences approach involving Quaternary geology, permafrost science, geophysics and geotechnical characterizations. The aims of the project are to provide a comprehensive vision of how the current infrastructure interacts with warming permafrost and to support the development of improved engineering designs to ensure infrastructure safety, performance and sustainability in the coming decades. All subsurface and surface terrain data and interpretations are integrated in a geographic information system (GIS). Ultimately, the GIS will be used as an interactive tool to communicate results and to better enable the inclusion of geoscientific information in the engineering design of repairs and infrastructure expansion. It is also the aim of this project to provide a better understanding of the thermal and physical processes affecting permafrost degradation under paved infrastructure. This paper presents a summary of the work that has been conducted thus far, including results from summer 2012 and current permafrost conditions.

Study area

Iqaluit is located in southeastern Baffin Island at the head of Frobisher Bay (63°45'N, 68°33'W), in a zone of continuous permafrost. Environment Canada weather station data collected adjacent to the airport from 1971 to 2000 yielded a mean annual air temperature (MAAT) of –9.8°C and annual precipitation of 412 mm, of which 48% occurs as rain (Environment Canada, 2011). Since 2000, the MAAT has been higher than the reference period; the warmest year was 2010 at –4.2°C. The airport is built on flat terrain surrounded by hills and rocky plateaus of the Precambrian Shield (St-Onge et al., 2006).

Methodology

A combination of traditional surficial geology mapping, near-surface drilling, shallow geophysical surveys, and ground thermal and ground movement instrumentation was used during the summers of 2010, 2011 and 2012 and the winter of 2011; InSAR mapping of ground surface movements was also undertaken. Details of the research and the location of surveys and instrumentation are shown in Figure 1.

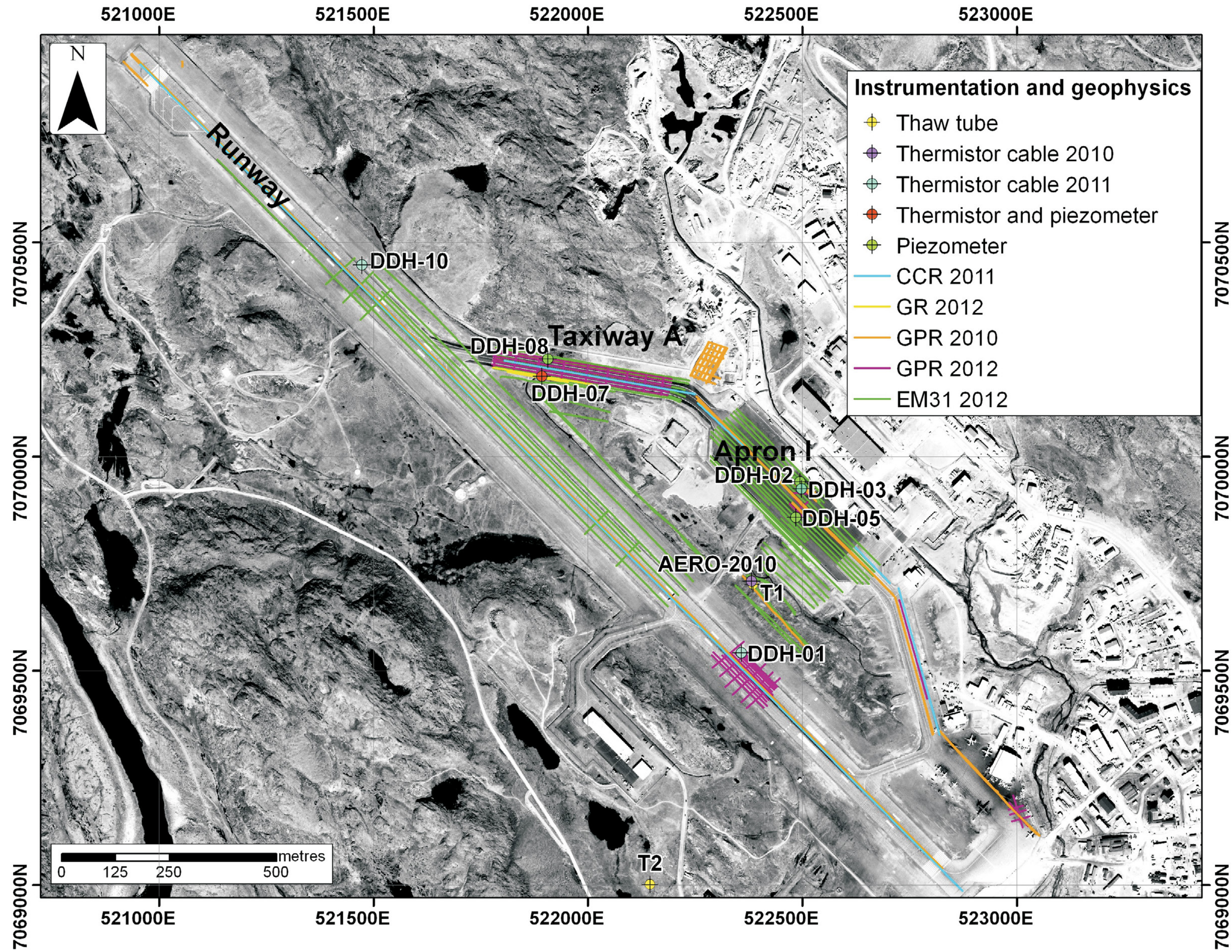

Figure 1: Location of the geophysical surveys and instrumentation at the Iqaluit International Airport, Nunavut. Background image (WorldView-1; DigitalGlobe, Inc., 2008) includes copyrighted material from DigitalGlobe, Inc., all rights reserved. UTM zone 19. Abbreviations: CCR, capacitively coupled resistivity; EM31, electromagnetic; GPR, ground penetrating radar; GR, galvanic resistivity.

Field observations

The surficial geology of the Iqaluit area was mapped by Allard et al. (2012) and is described below. Observations of permafrost features were also made as part of this mapping activity (Mathon-Dufour, 2011). To measure the spatial variability of ground temperatures, one thermistor cable was installed in 2010 in the undeveloped terrain (AERO-2010, Figure 1), while four others were installed in 2011 within various embankment locations (DDH-01, DDH-03, DDH-07, DDH-10, Figure 1). A total of four piezometers were also installed in 2011 (DDH-02, DDH-05, DDH-07, DDH-08, Figure 1). Only visual observation of disturbed soil samples and approximate stratigraphic depths was possible during the borehole installation since an air rotary drill was used. Two thaw tubes were installed in 2010, one in well drained sediments (T1, Figure 1) and the other in poorly drained sediments (T2, Figure 1), in order to validate the remote sensing data using annual maximum heave/subsidence measurements (cf., Nixon and Taylor, 1994). Electrical resistivity imaging (ERI), including galvanic resistivity (GR) and capacitively coupled resistivity (CCR) along with electromagnetic surveys (EM31) and ground penetrating radar (GPR), were conducted in 2010, 2011 and 2012 to support the field and airphoto-based observations (Figure 1). In addition to the standard characterization of permafrost by geophysical investigations, a permanent array of 72 electrodes at 2 m spacing was buried along the shoulder of taxiway A during summer 2012 (see GR 2012 on Figure 1). This installation is part of an innovative experiment for imaging the in situ seasonal and spatial variability of unfrozen water content. Unfrozen water content is an important parameter in calculating the thermal properties of soil, which is used to predict the behaviour of the ground upon warming and thawing. Results from this research will be used in a new coupled heat and water transport model to simulate the thermal regime within and under airport embankments. Interpretation of InSAR displacements will also benefit from knowledge of the seasonal variation in soil water and ice contents in relation to freezing and thawing.

Remote sensing data

Field observations can be complemented by ground displacement values using InSAR data (Gabriel et al., 1989; Massonnet and Feigl, 1998). The method is based on the principle that local surface elevation can be detected and measured from returning active microwave radar signals transmitted from a satellite to a reflective surface on the Earth. From the analysis of the phase shift between repeat-track synthetic aperture radar (SAR) acquisitions separated by a time interval (interferograms), the ground displacement in the SAR line-of-sight (LOS) can be calculated. In flat areas like the airport, satellite geometry can be used to convert the LOS observation to a vertical displacement. RADARSAT-2 Spotlight scenes (C-band SAR) on a descending orbit with an incidence angle of 45° were acquired on June 22, July 16, August 9, September 2 and September 26, 2011 and on May 23, June 15, July 10, August 3, August 27 and September 20, 2012. For each summer, the data were interferometrically stacked and vertical displacement was projected from the calculated LOS displacement. Each displacement measurement represents an area of approximately 1.5 by 1.5 m on the ground, and is a smoothed product of neighbouring pixels.

Permafrost characterization

Surficial geology

Approximately 67% of the length of the runway, which represents the initial runway built during World War II along with aprons and access roads, is built on glaciomarine deltaic deposits composed mainly of sand, boulders and gravel with the noted presence of some silty layers in the stratigraphy (Figure 2; Allard et al., 2012). Alluvial channels and lacustrine deposits are also present under the aprons and access road embankments. The northwestern extension of the runway built after 1948 overlies a glaciofluvial outwash terrace, a small esker and bedrock. Till and marine veneer complete the surficial geology surrounding the airport. Results shown by Mathon-Dufour (2011) and Mathon-Dufour et al. (2012) clearly indicate a strong link between surficial geology, permafrost features and the recurrent settlement and frost cracking problems affecting asphalt surfaces and embankments. Among these features, a dense network of ice wedge polygons present in the glaciomarine deltaic deposits appear to currently affect surface cracking on the runway. At least one pre-existing lake and one small stream (Lv and Ap, Figure 2) also appear to affect the largest apron (apron I, Figure 1) and one of the access roads (taxiway A, Figure 1).

Ground thermal regime

The permafrost temperature was recorded over two years (summer 2010 to summer 2012) at the AERO-2010 natural terrain site (Figure 1). During the second year of recording, the permafrost temperature was approximately –5.3°C at a depth of 10 m, with a maximum active layer thickness of 1.5 m (Figure 3, AERO-2012). However, additional data collected at thermistor site DDH-01 (Figure 1) from summer 2011 to summer 2012 shows that the active layer under a paved embankment reached a thickness of 2.5 m with a permafrost temperature of –4.6°C at a depth of 10 m (Figure 3, DDH-01).

Geophysical characterization

Surface observations made in the field and on airphotos indicated that some features now buried under embankments (e.g., ice wedges, filled river channels, drained lakes) are related to recurrent asphalt and embankment damages. The

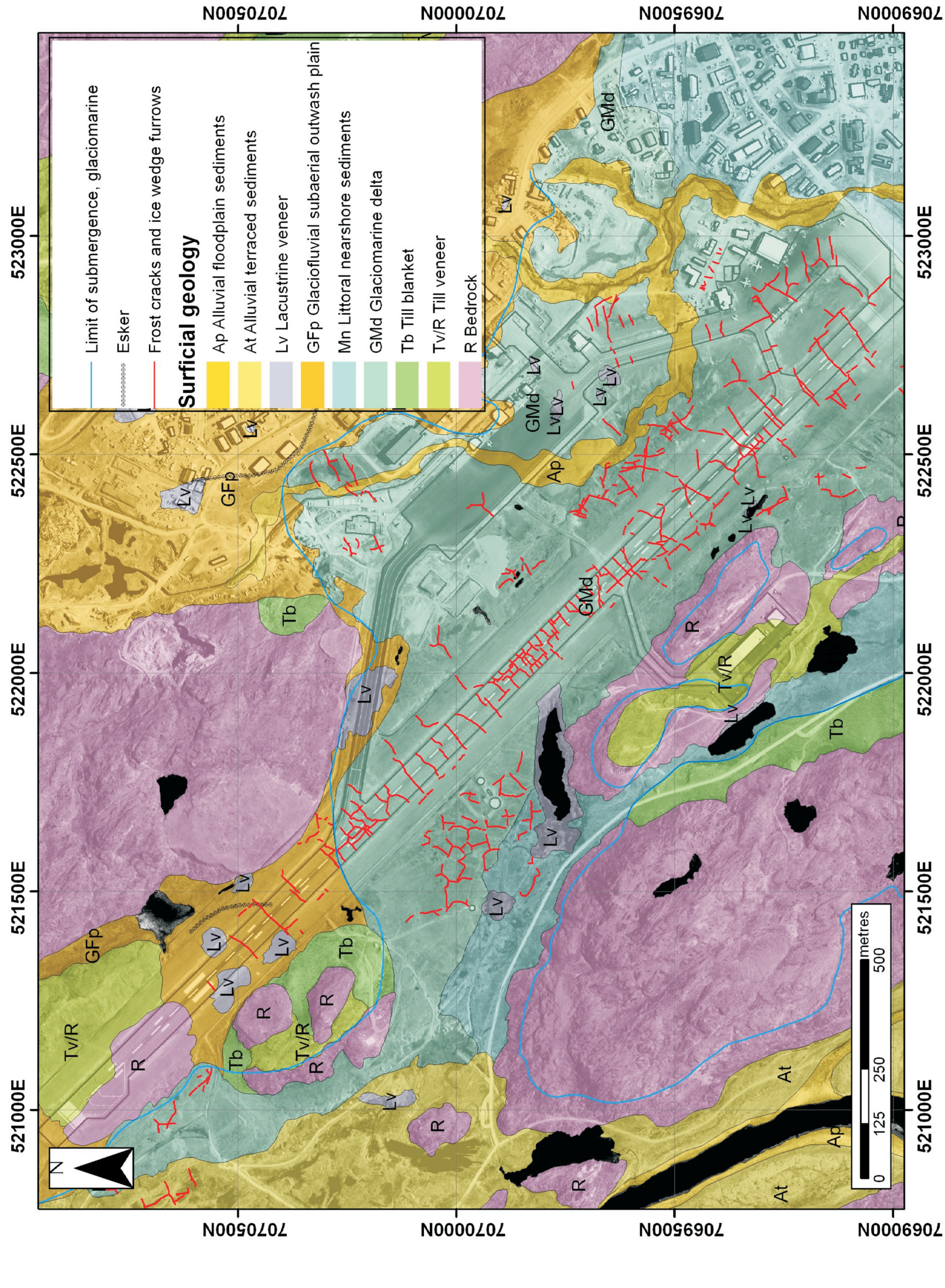

Figure 2: Surficial geology in the area of the Iqaluit International Airport, Nunavut (from Allard et al., 2012). Background image (WorldView-1; DigitalGlobe, Inc., 2008) includes copyrighted material DigitalGlobe, Inc., all rights reserved. UTM zone 19.

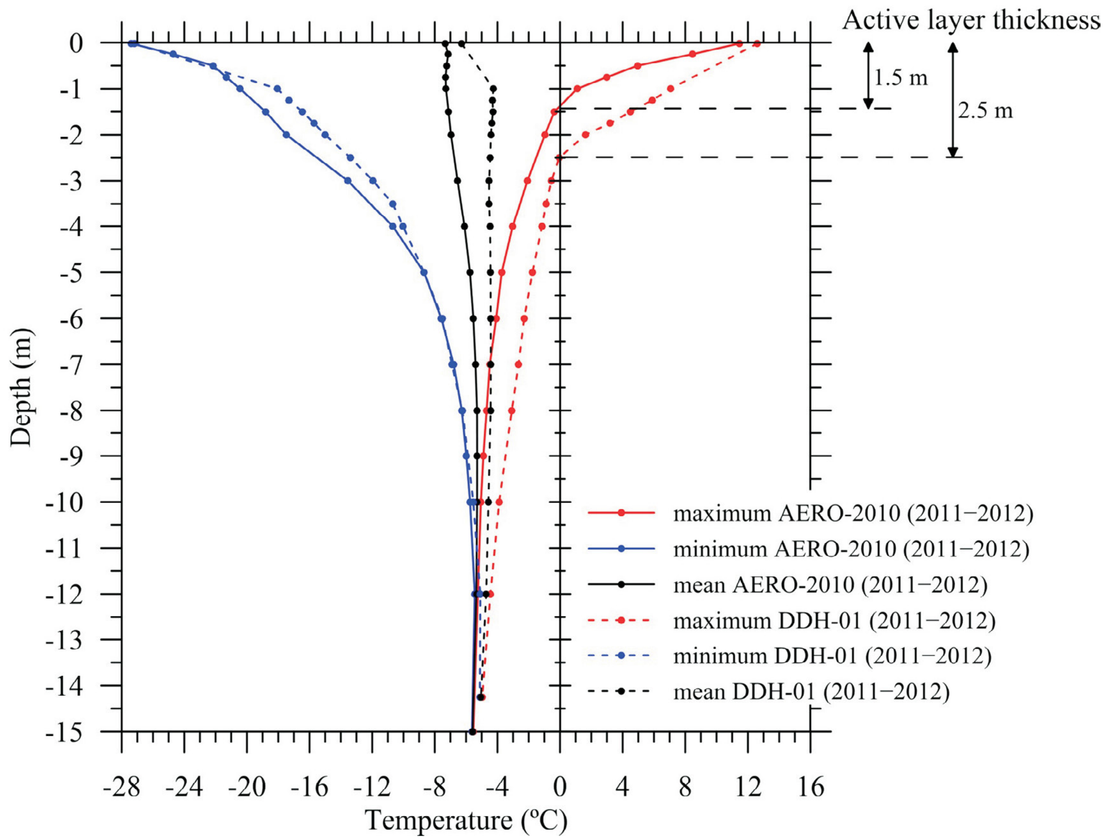

Figure 3: Annual maximum, minimum and mean ground temperatures over the period of August 2011 to July 2012 at two thermistor cables: boreholes AERO-2010 (paved runway) and DDH-01 (natural ground). See Figure 1 for borehole locations at Iqaluit International Airport, Nunavut.

GPR surveys were used to characterize the general stratigraphy and identify possible ice wedges under the paved surfaces at locations of prominent frost cracks. The ERI (CCR and GR) and EM31 surveys were used to delineate ice-rich permafrost areas and conductive anomalies.

LeBlanc et al. (2012) presented the results of GPR and CCR surveys conducted in 2010 and 2011 for the total length of the runway. The GPR results along the centre line of the runway show that within the glaciomarine sediments, the contact between the embankment and the natural ground does not correspond to a clear GPR reflection, possibly due to the similarity of the material used to build the embankment and the underlying deposit. Furthermore, Mathon-Dufour et al. (2012) reported a maximum embankment thickness over the glaciomarine sediments of approximately 2.5 m, which is similar to the maximum active layer thickness (Figure 3). The thawing front would produce a stronger GPR reflection due to the transition from unfrozen to frozen pore water as opposed to the transition between underlying natural ground and embankment of similar material. Along the centre line of the runway, hyperbolic reflectors indicative of ice wedges (Fortier and Allard, 2004) were also visible below the base of the active layer and beneath most of the major frost cracks (see Figure 2 for frost crack locations). Mathon-Dufour et al. (2012) studied in detail one area particularly affected by frost crack depressions (see GPR 2012, Figure 1). One GPR line conducted parallel to the runway, along with its interpreted cross-section, is shown in Figure 4. Results corroborate the GPR results obtained in 2010. However, according to the ground temperature record at DDH-01 and the maximum 2.5 m active layer thickness (Figure 3), it was possible to better calibrate the depth of the thawing front on the 2012 GPR profile at approximately 2.5 m depth (Figure 4). Hyperbolic reflectors below the active layer (interpreted as ice wedges) coincide with locations of frost cracks observed at the surface, whereas hyperbolic reflectors observed within the active layer are probably associated with open frost cracks (void left by melted ice veins within the active layer; Figure 4). This interpretation suggests that the thawing front has now reached the natural ground below the embankment and that settlement due to melting ice wedges will probably continue with further climate warming. Further interpretation of GPR profiles will allow a better assessment of the size of these ice wedges.

The 2011 CCR survey along the total length of the runway shows a conductive anomaly with resistivity below 200 Ω·m starting at the junction of taxiway A and extending approximately 650 m to the southeast (LeBlanc et al., 2012). There is a lack of ground information over this area

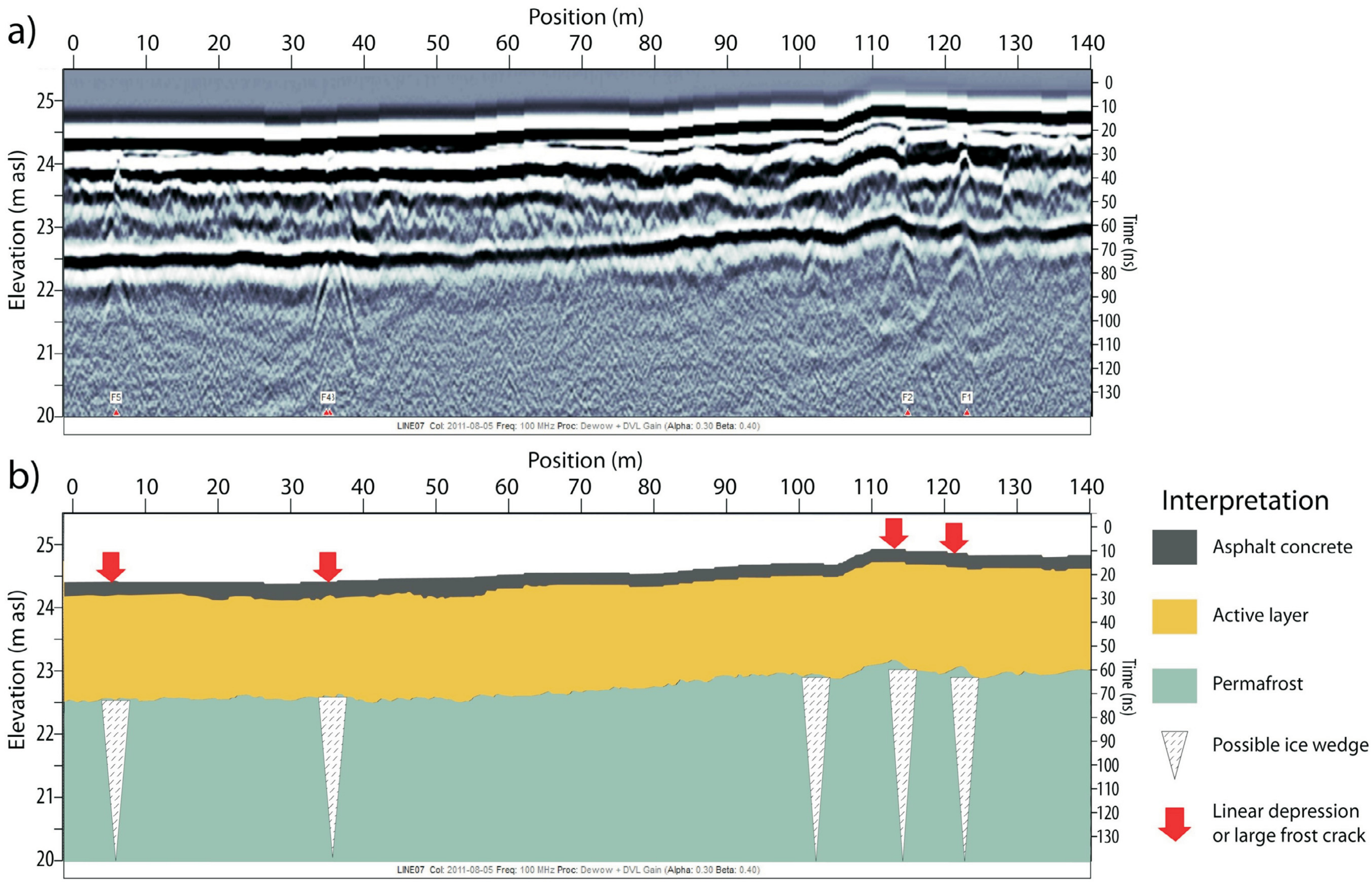

Figure 4: a) Ground penetrating radar (GPR) survey conducted over a section of the runway in 2012 and **b)** its interpreted cross-section, Iqaluit International Airport, Nunavut.

since the initial runway was already built before the earliest available aerial photographs were taken in 1948. The only information available up to now is a topographic map from 1942 indicating that there was a small lake adjacent to the west side of the runway close to the junction of taxiway A and the runway. The size of the lake is too small to fit with the extent of the conductive runway anomaly and the runway anomaly is more resistive than that associated with the historical lake sediments along taxiway A. Preliminary 2012 GR results along taxiway A indicate resistivity values below 20 Ω·m (Figure 5), similar to resistivity values given by a previous CCR survey over the same section. To investigate the spatial extent of the conductive anomaly observed below the runway and taxiway A, EM31 data were collected in 2012 along several lines on and adjacent to the runway and taxiway A. Apparent resistivity maps for shallow and deep EM31 measurements are shown in Figure 6. The shallow map represents an integrated measure of conductivity to approximately 3 m depth (Figure 6a) and the deep map represents an integrated measure of conductivity to approximately 6 m depth (Figure 6b). The maps are produced by interpolation between widely spaced lines and thus, care must be taken when interpreting features away from actual measurement points (Figure 1). However, in general, both shallow and deep expressions of a conductive anomaly (in blue, Figure 6) are observed along taxiway A. The anomaly strengthens with depth and to the southeast. It extends across the undeveloped region between the runway and taxiway A and seems to have some presence along the runway. Although the depth of investigation of the EM31 does not correspond to that of the CCR data or the GR data, there may be some connection between taxiway A and runway anomalies. Further data integration is required to investigate this relationship. In general, conductive anomalies are often associated with fine-grained permafrost soils that are thaw sensitive.

The InSAR-derived vertical displacement map

The InSAR data acquisition for the summer 2012 had just been completed over Iqaluit at the time of this report and its analysis has only begun. To give a sense of the results that are expected for this year, the InSAR vertical displacement map for 2011 is shown and described in this section (Figure 7). The 2011 summer InSAR data provided the seasonal distribution of relative ground surface displacement in the area of the airport and was used to identify thaw sensitive areas that might affect the performance of infrastructure. The InSAR results were interpreted based on surficial geology, knowledge acquired from the geophysical investigations and a comparison of ground movement with settlement values from two thaw tubes (LeBlanc et al., 2012; Short et al., 2012). The second set of InSAR images acquired in summer 2012 will

- improve understanding between the calculated displacements and the observed movement and properties of the underlying permafrost;
- assess how results may vary year to year; and
- start to differentiate between seasonal and multiyear trends in ground surface displacement.

Unfortunately, the smooth and asphalted surfaces of the runway, taxiways and aprons appear as areas of no data (Figure 7), as a result of loss of interferometric coherence. However, the displacement data can be analyzed on the adjacent shoulders and the terrain on both sides of the paved surfaces. The results of summer 2011 correlate very well with the mapped surficial geology (Figures 2, 7). Stable ground or very low downward surface movement correlates with bedrock and till units. In the airport surroundings, the greatest downward displacements were associated with marine and glaciomarine deltaic deposits. These displacements reflect seasonal settlement caused by thawing of the active layer and may also reflect thawing in near-surface permafrost. On both sides of the runway embankment, southeast of the junction between taxiway A and the run-

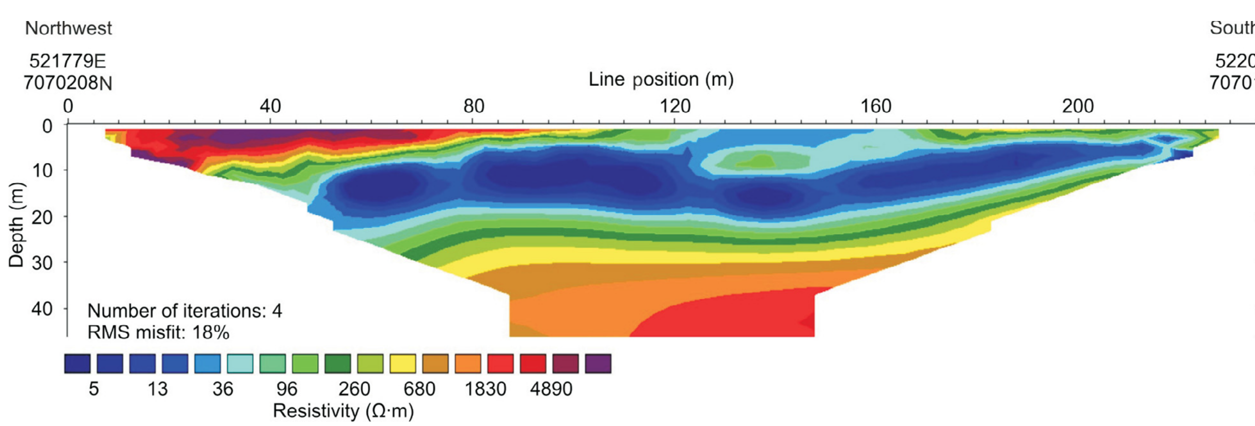

Figure 5: Electrical resistivity survey (GR) conducted along the embankment shoulder of taxiway A in 2012, Iqaluit International Airport, Nunavut. Abbreviation: RMS, root-mean-square.

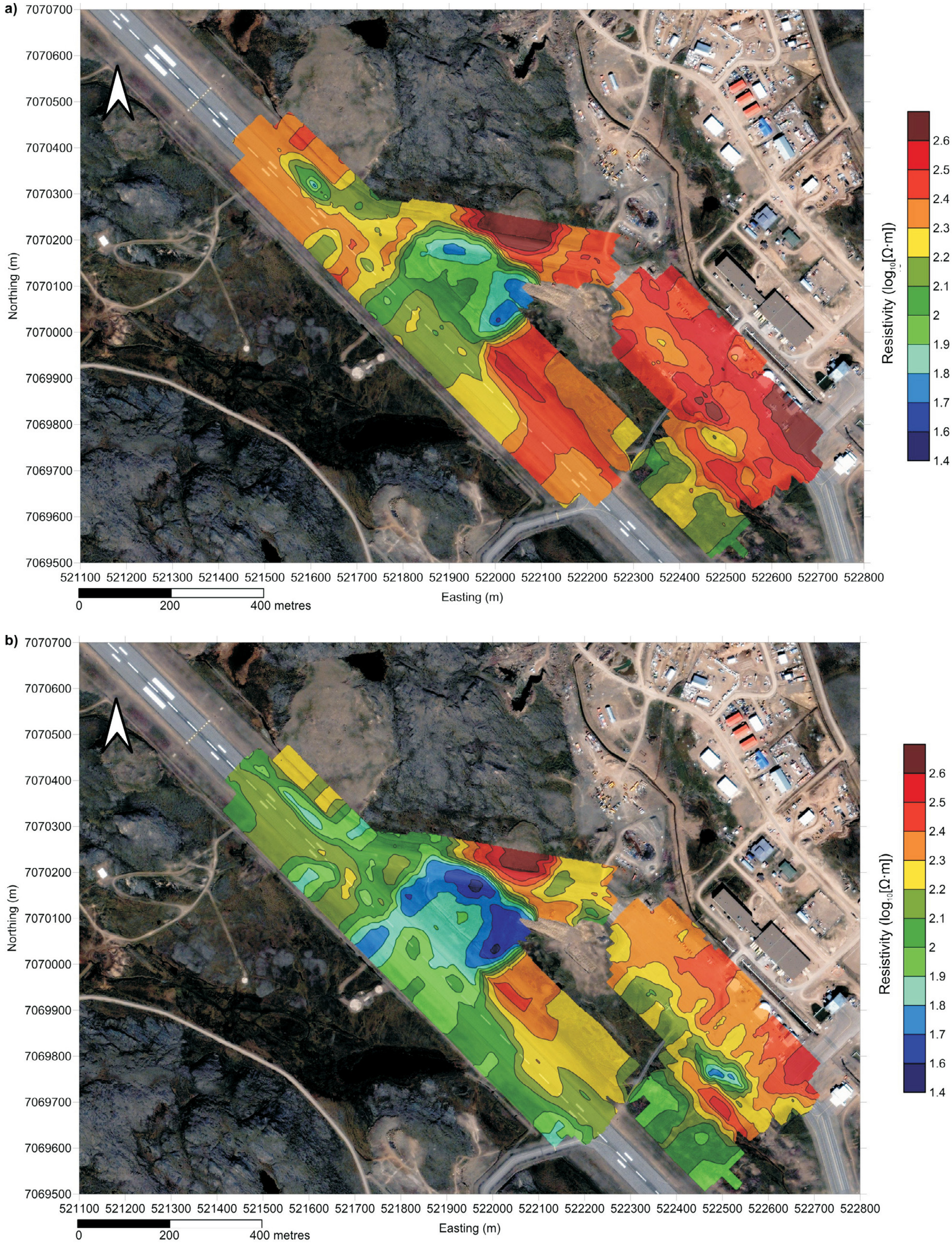

Figure 6: Electromagnetic survey (EM31) data collected along several lines along and adjacent to the runway and taxiway A, Iqaluit International Airport, Nunavut: **a)** integrated measure of conductivity to approximately 3 m depth, **b)** integrated measure of conductivity to approximately 6 m depth. Background image (QuickBird; DigitalGlobe, Inc., 2006) includes copyrighted material DigitalGlobe, Inc., all rights reserved. UTM zone 19.

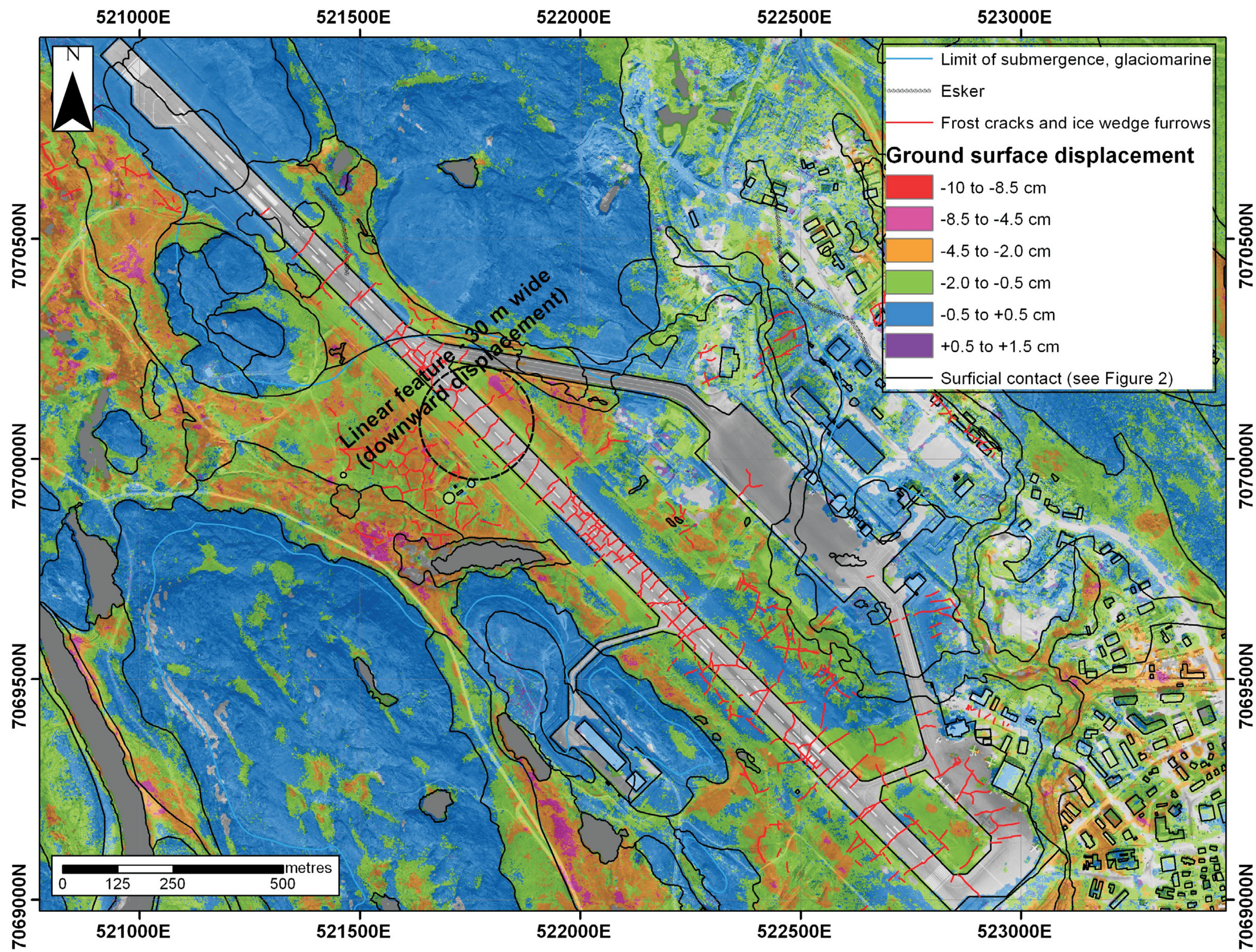

Figure 7: Interferometric synthetic aperture radar (InSAR)–derived vertical displacement map, showing the spatial distribution of the relative ground surface displacement during summer 2011 (June 22–September 26, 2011) in the area of the Iqaluit International Airport, Nunavut. Negative values represent downward displacement (from Short et al., 2012). Circle adjacent to the western end of taxiway A corresponds to the conductive anomaly shown in Figure 6. Background image (WorldView-1; DigitalGlobe, Inc., 2008) includes copyrighted material DigitalGlobe, Inc., all rights reserved. UTM zone 19.

way, a linear corridor about 30 m wide shows a deeper downward displacement compared to the surroundings. The trench at the embankment toe on the southwest side of the runway is deformed and saturated with water. Furthermore, the InSAR linear feature is more or less located between two major frost cracks and matches the conductive linear feature shown by the EM31 results (Figure 6). The InSAR 2012 results will help determine if this linear depression is recurrent over time or if it is deepening with time.

Although, the 2011 InSAR results correlate very well with the surficial geology, the results did not exactly match with the thaw tube settlement values. The calculated displacements were about half the settlement values observed in the field. Besides the fact that highly variable local conditions around thaw tubes may not have been reproduced by the averaging of the approximately 1.5 by 1.5 m ground pixel in the InSAR data, the InSAR acquisition of 2011 also started June 22nd, one month after ground settlement initiation, which can make a significant difference in measured total downward displacement. To overcome that, the data of 2012 were acquired from the beginning of the thawing season (May 23). Furthermore, in 2012, field observations, such as near-surface soil moisture and settlement, were taken at the same dates as the satellite image acquisition. Since InSAR is an emerging technology, its application to permafrost terrain will certainly improve the way permafrost is characterized at a useful scale for infrastructure monitoring and for assessing terrain for resources development.

Economic considerations

Development of Nunavut's mineral resources and the infrastructure required to service development and communities are important factors supporting the territory's economy (Aboriginal Affairs and Northern Development Canada et al., 2012). The Iqaluit International Airport is one piece of infrastructure on which mineral exploration and exploitation in Nunavut, and particularly of the Qikiqtaalik Region, strongly depend on for their growth. Several exploration projects in the region use Iqaluit as their main centre for supplies and services. As an example, Baffinland Iron Mines Corporation operates weekday flight service, providing transport for workers from Iqaluit to the Mary River mine development site. The recently announced construction phase of the mine will probably add more pressure on the use of airport facilities.

Each year, considerable investments need to be made by the Government of Nunavut to repair and maintain transportation infrastructure. In addition, the Iqaluit runway is now due for resurfacing along with a need for a general enhancement of airport buildings. Recently announced by the federal government, new funds granted to the Government of Nunavut will allow significant improvement of the Iqaluit airport (new terminal building, expanded aprons, upgraded runway, etc.) and thereby highlights the crucial importance of this ongoing research. This study has already documented some of the difficult permafrost conditions on which the airport was built in the early 1940s. With the onset of climate warming, the underlying permafrost will continue to degrade causing additional maintenance and sustainability problems. This information and understanding generated by this study will contribute to informed decision-making, and application of improved engineering design and development.

Acknowledgments

This work was supported through collaboration between NRCan (GSC and Canada Centre for Remote Sensing), Université Laval (Centre d'études nordiques) and CNGO. Special thanks goes to D. Mate of CNGO. Additional resources were provided by the Canadian Space Agency through the Government Related Initiatives Program. The authors would also like to express their thanks to J. Graham, J. Hawkins, the manager of the Iqaluit International Airport and his staff, especially B. Duguay and L. Twerdin, and to J. Doyon and R. Boivin for their help with the digital cartography. A-S. Carbonneau, P. Gosselin and C. Falardeau Marcoux were helpful field assistants during the field investigations.

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Coastal geoscience for sustainable development in Nunavut: 2012 activities

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Abstract

In partnership with the Canada-Nunavut Geoscience Office, scientists in the Earth Sciences Sector of Natural Resources Canada and their collaborators have carried out activities in several regions of resource industry activity in Nunavut under the Coastal Infrastructure Project of the Earth Sciences Sector's Climate Change Geoscience Program. These activities focused on coastal characterization, coastal instability, sea-level change, coastal hazards and vulnerability in the context of climate change. A mosaic of satellite imagery (SPOT) and interpretation of coastal video of Coronation Gulf and surrounding regions provide baseline coastal characterization. Potential applications include assessment of the accessibility and nature of candidate port sites, and assessment of available aggregate resources. A coastal change study of the community of Kugluktuk reveals that the town-site coastline is largely stable, but there is rapid coastal change near the port site and on islands of the Coppermine delta, as well as localized bank erosion in town. A coastal hazard assessment of Iqaluit, the capital of Nunavut, reveals infrastructure at risk from rising sea levels. In contrast to Iqaluit, a relative sea-level projection for the outlet of Baker Lake indicates that sea level is expected to continue to fall throughout the 21st century because of the large rate of land uplift.

Résumé

En partenariat avec le Bureau géoscientifique Canada-Nunavut, les scientifiques du Secteur des sciences de la Terre de RNCan et leurs collaborateurs ont mené des travaux dans plusieurs régions où l'industrie des ressources est active au Nunavut, dans le cadre du projet d'infrastructure côtière du programme Géosciences des changements climatiques du Secteur des sciences de la Terre. Ces activités ont porté sur la caractérisation du littoral, l'instabilité côtière, le changement

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du niveau de la mer, les dangers menaçant la zone côtière et la vulnérabilité dans le contexte du changement climatique. Une mosaïque d'images satellites (SPOT) et l'interprétation de la vidéo côtière du golfe de Coronation et des régions environnantes permettent d'établir une caractérisation de base de la côte. Les applications potentielles comprennent l'évaluation de l'accessibilité et de la nature des sites portuaires candidats, et l'évaluation des ressources en granulats disponibles. Une étude sur le changement côtier de Kugluktuk révèle que la côte sur laquelle est érigée l'agglomération est en grande partie stable, mais qu'elle connaît des changements rapides près du port et sur les îles du delta de la rivière Coppermine, ainsi qu'une érosion localisée des berges dans la ville. Une évaluation des risques côtiers à Iqaluit, capitale du Nunavut, révèle que l'infrastructure est menacée par la montée des eaux. Contrairement à Iqaluit, une projection du niveau de la mer par rapport à la décharge du lac Baker indique que le niveau de la mer devrait continuer de baisser tout au long du XXI[e] siècle en raison du degré important de soulèvement des terres.

Introduction

Scientists in the Earth Sciences Sector (ESS) of Natural Resources Canada (NRCan) have been working with the Canada-Nunavut Geoscience Office (CNGO) to address coastal climate change issues across Nunavut under the Coastal Infrastructure Project of the ESS Climate Change Geoscience Program (CCGP; Figure 1). The focus of activities has been regions, localities and communities where the resource industry utilizes existing coastal infrastructure or where industry activity may lead to development of coastal infrastructure. These developments are affected by coastal conditions and processes that can be observed and interpreted by a variety of local and remotely sensed techniques. Presented here is a summary of CCGP activities that contribute to safe development on Canada's Arctic coasts in a changing climate. As shown on Figure 1, the focus this year has been Coronation Gulf and surrounding regions, although activities have also occurred in other parts of Nunavut.

Coronation Gulf video mapping

Scientists in the CCGP, with support from CNGO and the ESS Environmental Geoscience Program, will use nine hours of colour aerial video coverage, including shore-zone commentary, for the coastline of Coronation Gulf to map coastal landforms and material composition. The aerial video survey was flown for Environment Canada from August 18–25, 1994 (Figure 2) to provide a general physical characterization of the shoreline for oil spill contingency planning (Gillie, 1995). Seven of the original 14 tapes (for the Coronation Gulf coastline) were converted to DVD to ensure that the quality of the imagery was suitable for coastal mapping and interpretation. An initial assessment has confirmed that this imagery will provide useful information about the coastal zone that can be used to not only populate NRCan's CanCoast coastal geospatial database (Manson et al., 2012), but also to provide specific coastal attribute information for Kugluktuk and the potential port site of Grays Bay.

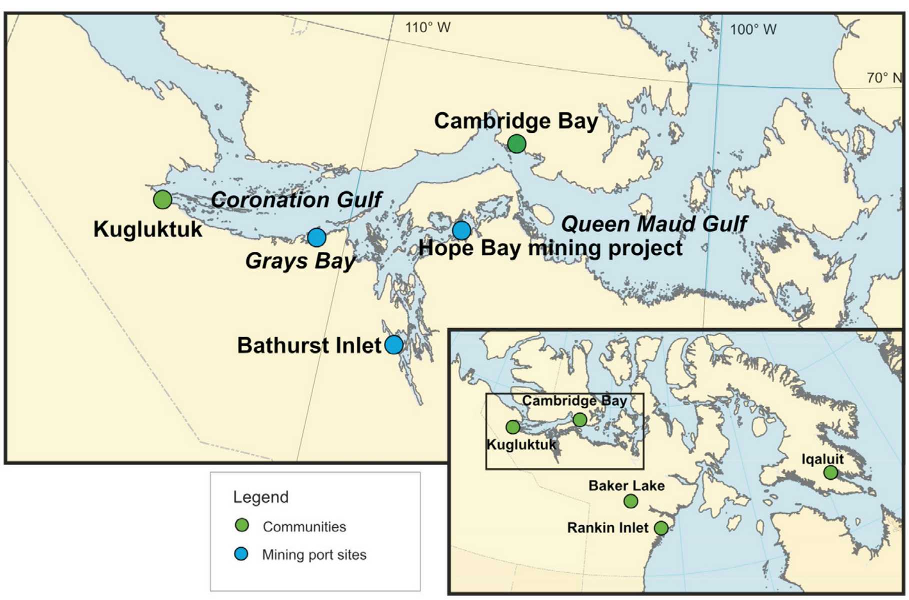

Figure 1. Location of Climate Change Geoscience Program activities in Nunavut in 2012. Port sites shown in the large map have been developed (Hope Bay mining project) or are being considered for development (Grays Bay and Bathurst Inlet) by mining companies.

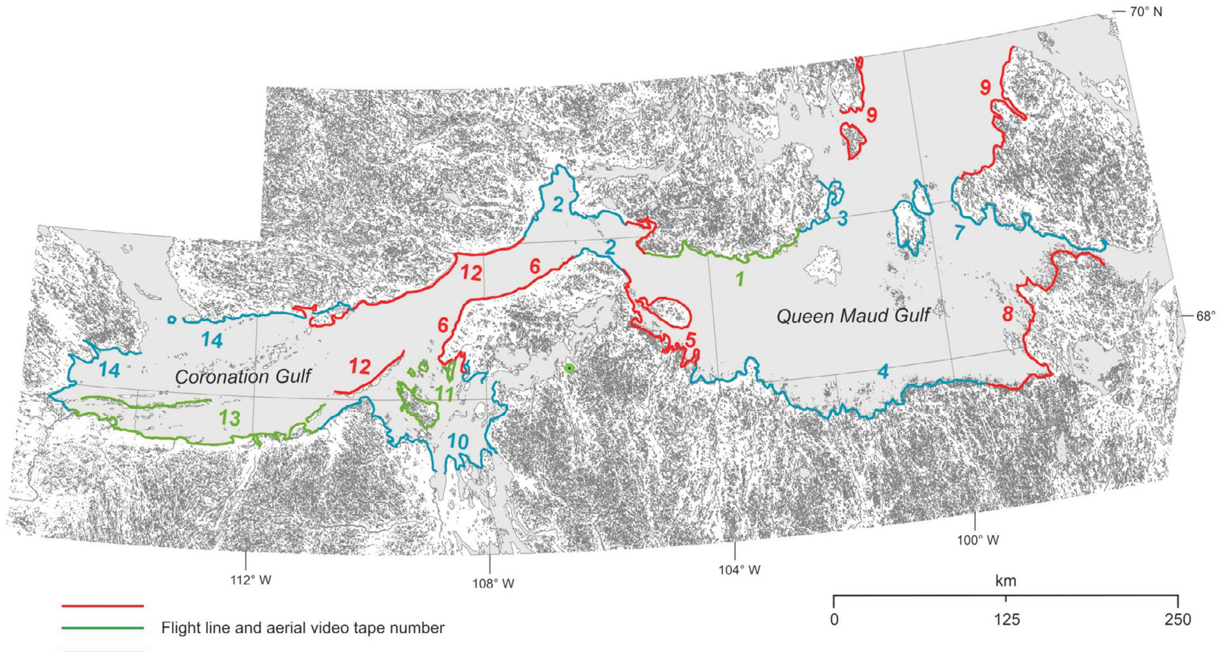

Figure 2. Location map showing flight lines and tape numbers for the 1994 aerial video coverage of Coronation Gulf and Queen Maud Gulf, Nunavut. Tapes 2, 6, 10, 11, 12, 13 and 14 will be used for mapping physical shoreline features for Coronation Gulf.

The mapping, interpretation and transfer of the physical features of the shoreline into the existing ArcGIS-based CanCoast database will enable user-defined queries of specific coastal forms and materials and provide information on accessibility to proposed port sites. The coastal classification will comprise a single layer of information, which can then be used to understand the variability of this section of coast, to assess coastline sensitivity, to improve the understanding of coastal hazards and to be used as a baseline from which future coastal change can be determined. The mapping and input of Coronation Gulf coastal information into the database is planned to be completed by March 31, 2013.

SPOT mosaic for Coronation Gulf, Nunavut: pilot study for a mosaic of Canada's Arctic coast

In a collaborative project by ESS, CNGO and GeoNet Technologies Inc., a pilot study was initiated to explore the feasibility and uses of a coastal mosaic of SPOT satellite imagery in the Coronation Gulf and to assess the effort required to create a medium resolution optical mosaic of Canada's Arctic coast. The SPOT imagery was chosen because it is freely available from GeoBase® thus derived products are not subject to licensing and can be freely distributed. Additionally, it is available at 10 m resolution in the panchromatic band (resampled from 5 m resolution data) so it shows much more detail than freely available 15 m Landsat (Figure 3). Finally, SPOT imagery is already orthorectified and requires no processing other than mosaicking and colour-matching, thus substantially reducing effort.

The mosaic comprises almost 60 scenes collected between 2005 and 2010. It covers approximately 3000 km of the mainland coast of Nunavut between Coronation Gulf and Queen Maud Gulf, including the community of Kugluktuk, the port site at the Hope Bay mining project and other potential port sites in Grays Bay and Bathurst Inlet (Figures 1, 4). These local sites are influenced by broader regional coastal conditions and processes that can be interpreted from the SPOT satellite imagery. Because the images have been acquired over several years, the mosaic does not represent a single point in time so it cannot be used in a landscape change study or for sea-ice mapping. Nevertheless, placing local areas in a regional context gives pertinent information, which may contribute to safe development on Canada's Arctic coasts.

Accumulations of unconsolidated material, which may represent sources of aggregate on land, can be recognized in the imagery suggesting the mosaic could be of use in targeting areas of aggregate exploration. This is of particular importance in permafrost-rich areas as development requires significant amounts of aggregate.

The pilot study has confirmed that the methodology is proven and it is feasible to construct a mosaic for the Canadian Arctic coast south of the 81st parallel.

Coastal sensitivity analysis to support development

The communities of Kugluktuk and Cambridge Bay, as well as mining port sites at the Hope Bay mining project

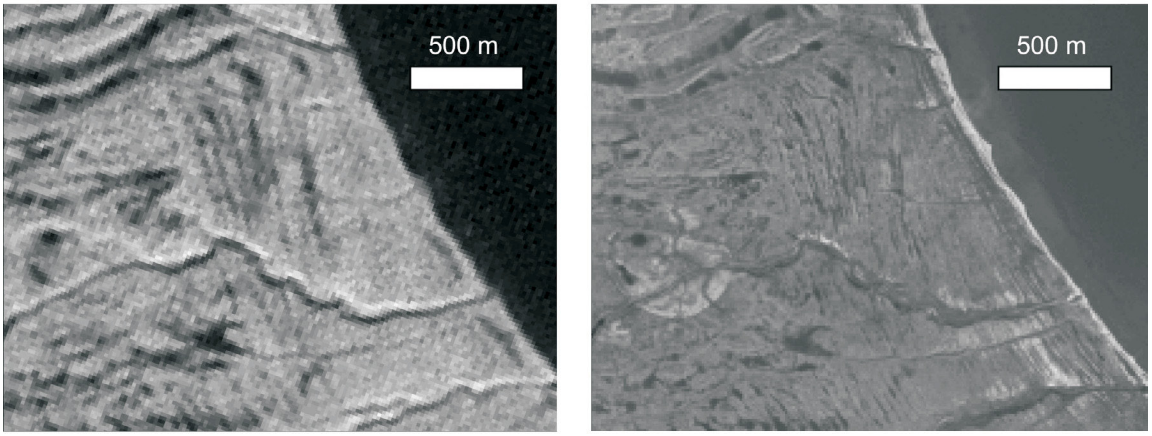

Figure 3. Comparison of 15 m Landsat imagery (left; GeoBase®, 1999–2003) with 10 m SPOT imagery (right; GeoBase®, 2005–2010) for a raised beach ridge plain west of Kugluktuk, Nunavut.

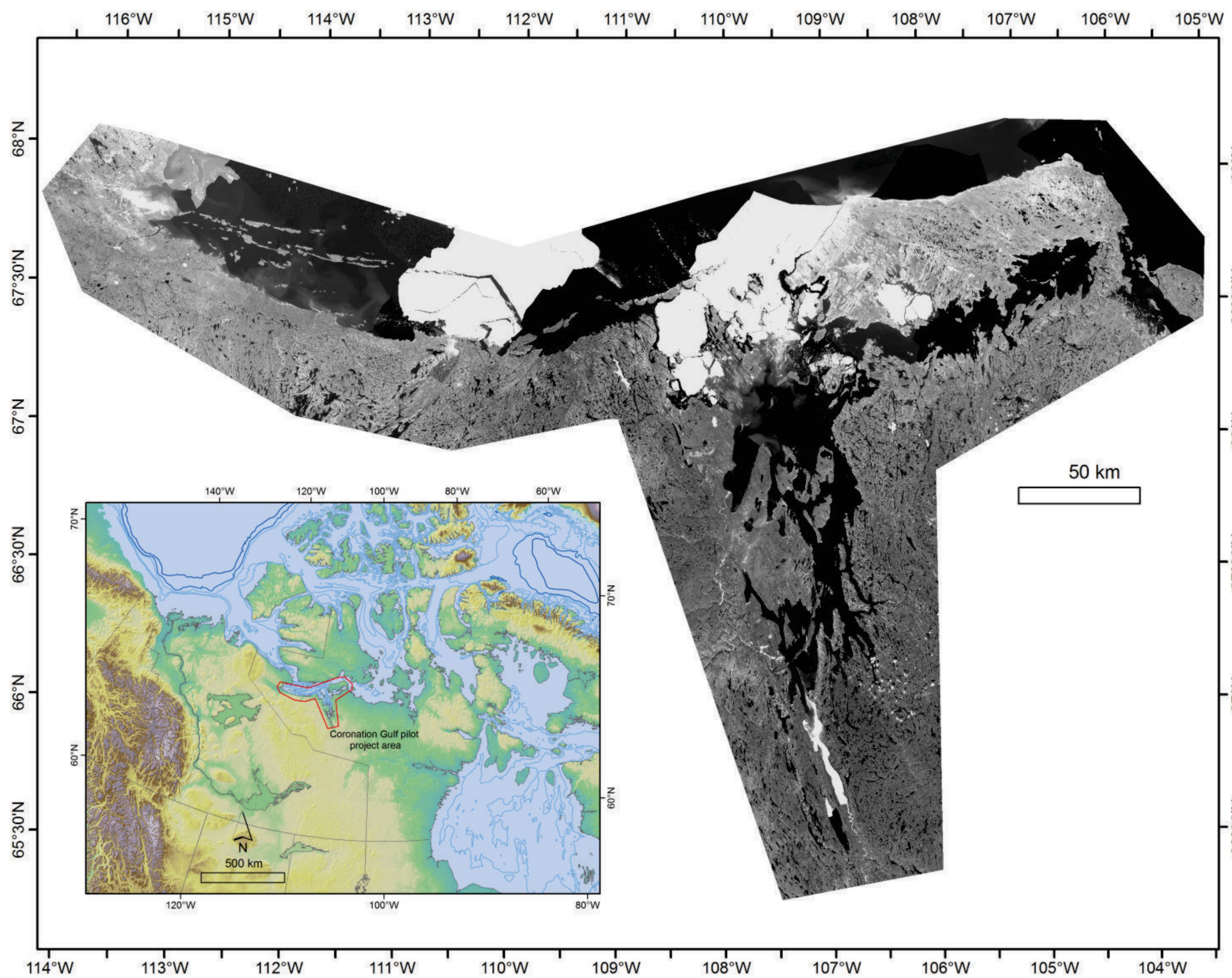

Figure 4. The area in Nunavut covered by the Coronation Gulf SPOT mosaic pilot project (GeoBase®, 2005–2010). Grey tones are land, white areas are sea ice (or lake ice), and black areas are open water.

(existing) and Grays Bay (proposed), were chosen for detailed coastal change studies. The impacts of a warming climate are uncertain, but an assessment of historical coastal change can indicate areas that may be especially vulnerable to future environmental change. In this activity, the position of the coast is compared over time, based on historical airphotos and satellite imagery, to determine areas of high erosional and depositional activity.

Preliminary results at Kugluktuk reveal that the town site has remained relativity stable since the 1950s (Figure 5; Covill, 2012; Whalen et al., 2012), although field investigations show that there is localized bank erosion in town. However, high rates of shoreline retreat (average 0.7 m/yr, maximum 1.3 m/yr) have occurred on either side of the town barge site and on the eastern edge of the Coppermine River. Also, the unconsolidated material surrounding the rocky islands located at the mouth of the river has been reworked and shifted around. In fact, the outer islands appear to be migrating to the west with a net decrease in size by almost 25% over the last 60 years. This suggests that fluvial sediments are bypassing this zone and being deposited farther offshore. It is possible that sediment progradation on coastlines farther to the west is favoured by this source of sediment.

This work is planned to be completed by March 31, 2013, as a deliverable to the CCG and the Environmental Geoscience programs.

Coastal hazard mapping in Iqaluit

Fieldwork for coastal hazard mapping in Iqaluit was undertaken in 2010 and 2011, with the aim of supporting sustainability planning and climate change adaptation initiatives for the City of Iqaluit and the Government of Nunavut. The work was funded through the ArcticNet Networks of Centres of Excellence of Canada (NCE) program, the C-Change International Community-University Research Alliance (ICURA) project, Memorial University (Department of Geography) and the Aboriginal Affairs and Northern Development Canada's Northern Scientific Training Program. It also included an M.Sc. thesis (S.V. Hatcher, Memorial University). Fieldwork was conducted under the CCGP and was run collaboratively by members of the Geological Survey of Canada and CNGO.

Real time kinematic (RTK) GPS surveying of the coastline was carried out for geomorphological mapping of the tidal flats of Koojesse Inlet and to determine the foundation elevations of waterfront structures. Marine mapping was conducted from a chartered freighter canoe using sidescan sonar and single-beam echo sounding. This was combined with acoustic doppler current profilers moored in three locations off the flats, and four tide and wave recording instruments running continually until early November 2011. A detailed report on all field activities will be published in a GSC open file.

The coastline of Iqaluit is dominated by the subarctic tidal flats of Koojesse Inlet, composed of a sand-silt veneer un-

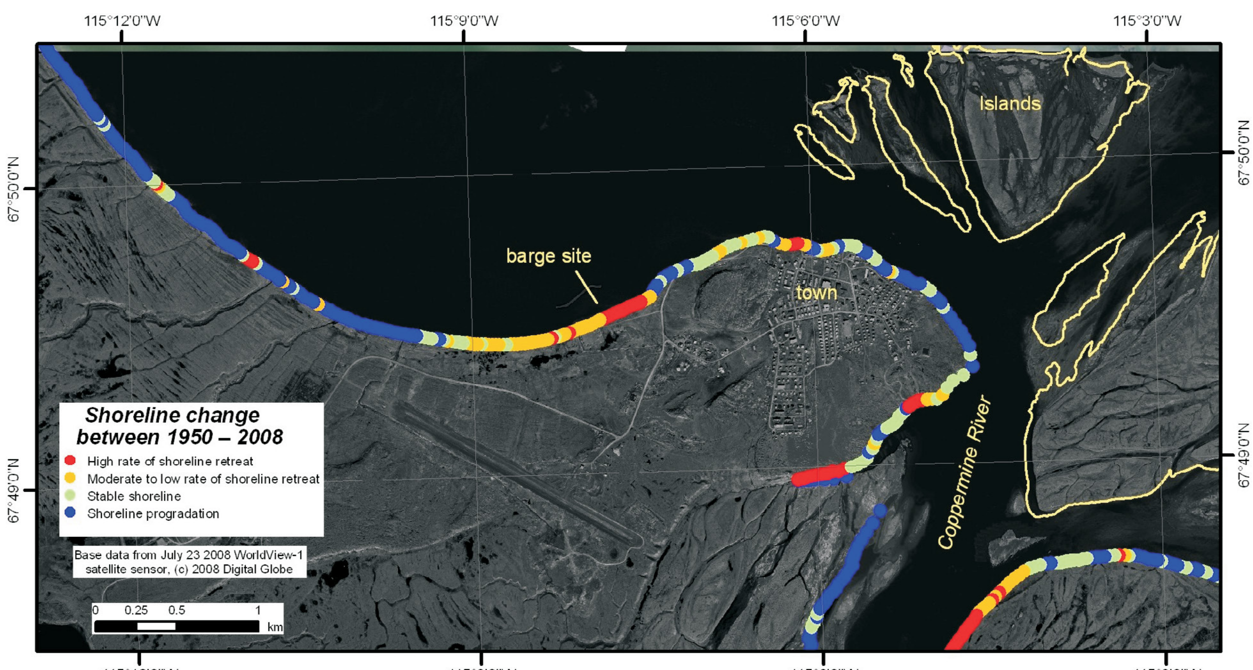

Figure 5. Measurements of shoreline change calculated from comparison of historic airphotos and current satellite imagery at Kugluktuk, Nunavut. The yellow lines show the shorelines of the islands in 1950. Image from DigitalGlobe, Inc., 2008.

derlain by stiff glaciomarine clay. Despite a tidal range of 8–12 m, current velocities are low and wave energy is constrained by the limited fetch. Storm surge effects are limited and extreme water levels are largely a function of tidal variance.

Prior to the 1970s, there was very little waterfront development in Iqaluit. Since that time, a wide array of private, municipal, federal and subsistence infrastructure has been constructed close to the shore. There is now no buffer between historical high waters and the foundation elevations of some waterfront infrastructure (Figure 6). Sea level is projected to rise by as much as 0.8 m in Iqaluit by the year 2100 (James et al., 2011). This has the potential to increase the frequency of flooding in coming decades (Hatcher et al., 2010).

Most coastal use in the city is related to subsistence hunting and fishing. The informal infrastructure (sheds and equipment) that supports these activities is vulnerable to extreme sea-level events (see ‘Shore infrastructure’ in Figure 6). At the same time, the proximity and density of formal development behind the beach may preclude relocation of subsistence infrastructure as an adaptation measure. Some roads, homes, drainage and pipeline facilities are within the reach of extreme tides today. The projected water-level probability distribution with 0.8 m of sea-level rise would pose some risk to the seaward end of the cemetery, additional roads and housing, and the visitor centre (Figure 6).

Sea level projections

Globally, sea level may rise by a metre or more by the year 2100. Locally, however, sea-level change depends on vertical land motion. Land uplift can reduce the amount of relative sea-level rise experienced at a location, and land subsidence can increase the amount of relative sea-level rise. In an earlier study carried out in co-operation with CNGO, sea level projections were provided for five communities of the Nunavut Climate Change Partnership (James et al., 2011). For some communities, such Arviat and Rankin Inlet, land uplift rates are large enough that relative sea level is likely to continue to fall throughout this century.

In previous work, vertical land motion was estimated through observations of past sea-level change because sea-level observations are abundant throughout most of the Canadian Arctic and because the GPS network of permanent continuous trackers was relatively sparse. The GPS network in northern Canada is, however, becoming denser. Globally, GPS is the preferred method of determining vertical crustal motion. Consequently, efforts have been made to generate sea-level projections using uplift rates from GPS. As part of this effort, the CCGP, in partnership with the Geodetic Survey Division of the Canada Centre for Remote Sensing, has contributed towards the installation of a continuous GPS tracker at Rankin Inlet and reoccupation of campaign benchmark sites in Rankin Inlet and Arviat. The new continuous tracker and reoccupation of campaign benchmarks will lead to better observations of crustal uplift on the west coast of Hudson Bay.

Figure 7 shows sea-level projections for two communities where GPS trackers have been established for a sufficiently long time that the uplift of the bedrock is relatively well determined. For Kugluktuk, the projection using the GPS uplift rate is very similar to that reported by James et al. (2011), showing the agreement in vertical crustal motion at this location derived from GPS and from paleo–sea-level observations. The projection for Baker Lake is new. The community of Baker Lake is located inland, on the freshwater Baker Lake, and is supplied by ocean-going ships entering Baker Lake through Chesterfield Inlet. The sea-level

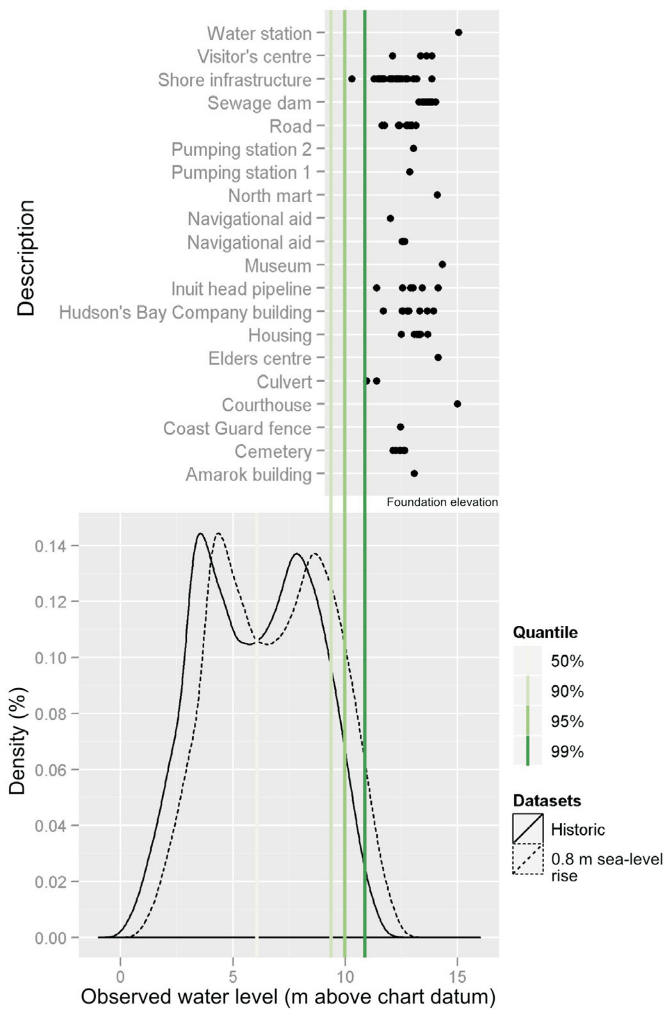

Figure 6. Results of coastal infrastructure surveys in Iqaluit, Nunavut. The lower graphs shows the distribution of historical tide-gauge records, with the 90, 95 and 99 percentiles indicated. The upper graph shows foundation heights of infrastructure found along the coast, divided into categories based on primary use.

projection at the outflow of Baker Lake into Chesterfield Inlet is expected to be similar to the projection for the community of Baker Lake, shown in Figure 7. It shows that sea level will continue to fall throughout this century, indicating a shallowing of the approaches to the Baker Lake outflow.

Economic considerations

The coastal zone is of paramount economic, social and cultural importance in Nunavut. Road and rail networks to southern Canada are lacking. Air transportation is a cost-effective way of transporting persons and valuable goods but, with the exception of diamonds, it is not an economical means of transporting the raw or refined outputs of the mining and oil and gas industries. Consequently, access to, and utilization of, the coastal zone is especially important for resource industries in Nunavut.

Ports, wharfs and landing sites at communities and at sites developed by companies are key locations. Through them, goods and supplies flow into Nunavut. They support communities, enable resource exploration and the development and operation of mines, and, in the future, may support the development and extraction of oil and gas reserves. At present, ore is delivered to ocean-going ships and shipped south at Baker Lake, through the lake outlet and Chesterfield Inlet. In the past, ore was shipped from Little Cornwallis Island, Nanisivik (Baffin Island) and Rankin Inlet and oil was shipped from the Bent Horn field on Cameron Island. Several new mining projects are in development in Nunavut and the number of ports exporting ore is expected to grow. In Nunavut, 26 of 27 settlements are coastal communities. The 27th, Baker Lake, is supplied by ocean-going ships and shares many of the characteristics of a coastal community. Numerous traditional hunting and fishing activities take place at or near the coast.

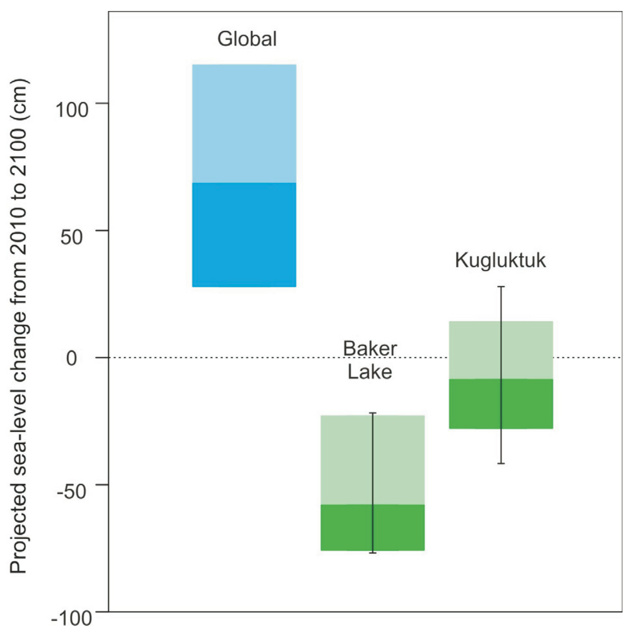

Figure 7. Projected changes to mean global sea level (left) and site-specific projections for the communities of Baker Lake and Kugluktuk, Nunavut, from 2010 to 2100. The site-specific projections take into account vertical land motion, as well as the uneven redistribution of meltwater in the global oceans. The dark shading on the global sea-level bar has a minimum value of 28 cm, which corresponds to the late 20th century sea-level rise rate of 3.1 mm/yr. The maximum value is 69 cm, which corresponds to the Intergovernmental Panel on Climate Change's (IPCC) maximum emissions scenario plus an additional contribution due to ice dynamics, as described in the IPCC 4th Assessment Report (Meehl et al., 2007). The light shading includes later 'semi-empirical' projections of larger amounts of sea-level rise. The black lines in the community-specific projections indicate the uncertainty arising from the measurement of vertical crustal motion. See James et al. (2011) for more information.

The central role of coasts and the importance of coastal infrastructure in Nunavut require an understanding of the complex and distinctive features of Arctic coastal systems, including the potential impacts of climate change on coastal stability and hazards. The activities described here are focused on regions where there is substantial resource industry activity, such as Coronation Gulf, or where there is a population base, such as Iqaluit. They will

- provide information on the coastal stability and hazards of human settlements (Kugluktuk and Iqaluit);
- have the potential to contribute to the assessment of aggregate resources and the nature and accessibility of candidate port sites (Coronation Gulf); and
- provide information on expected changes to local relative sea level that differ substantially from projected changes to mean sea level (with implications for future under-keel depths and navigability, particularly in western Hudson Bay).

Collectively, this information will contribute to reducing the risk to existing and proposed future coastal infrastructure in Nunavut.

Conclusion

Improved characterization of the coastline and coastal processes throughout Nunavut arms decision-makers with knowledge to better plan for development and protect existing infrastructure from the impacts of climate change. Natural Resources Canada and the Canada-Nunavut Geoscience Office, through the Climate Change Geoscience Program, are providing this knowledge and working with local and territorial governments to ensure its uptake.

Acknowledgments

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Nunavut Carving Stone Deposit Evaluation Program (2010–2013): third year results

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Abstract

The Nunavut Carving Stone Deposit Evaluation Program is a collaborative project led by the Government of Nunavut, Department of Economic Development & Transportation and includes the Canada-Nunavut Geoscience Office, the University of Manitoba and Natural Resources Canada. The primary goals of this four-year program are to verify the quality and size of hand-mined carving stone deposits and to identify new deposits throughout Nunavut. To date, many sites of carving stone resources in two of the three regions in Nunavut have been evaluated. Deposits have been characterized by artisan-derived quality, tonnage and composition. A total of 75 sites in proximity to 19 communities were visited and evaluated. A total of 45 carving stone deposits have been defined, of which nine quarries and a further nine undeveloped deposits contain substantial resources of high-quality stone. Sites and deposits in the Kitikmeot Region (western mainland) are to be evaluated in 2013. Two ‘major’ deposits, previously unknown to the nearest communities, have been confirmed: one in the Kivalliq Region (eastern mainland) west of Repulse Bay and one west of Hall Beach in the Qikiqtaaluk Region (Arctic islands). These findings suggest that Nunavut will have sufficient resources of carving stone to access for many years to come. Research on specific characteristics (e.g., geochemical, isotopic signatures) of selected deposits is being conducted through the University of Manitoba. These results will assist in determining which characteristics of the various rock types are most important in determining suitability as carving stone.

Résumé

Le Programme d’évaluation des gisements de pierre à sculpter du Nunavut est un projet conjoint dirigé par le ministère du Développement économique et des Transports du Nunavut et auquel participent le Bureau géoscientifique Canada-Nunavut, l’Université du Manitoba et Ressources naturelles Canada. Les principaux objectifs de ce programme de quatre ans sont de vérifier la qualité et la taille des gisements de pierre à sculpter exploités manuellement et de trouver de nouveaux gisements dans tout le Nunavut. À ce jour, bon nombre des sites de pierre à sculpter dans deux des trois régions du Nunavut ont été évalués. Les gisements ont été caractérisés en termes de qualité évaluée par les artisans, de tonnage et de composition. En tout, 75 sites à proximité de 19 collectivités ont été visités et évalués. En tout, 45 gisements de pierre à sculpter ont été identifiés, dont neuf carrières et neuf autres gisements non exploités contenant d’importantes quantités de pierre à sculpter de haute qualité. Les sites et les gisements dans la région de Kitikmeot (partie continentale occidentale) doivent être évalués en 2013. L’existence de deux « grands » gisements, jusque-là inconnus des collectivités les plus proches, a été confirmée : un dans la région de Kivalliq (partie continentale orientale) à l’ouest de Repulse Bay, et un à l’ouest de Hall Beach dans la région de Qikiqtaaluk (îles de l’Arctique). Ces résultats semblent indiquer que le Nunavut disposera de ressources suffisantes en pierre à sculpter pour de nombreuses années à venir. L’Université du Manitoba procède à des recherches sur les caractéristiques spécifiques (p. ex., géochimie, signatures isotopiques) de gisements choisis. Les résultats obtenus aideront à identifier chez les différents types de roches les caractéristiques les plus importantes servant à déterminer celles qui conviennent le mieux comme pierre à sculpter.

This publication is also available, free of charge, as colour digital files in Adobe Acrobat® PDF format from the Canada-Nunavut Geoscience Office website: http://nunavutgeoscience.ca/.

Introduction

The Nunavut Carving Stone Deposit Evaluation Program (NCSDEP) is a collaborative project led by the Government of Nunavut, Department of Economic Development & Transportation (GN-EDT) and includes the Canada-Nunavut Geoscience Office (CNGO), the University of Manitoba (through graduate research) and Natural Resources Canada (NRCan) through the Polar Continental Shelf Program (PCSP). This program also relies on assistance from local carvers in each community.

Article 19.9.1 of the Nunavut Land Claims Agreement (NLCA) requires government to inform Inuit of discoveries of any deposits of carving stone on Crown lands. Article 19.9.4 establishes the right of Inuit to gather carving stone, stating "An Inuk shall have the right to remove up to 50 cubic yards per year of carving stone from Crown lands without a permit". In 2007, the GN-EDT released *Ukkusiksaqtarvik: The Place Where We Find Stone:* Carving Stone Supply Action Plan (Nunavut Department of Economic Development & Transportation, 2007a). The action plan was prepared in connection with *Sanujgait: A Strategy for Growth in Nunavut's Arts and Crafts Sector* (Nunavut Department of Economic Development & Transportation, 2007b). The action plan was developed to contribute to the arts and crafts sector's strategic goal of increasing the quality of Nunavut art. It presented ideas to address a number of challenges for the carving stone and arts sectors within Nunavut, with one challenge being the lack of accurate information about carving stone quarry sites. The NSCDEP (2010–2013) is the territorial and federal government's response to this challenge identified in the action plan and also to Article 19 in the NLCA.

A primary goal of, and the carvers' stated priority for, the Nunavut Carving Stone Deposit Evaluation Program is to identify new deposits of carving stone in Nunavut. Since the initiation of the program in 2010, sites across two regions of the territory have been visited and the number of known substantial deposits of carving stone in Nunavut has doubled. All evaluated deposits have been characterized by artisan-derived quality, tonnage and composition.

Community consultations

Nunavut's elders and carvers were consulted with regards to local carving stone localities and were generous with sharing their considerable traditional knowledge. As of December 2012, citizens in all 25 communities in Nunavut have been consulted through the NCSDEP. The program's efforts to date have been conducted in the Kivalliq and Qikiqtaaluk regions of the territory, with 75 carving stone sites evaluated within reach of 19 communities. The five communities in the Kitikmeot Region and Sanikiluaq (Belcher Islands) of the Qikiqtaaluk Region, were consulted in October 2012 and will be the focus of the summer 2013 field season. Table 1 lists the local carvers and guides who were consulted for the Kivalliq and Qikiqtaaluk regions.

In the program's first year (2010), 29 carving stone sites were evaluated in proximity to Arviat, Chesterfield Inlet, Coral Harbour, Repulse Bay and Whale Cove. In 2011, 21 carving stone sites were evaluated near the communities of Cape Dorset, Hall Beach, Igloolik, Iqaluit, Kimmirut, Pangnirtung, Pond Inlet and Repulse Bay. In 2012, 25 sites were evaluated close to Arctic Bay, Baker Lake, Clyde River, Iqaluit, Pond Inlet and Rankin Inlet; sites selected for evaluation in proximity to Qikiqtarjuaq could not be visited due to inclement weather.

Characterization of resources

Carving stone resources are not yet managed by the governments of Canada or Nunavut. The allowed annual extraction of 50 cubic yards of carving stone for an Inuit carver (as set out in the NLCA) is equal to 103 192 kg, or 103 tonnes. More simply, one cubic yard of stone is approximately equivalent to what can be gathered and transported on an average qamutik or sled with a length of 2.3 m.

Through the NCSDEP, Nunavut's carving stone deposits have been sorted into five categories based on the size of the deposit and the amount of stone that may be hand-mined from the deposit (Table 2). The progression of a quarry can be classified as recently opened to mature to abandoned. The evaluations undertaken through the NSCDEP involved brief site visits of only a few hours. Generally, the bigger the deposit, the more it is shared among carvers.

The NCSDEP staff and the carvers established a system for four distinct qualities and artisanal suitability of a carving stone (Table 3). A carbide hand file is the Nunavut carver's universal tool for testing the quality of the carving stone. In determining the suitability of stone for carving, many experienced carvers compare the gathered materials against excellent-quality serpentinite, such as the rock found in the Korok Inlet deposits east of Cape Dorset (Figures 1, 2). All grades of carving stone can be carved using carbide tools; all grades can be ultimately polished with wet sandpaper. Contemporary full-time carvers cut, grind and polish carving stone with diamond tools. Project carver J. Ell (who has been part of NCSDEP from 2010 to 2012) has asked carving stone gatherers to never use explosives when gathering carving stone because the resulting fracturing causes damage to the rocks.

An additional goal of the NCSDEP was to identify deposits with, and screen rocks for, the presence of asbestos. Asbestos content in a carving stone resource is of particular concern to artists as it may be a health hazard. Traces of asbestos have been reported in three known quarries that have been used historically by carvers. These deposits are the Murchison River quarry in the Kitikmeot Region; the

Table 1. Local carvers and guides who assisted in the Nunavut Carving Stone Deposit Evaluation Program (NCSDEP) 2010–2012, from the Kivalliq and Qikiqtaaluk regions, Nunavut.

Carvers and guides	Community	Year	Region
Robert Hallauk (carver)	Arviat	2010	Kivalliq
Salomonie Pootoogook (carver)	Baker Lake	2010 2012	Kivalliq
Elie Kimmaliadjuk (elder)	Chesterfield Inlet	2010	Kivalliq
Johnny Kataluk (elder), Mark Paniyuk (hunter)	Coral Harbour	2010	Kivalliq
Jocham Karvik (carver), Harry Ittinaur (quarrier)	Rankin Inlet	2010 2012	Kivalliq
John Ivalutanar (elder), Paul Malliki (carver)	Repulse Bay	2010	Kivalliq
Sam Arualuk (elder)	Whale Cove	2010	Kivalliq
Oluyuk Naqitarvik (carver), Paul Oqalluq (carver)	Arctic Bay	2011 2012	Qikiqtaaluk
Qimiataq Nunusuitaq (carver), Nuna Parr (carver), Ajaganyuk Shaa (carver), Jimmy Manning (soapstone manager)	Cape Dorset	2011	Qikiqtaaluk
Ilkoo Anguitjuak (elder), Peter Paneak (carver)	Clyde River	2011 2012	Qikiqtaaluk
Looty Pijamini (carver)	Grise Fiord	2011	Qikiqtaaluk
Ike Angotialuk (carver)	Hall Beach	2011	Qikiqtaaluk
Eugene Ipkarnak (elder)	Igloolik	2011	
Jerry Ell (Project Carver, former Iqaluit resident, now residing in Rankin Inlet)	Iqaluit	2010 2012	Qikiqtaaluk
Sandy Akavak (elder)	Kimmirut	2011	Qikiqtaaluk
Jako Ishulutaq (carver), Philipoosie Kooneeliusie (carver)	Pangnirtung	2011	Qikiqtaaluk
Moses Koonark (carver), Sam Omik (hunter)	Pond Inlet	2011 2012	Qikiqtaaluk
Gary Arnaqq (elder), Markossie Audlakiak (carver)	Qikiqtarjuaq	2011	Qikiqtaaluk
Simon Idlout (carver)	Resolute Bay	2011	Qikiqtaaluk

Tawsig Fiord deposit on the north shore of the Hall Peninsula, Qikiqtaaluk Region; and a large quarry in the Clyde River area, Qikiqtaaluk Region. One new occurrence of asbestos in carving stone material was recently reported by Agnico-Eagle Mines Ltd. in portions of the rock uncovered in the open pit of the Meadowbank gold mine near Baker Lake (Kivalliq Region).

Results (2010–2012)

The NCSDEP results to date have determined that there are at least 45 deposits throughout Nunavut accessible for carving stone resources. Eighteen of these quarries and deposits contain substantial resources. These 18 are shown in Figure 2 and outlined in Tables 4–6. There are two major, undeveloped deposits of good to excellent quality of stone that have been confirmed by the NCSDEP work: Kovic, located in the Kivalliq Region west of Repulse Bay, and Kingora, located west of Hall Beach in the Qikiqtaaluk Region (Figure 1). The results suggest that Nunavut has sufficient resources of carving stone for years to come.

The large to major deposits of carving stone in eastern Nunavut appear to be associated with the Prince Albert Group rocks of Proterozoic age, as determined by earlier geological mapping (e.g., Murphy, 1973; Caine, 1977; Gibbins, 1987, 1988; McDermott, 1990, 1992; Zaleski et al., 1999) and by work done through the NCSDEP. The Prince Albert Group extends from Baker Lake of central Nunavut to the Melville Peninsula and onto central Baffin Island (Figure 2). The deposits evaluated through the NCSDEP that are likely associated with the Prince Albert Group include the large serpentinite formation in the open pit at the Meadowbank gold mine, the major Kovic deposit

Table 2. Preliminary estimates for size and tonnage characteristics of carving stone resources, Nunavut.

Size	Supply	Volume	Comments
Tiny	Individual use	1–3 tonnes	Many such sites commonly contain material that is difficult to extract.
Small	Individual use	Hundreds of tonnes	A carver is permitted to collect up to 103 tonnes in a year.
Modest	Community supplier	Up to thousands of tonnes	A resource this size will service a community.
Large	Regional supplier	Up to ten of thousands of tonnes	A hand-mined resource this size can service its nearest communities for decades.
Major	Nunavut-wide	Millions of tonnes	A resource this size could potentially service all of Nunavut for many years.

Table 3. Quality and artisan suitability of carving stone, Nunavut.

Grade	Hardness	Characteristics	Availability
Excellent	2.0–2.5	Excellent consistency, very tough or interlocking matrix, rock holds fine detail, good colour, polishes well	Available in large blocks
Good	2.5+	Lacking of one of above standards	
Fair	3	Lacking in one or more of above standards	
Poor		Rock still will take a file, variable consistency	Small pieces

150 km inland from Repulse Bay, the major Kingora deposit 120 km inland from Hall Beach and the large Koonark carving stone deposit at Mary River (Figure 2). Additionally, the Committee Bay volcanic belt in the eastern Kitikmeot Region is underlain by rocks of the Prince Albert Group (Sandeman et al., 2001). It is unknown at this time if the ultramafic rocks associated with the Committee Bay volcanic belt will yield substantial carving stone resources for the eastern Kitikmeot Region.

Kivalliq Region

Carving stone resources were confirmed or augmented in the vicinity of Baker Lake, Coral Harbour, Rankin Inlet and Repulse Bay (Tables 4–6, Figure 2). Arviat, Chesterfield Inlet and Whale Cove remain impoverished for carving stone resources with little or no stone remaining or available only in tiny to small deposits. Through the NCSDEP, 41 sites in proximity to the seven hamlets in the Kivalliq Region were evaluated.

The hamlet of Baker Lake has traditionally collected stone from the Jigging Point quarry, located 56 km from the community. Additional resources are available for Baker Lake from an undeveloped modest-sized carving stone deposit in the Schultz Lake area. Furthermore, Agnico-Eagle Mines Ltd. (AEM), the owners of the Meadowbank gold mine located approximately 100 km from the community, have supplied limited amounts of carving stone from the open pit to the Kivalliq communities. However, with the recent discovery of asbestos seams in the hostrock serpentinite, the carving stone sharing from the company mine site to the community carvers may stop, or be suspended, until further research is undertaken.

Visits facilitated by AEM at the Meadowbank gold mine assisted the NCSDEP in the evaluation of serpentinite formations on the mine property previously mapped by the Geological Survey of Canada (Zaleski et al., 1999). A total of more than 2500 kg of suitable serpentinite material exposed in the open pit was selected by carvers to be used in the hamlet of Baker Lake. However, except for the material in the open pit, serpentinite formations examined elsewhere through NCSDEP work did not prove to be favourable carving stone. AREVA Resources Canada Inc. (AREVA) invited the NCSDEP staff to sample the drillcore recovered on the Kiggavik property 80 km west of Baker Lake. A soft rock was discovered in the drillcore, referred to locally as ‘pipestone’, which comprises kaolinite-altered material. If this material proves suitable for artisan use, AREVA may be able to incorporate the recovery of this stone into their future mine site planning.

For the hamlet of Coral Harbour, carving stone resources are locally available to carvers from five carving stone deposits and one limestone site. Two of these are undeveloped modest-sized deposits near Coral Harbour. The Paniyuk site, located 19 km north of the hamlet, is composed of good-quality, dark green stone. The Qilaliaqvik deposit, located 74 km northeast of Coral Harbour on the coast near the Ascension Islands, is dark green stone of fair quality. Neither of these two deposits is listed in Tables 4-6 because of their modest size.

During the late 1950s and early 1960s, carving stone had been brought to the surface from the underground workings of the formerly producing North Rankin nickel mine in the hamlet of Rankin Inlet. A 100 m wide serpentinite sill had been intersected in the workings while extracting the nickel-copper ore. A 1989 diamond drilling exploration report (Hassell, 1989) also indicates that a near-surface soapstone deposit is accessible in the same area.

Substantial carving stone resources were determined and confirmed to be available to Repulse Bay carvers from six soapstone deposits and one marble site. A major carving stone deposit (Kovic) of extraordinary size (likely more than 1 Mt) was confirmed 150 km inland from Repulse Bay (Table 6).

Qikiqtaaluk Region

Through the NCSDEP, 34 carving stone sites in proximity to 12 communities in the Qikiqtaaluk Region were evaluated. However, many additional sites known to local carvers could not be evaluated due to poor weather. Nine of the twelve communities—Arctic Bay, Cape Dorset, Clyde River, Hall Beach, Igloolik, Iqaluit, Kimmirut, Pangnirtung and Pond Inlet—have new or augmented carving stone resources in the vicinity of their community (Figure 2).

Three communities in the Qikiqtaaluk Region—Qikiqtarjuaq, Resolute and Grise Fiord—remain impoverished for carving stone resources. The nearest carving stone resource

Figure 1. Selected large deposits and occurrences confirmed by the Nunavut Carving Stone Deposit Evaluation Program (NCSDEP): **a)** Repulse Bay's Kovic deposit; **b)** Pond Inlet's Koonark deposit at Mary River; **c)** Cape Dorset's Andrew Gordon Bay marble; **d)** Tatsituya deposit at Aberdeen Bay, 160 km west of Kimmirut; **e)** Cape Dorset's Kangiqsuqutaq quarries at Korok Inlet; **f)** Kangiqsuqutaq Lower Quarry; **g)** Clyde Inlet's marble quarry; **h)** back harbour of Repulse Bay, Naujaat deposit.

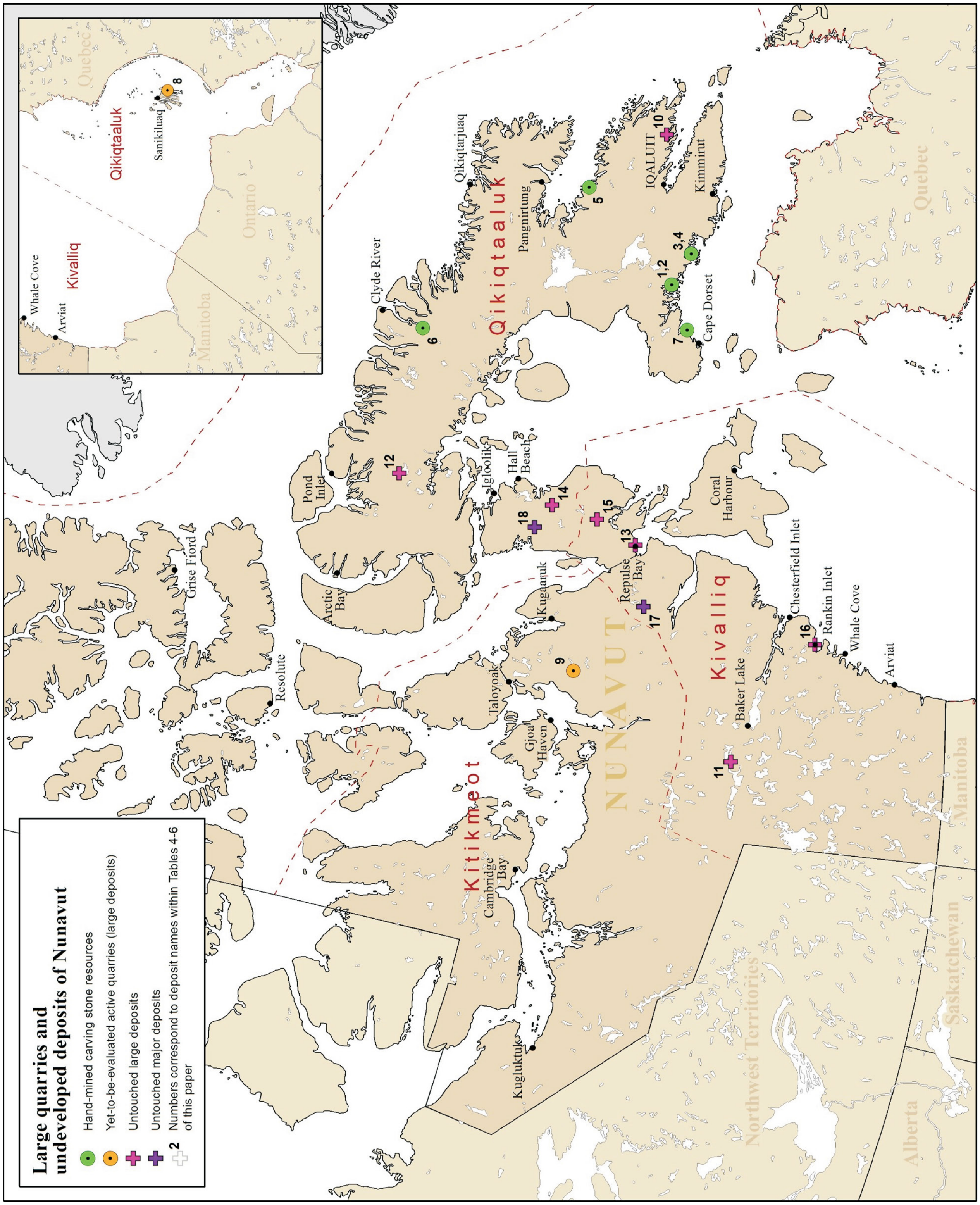

Figure 2. Large quarries and undeveloped deposits of Nunavut; numbers correspond to site numbers as listed in Tables 4–6.

Table 4. Characteristics of deposits and occurrences confirmed by the Nunavut Carving Stone Deposit Evaluation Program (NCSDEP) 2010–2012, corresponding to numbers 1–9 on Figure 2.

Map	Name	Region	Proximity to community	Latitude/ Longitude	Rock	Quality	Notes and recommendations
	Hand-mined carving stone resources						
1	Kangiqsuqutaq, Korok Inlet, Lower Quarry	Qikiqtaaluk	160 km east of Cape Dorset	64d 23m 50s N, 73d 19m 10s W	Serpentinite, streaked yellowish brown to dark green soapstone	Excellent	Lower Quarry is world's largest Inuit hand-mined excavation—now abandoned after 70 years of use; this quarry is debris filled; recommend ground magnetic survey and carver-geologist team mapping of area.
2	Kangiqsuqutaq Qullimi, Korok Inlet, Upper Quarry	Qikiqtaaluk	160 km east of Cape Dorset	64d 23m 50s N, 73d 19m 10s W	Serpentinite	Excellent	This Upper Quarry is now being used; it is mature and debris impacted.
3	Tatsituya, Aberdeen Bay	Qikiqtaaluk	160 km west of Kimmirut	63d 45m 29.7s N, 72d 10m 55.8s W	Altered marble to apple-green, soft soapstone	Excellent	Recommend geophysical surveys and carver-geologist team mapping the area.
4	Tatsitui Tiniiniya, Aberdeen Bay	Qikiqtaaluk	160 km west of Kimmirut	63d 46m 02.9s N, 72d 11m 55.8s W	Serpentinite, dark green soapstone	Good	Ledge in tidal flat; gathering is accessible by boat from serpentinite ledge at low tide with untouched similar material onshore; recommend geophysical surveys and carver-geologist team mapping of area.
5	Opingivik	Qikiqtaaluk	120 km south of Pangnirtung	65d 15m 01.6s N, 67d 04m 25.2s W	Serpentinite, dark green to black soapstone	Excellent	Recent community-used quarry, debris impacted, near tidewater; community quarry with potential to be a regional supplier; recommend ground magnetic survey of locale for future development.
6	Clyde River marble	Qikiqtaaluk	80 km southwest of Clyde River, 5 km inland	69d 48m 52.2s N, 70d 37m 44.9s W	Pink marble	Good	Minor usage; community-sized deposit with untouched green marble and black marble.
7	Andrew Gordon Bay marble	Qikiqtaaluk	40 km east of Cape Dorset	64d 23m 29s N, 75d 43m 40s W	White marble with lesser amounts of rose, yellow and light pastel colours	Good	Minor recent usage; 2 m wide band exploited from 30 m wide marble formation on tidewater; many linear kilometres of marble formation occur inland and are untested; mostly vertical-dipping marble formations.

Table 5. Characteristics of deposits and occurrences confirmed by the Nunavut Carving Stone Deposit Evaluation Program (NCSDEP) 2010–2012, corresponding to numbers 10–16 on Figure 2.

Map	Name	Region	Proximity to community	Latitude/ Longitude	Rock	Quality	Notes and recommendations
	Yet-to-be-evaluated active quarries (large deposits)						
8	Qullisajaniavik, Belcher Islands	Qikiqtaaluk	48 km southeast of Sanikiluaq	56d 11m N, 79d 53.5m W	Argillite	Good	Mature argillite quarry near tidewater.
9	Murchison River	Kitikmeot	135 km west of Kugaaruk	68d 07m N, 92d 58m W	Serpentinite	Good	Mature, inland soapstone quarry; also accessible to 120–160 km south-southeast of Gjoa Haven, 125 km south of Taloyoak.
	Undeveloped large deposits						
10	Hamlen Bay, Ikatuyak, Hall Peninsula	Qikiqtaaluk	110 km southeast of Iqaluit, 12 km inland from tidewater	63d 13m 51.7s N, 66d 21m 29.5s W	Soapstone, mottled dark pattern	Excellent	Newly discovered by Canada-Nunavut Geoscience Office; accessible by snowmobile; approximately 450 m in elevation.
11	Schultz Lake	Kivalliq	95 km west of Baker Lake, 3 km inland from Schultz Lake	64d 39m 39s N, 97d 52m 12s W	Green soapstone; untouched soft grey stone	Good (green); excellent (grey)	Modest deposit, minor usage of good-quality green soapstone; undeveloped resource of excellent grey soapstone 250 m further west; best stone is on the east and west margins of a set of small, east-west–trending hills.
12	Koonark, Mary River	Qikiqtaaluk	160 km inland and south of Pond Inlet	71d 17m 01s N, 79d 09m 25s W	Dark green to black soapstone	Excellent	New deposit 2012; site is 5 km southeast of Baffinland's Mary River iron ore Deposit No. 1; this resource has the potential to be an additional community quarry; additional small occurrences with a variety of colours also are found in the area; recommend prospecting-mapping of extensive serpentinite belt by team of carver-geologist.
13	Naujaat	Kivalliq	Back harbour of Repulse Bay	66d 32m 03.0s N, 86d 11m 24.6s W	Fine-grained, dark grey serpentinite	Good	Deposit on tidewater; stone is slightly harder than marble.
14	Ajuqutalik River	Qikiqtaaluk	75 km inland southwest of Hall Beach	68d 11m 08.7s N, 83d 10m 46.8s W	Serpentinite, dark green soapstone	Fair	This rock is a harder stone (H = 3.0) with minor amounts of good-grade softer rock; stone is slightly harder than marble with good-quality, soft, grey-coloured sections.
15	Qukiutitalik Lake area	Kivalliq	75 km inland and northeast of Repulse Bay	67d 16m 40.2s N, 84d 27m 14.4s W	White marble outcrop	Good	This rock is a harder stone (H = 3.0).
16	North Rankin mine	Kivalliq	Inside municipal boundaries	62d 48m 51s N, 92d 05m 24s W	Serpentinite sill	Good to unknown near-surface	Good-quality samples at surface from underground workings of the former nickel mine; serpentinite sill was intersected during mining operations; near-surface resources (at a depth of 1–3 m?) under two undeveloped lots next to Health Centre; resource and depth yet to be determined.

Table 6. Characteristics of deposits and occurrences confirmed by the Nunavut Carving Stone Deposit Evaluation Program (NCSDEP) 2010–2012, corresponding to numbers 17–18 on Figure 2.

Map	Name	Region	Proximity to Community	Latitude/ Longitude	Rock	Quality	Notes and Recommendations
	Undeveloped Major Deposits						
17	Kovic	Kivalliq	150 km inland west of Repulse Bay	66d 30m 15.05s N, 89d 35m 06.31s W	Serpentinite, dark green to black soapstone	Good to excellent	Kovic is 1.6 km long and 46 m wide or the size of 100 Korok Inlet quarries
18	Kingora	Qikiqtaaluk	120 km inland southwest of Igloolik and west of Hall Beach	68d 38m 34.8s N, 84d 16m 57.4s W (southern portion)	Serpentinite, dark green soapstone with sections of black and grey	Fair to good to excellent	Kingora is 610 m long and 38 m wide or the size of 40 Korok Inlet quarries; fair to good quality overall with excellent quality sections

to Qikiqtarjuaq is Pangnirtung's Opingivik quarry—a distance of approximately 300 km by snowmobile. Because of the paucity of suitable carving stone resources in proximity to Grise Fiord and Resolute, local carvers are encouraged to prospect other geological targets for potential resources of carving stone.

There are small deposits of marble accessible to Arctic Bay. The NCSDEP staff is recommending mapping of the many small sites of marble adjacent to the Franklin gabbro dikes outcropping around Arctic Bay (Harrison et al., 2011) to determine if there are any potential carving stone resources associated with these rocks.

There are four carving stone deposits in the southern Baffin Island area occurring along the shores between Cape Dorset and Kimmirut that have been traditional carving stone quarries. A serpentinite deposit, Kangiqsuqutaq, at Korok Inlet 160 km east of Cape Dorset, hosts two quarries (Figure 1). The Kangiqsuqutaq Lower Quarry deposit is now abandoned but was the largest and oldest hand-mined excavation for carving stone in Nunavut. This 100 m long site is currently filled with wasterock debris from 70 years of ad hoc gathering by carvers from many communities. The active Kangiqsuqutaq Qullimi Upper Quarry site is a mature quarry and partially filled with debris. Ground magnetometer surveying and future resource mapping by a team of a local carver and geologist is recommended for Korok Inlet.

There are two separate deposits on tidewater at Aberdeen Bay, 160 km west of Kimmirut (Figure 1). The Tatsituya deposit is an excellent-quality, modest-sized, apple green, altered marble quarry that has been worked for more than 50 years and is currently filled with debris. A second serpentinite deposit, Tatsitui Tiniiniya, is found on a rock ledge in a tidal flat. Similar undeveloped material occurs onshore at this locality in the same ultramafic rock unit. An airborne magnetometer and resource mapping survey is recommended at Aberdeen Bay over the marble and ultramafic formations within a north-trending fault structure. Additionally, good-quality white marble occurs at Andrew Gordon Bay on tidewater 40 km east of Cape Dorset.

There are resources of coloured marble available to Clyde River from the community quarry located 80 km from the hamlet. At this quarry, historical gathering of pink marble has occurred during the winter months. Through the NCSDEP, it has been determined that there are also undeveloped green and black marble outcrops adjacent to the quarry. A large, known carving stone deposit in the Clyde River area is suspected to contain asbestos but has not been used by carvers for more than a decade. Testing for asbestos will be performed as part of the NCSDEP.

Through the NCSDEP, it has been determined that there are substantial carving stone resources available to Hall Beach and Igloolik from three undeveloped deposits on the Melville Peninsula. The largest of these is a 1 Mt major deposit (Kingora) of extraordinary size with portions of excellent-quality carving stone. Kingora was confirmed on Crown land 120 km inland in the headwaters of the Kingora River. The other two deposits (Ajaqutalik River, Qukiutitalik Lake) are considered to be large deposits and accessible to both Hall Beach and Repulse Bay. Ground magnetometer surveying and future resource mapping is recommended for these three substantial deposits.

Iqaluit, centred on the Cumberland Batholith (Whalen et al., 2010; Harrison et al., 2011), has been considered historically to have limited amounts of available resources suitable for carving stone. However, following the 2012 field season of the Canada-Nunavut Geoscience Office's Hall Peninsula Integrated Geoscience Project, a modest-sized deposit was identified (Ikatuyak) of excellent-quality serpentinite, as well as several other carving stone occurrences (Budkewitsch et al., 2013; Machado et al., 2013; Senkow, 2013). The smaller occurrences were not visited due to inclement weather; future work will define and evaluate these deposits. However, until such work is completed, Iqaluit carvers will continue to rely on resources supplied by commercial operators hauling excellent-quality stone—with small boats on round trips of up to 1200 km—from the historical quarries on Baffin Island's south coast.

There are substantial carving stone resources available from the Mary River iron ore property (owned by Baffinland and ArcelorMittal) for communities of western Baffin Island and the Melville Peninsula. Koonark is a large undeveloped deposit of good- to excellent-quality dark green to black carving stone and is located 5 km to the southeast of Baffinland's Deposit No. 1. Through the NCSDEP, it has been determined that there are additionally six small carving stone deposits and one modest-sized deposit, all located on the Mary River property, accessible to the hamlet of Pond Inlet. Resource mapping and prospecting is recommended for the serpentinite belt at Mary River.

Abundant resources are available to the hamlet of Pangnirtung from several deposits. The Opingivik quarry is part of a large and mostly undeveloped deposit of excellent-quality stone. Ground magnetometer surveying and resource mapping is recommended.

Fieldwork at possible resource sites identified during Qikiqtarjuaq community consultations could not be performed due to poor weather conditions and the unavailability of local carvers and guides who were otherwise employed. There is a promising carving stone occurrence located across Sunneshine Fiord from the Cape Dyer distant early warning (DEW)–line site. Large boulders of carving stone from gravel pits at Cape Dyer were sampled.

Future work

During the summer 2012 field season, carving stone deposit evaluations were examined in collaboration with the University of Manitoba. Samples were collected and will be systematically evaluated. Although measures of the quality and the criteria for selection of carving stone may be standard among Inuit artists throughout Nunavut and other places, understanding of the geochemical compositions, isotopic signatures and microstructural features of common carving stone varieties may strengthen these criteria and benefit the artisan industry. The carving stone deposits of the Qikiqtaaluk and Kivalliq regions evaluated in 2012 will be thoroughly examined with extensive laboratory analyses. Laboratory analyses should aid in understanding any characteristics of a rock that could dictate its suitability and appropriateness for artisanal carving purposes.

Furthermore, examination of how the carving stones' geochemical signatures and microstructural features are influenced by fluid flow patterns in the middle and upper crust may provide insight into the tectonic settings that occurred at the time of formation of carving stone deposits as well as the common alteration processes. This information could help with prospecting for carving stone because, for example, the characteristics determined by the analysis of excellent-quality carving stone may be recognizable in the field.

Another objective of the research work is to integrate laboratory results (petrography, mineral chemistry and isotope geochemistry), microstructural analyses and estimates of the metamorphic conditions of the selected carving stone deposits with the standard measures (hardness, toughness and colour) of traditional artisanal quality. These factors will all determine the suitability of a deposit for carving material.

The specific carving stone deposits evaluated in 2012 were selected for analyses based on artisanal suitability, size, locality and surface exposure of the deposit. Samples of each deposit, as well as samples of the surrounding country rock, were systematically collected. These samples will be evaluated petrographically using transmitted and reflected light microscopy, to determine mineralogy and also to determine textural relationships of the minerals in the rocks and any microstructural features. These identifiable textural and microstructural features may indicate the overall toughness or brittleness of the carving stone because planar and linear fabrics and fractures or microfractures cause weakness in a rock.

Electron microprobe analyses and scanning electron microscopy will be used for mineral identification because these methods of analysis determine mineral compositions and chemistry. From the compositions, estimates of the metamorphic conditions, such as temperature and pressure, may be calculated. Knowledge of the metamorphic conditions prevailing at the time of rock formation may provide insight into the tectonic environments in which the carving stones were formed, and may also provide insight into the alteration processes affecting the rocks.

Powder X-ray diffraction (XRD) will be used to qualitatively determine the bulk rock chemistry. X-ray diffraction will also be used to identify any asbestos present in the rocks because the presence of asbestos is a potential health concern. Radiometric isotopes will be analyzed to determine the age of carving stone deposits and the timing of metamorphism and alteration processes. In particular, the ^{40}Ar-^{39}Ar method will be used to date specific events. Stable isotope contents, specifically oxygen isotopes, will also be analyzed. These analyses will be performed using secondary ion mass spectrometry and the results will help to identify the source of alteration fluids.

Economic implications

The results of the field evaluations have doubled the amount of known carving stone resources by confirming 45 sites of a sufficiently suitable quality of stone close to communities. Eighteen of the sites confirmed have substantial resources that could service carvers for many years. Generally, quality is more important than quantity. It is rare to find consistently excellent quality coupled with large tonnage (size) in the same deposit.

Confirmed resources of new material adjacent to a community may provide immediate and valuable income to carvers; this potential value-added income may range between $10 and $100/kg. Over time, the value (per kilogram) of the finished product of new material may also increase significantly, subject to acceptance by the arts industry.

Conclusions

The Nunavut Carving Stone Deposit Evaluation Program has confirmed the quality and size of known carving stone resources in two of the three regions of Nunavut. Many sites of carving stone resources have been evaluated, with 75 sites in proximity to 19 communities documented. Deposits have been characterized by artisan quality, tonnage and composition, with 45 resources of carving stone defined. Of these 45 localities, a further 18 deposits have been characterized as containing substantial resources. Nine quarries and a further nine undeveloped deposits contain substantial resources of high-quality stone. Of significant interest, two previously unknown major deposits have been confirmed: one in the Kivalliq Region west of Repulse Bay, and the second west of Hall Beach in the Qikiqtaaluk Region.

The graduate research being conducted through the University of Manitoba will assist in determining which characteristics of the various rock types are most important for suitable carving stone. More work is recommended to validate sites of substantial undeveloped resources, particularly where excellent quality was noted. By using the results of these studies, carvers may have ready access to sufficient resources of stone, and, while gathering, be able to determine and hand-pick the materials most suitable for carving.

The findings to date suggest that Nunavut will have sufficient resources of accessible carving stone for years to come.

Acknowledgments

This overall work, and its results, would not have been possible without the site knowledge of the local carvers and guides; considerable acknowledgments and thanks go to all the carvers and guides involved.

Thanks go to the hamlet administrative officers and employees who helped with the logistics of the community consultations and the field visits.

Several mining companies provided access to their mine and/or exploration sites. In 2012, the field crew received assistance from two mining companies working in the Baker Lake area. Agnico-Eagle Mines Ltd. allowed us access to the Meadowbank mine site and provided shipments of stone from the mine's open pit to Kivalliq Region communities. Shipments of stone required considerable handling by AEM employees; these contributions of time and effort are all greatly acknowledged. AREVA also extended an invitation for the field evaluation team to visit and evaluate drillcore and rocks on the Kiggavik exploration property. Baffinland Iron Mines Corporation also graciously invited the field crew to visit the Mary River iron ore development project in both 2011 and 2012 and provided assistance in the field.

The Polar Continental Shelf Program based in Resolute and charter helicopter companies, namely Custom Helicopters, Trinity Helicopters and Universal Helicopters, provided helicopter support for the majority of the site visits. Considerable thanks and acknowledgments go to the pilots and PCSP for this indispensable service.

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Characterization of ultramafic occurrences on southern Hall Peninsula, Baffin Island, Nunavut, and evaluation of their potential as a source of carving stone

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Senkow, M.D. 2013: Characterization of ultramafic occurrences on southern Hall Peninsula, Baffin Island, Nunavut, and evaluation of their potential as a source of carving stone; *in* Summary of Activities 2012, Canada-Nunavut Geoscience Office, p. 163–168.

Abstract

This study is part of the Canada-Nunavut Geoscience Office's Hall Peninsula Integrated Geoscience Program, a multiyear bedrock and surficial geology mapping program with associated thematic studies. A total of 18 ultramafic occurrences were identified east of Iqaluit on Baffin Island during the 2012 field season; of these, 11 occurrences were identified as peridotite or pyroxenite. The occurrences of interest are olivine- and/or pyroxene-rich, often partially altered to, or containing veins of, serpentine. Four of these occurrences were evaluated in the field as part of this study and will be characterized using petrography and geochemical analysis of major, trace and rare earth elements. These occurrences will also be evaluated as potential sources of carving stone. Interviews will be conducted with one or more experienced Inuit carvers to determine what attributes distinguish a suitable carving stone and whether the samples collected from each site meet these criteria.

Résumé

Cette étude fait partie du Programme géoscientifique intégré de la péninsule Hall, du Bureau géoscientifique Canada-Nunavut, un programme pluriannuel de cartographie du substratum rocheux et de la géologie de surface accompagnée d' études thématiques connexes. En tout, 18 occurrences de roches ultramafiques ont été identifiées à l'est d'Iqaluit sur l'île de Baffin au cours de la campagne d'exploration de 2012, dont 11 ont été identifiées comme étant de la péridotite ou de la pyroxénite. Les occurrences d'intérêt sont riches en olivine ou en pyroxène, et sont souvent partiellement altérées en veines de serpentine ou en contiennent. Quatre de ces occurrences ont été évaluées sur le terrain dans le cadre de cette étude et leurs caractéristiques seront établies à l'aide d'analyses pétrographiques et géochimiques portant sur les principaux éléments, les éléments de traces et les éléments des terres rares. Le potentiel de ces occurrences comme source de pierre à sculpter fera également l'objet d'une évaluation. Des entrevues seront réalisées avec un ou plusieurs sculpteurs inuits expérimentés afin de déterminer les attributs d'une bonne pierre à sculpter et d'établir si les échantillons prélevés à chaque site répondent à ces critères.

Introduction

The Hall Peninsula Integrated Geoscience Program (HPIGP) is being led by the Canada-Nunavut Geoscience Office (CNGO) in collaboration with the Government of Nunavut, Aboriginal Affairs and Northern Development Canada, Dalhousie University, University of Alberta, Université Laval, University of Manitoba, University of Ottawa, University of Saskatchewan, Nunavut Arctic College and the Geological Survey of Canada. It is supported logistically by several local, Inuit-owned businesses. The study area comprises all or parts of six 1:250 000 scale National Topographic System (NTS) map areas north and east of Iqaluit (NTS 025I, J, O, P, 026A, B).

In the summer of 2012, fieldwork was conducted in the southern half of the peninsula (NTS 025 I, J, O, P) between June 22 and August 8. Fieldwork was supported by a 20–25 person camp located approximately 130 km southeast of Iqaluit. The focus was on bedrock mapping at a scale of 1:250 000 and surficial-sediment mapping at a scale of 1:100 000. A range of thematic studies was also supported. This included Archean and Paleoproterozoic tectonics, geochronology, landscape uplift and exhumation, detailed mapping in mineralized areas, micro-diamonds, sedimentary rock xenoliths and permafrost. Summaries and preliminary observations for all of these studies can be found in this volume.

During the summer of 2012, fieldwork under the HPIGP was carried out on southern Hall Peninsula, east of Iqaluit. To support the mapping efforts of the CNGO, Budkewitsch et al. (2013) made use of remote predictive mapping tools

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to identify areas within the Hall Peninsula, where weathering of rocks has resulted in high levels of iron-oxide staining. This exercise was carried out to identify units of potential economic interest, as well as to identify units that could serve as lithological markers. In the course of their study (Budkewitsch et al., 2013), they visited 20 sites identified through these techniques to determine which geological units corresponded to the iron-stained areas. A correlation was observed between several of the examined sites and exposures of ultramafic rock identified in the field as peridotite and pyroxenite, which were either partially or completely altered to serpentinite. The latter lithology is of singular importance in Nunavut, as the Nunavut Land Claims Agreement (Nunavut Tunngavik Inc., 2009) gives the Inuit rights to any discoveries on Crown lands of 'carving stone', defined as serpentinite, argillite and soapstone. The author was charged with carrying out a study designed to examine these occurrences geologically and to assess their potential as sources of raw material for use by local carvers (Figure 1).

In total, 18 ultramafic occurrences were identified during the field season, of which eleven (Figures 2a-e, 3a-f; Table 1) consist of peridotite or pyroxenite, a composition amenable to alteration to serpentinite or soapstone, and occur in sufficient volume to be considered for quarrying operations. The remaining occurrences are either of a different composition (hornblendite or lamprophyre) or are volu-

Figure 1. Ultramafic occurrences with potential as carving stone on southern Hall Peninsula, Baffin Island, Nunavut.

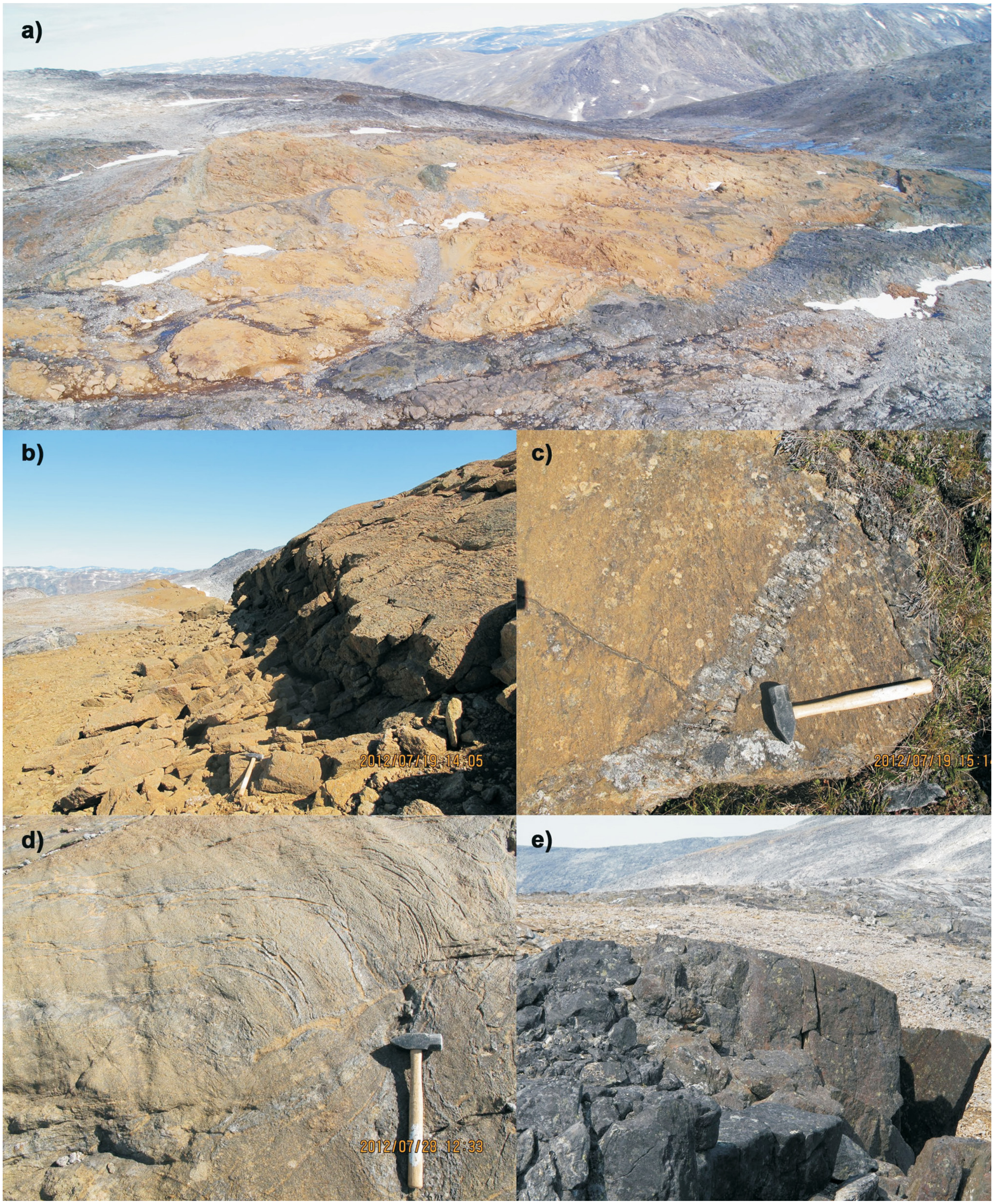

Figure 2. Photographs of ultramafic occurrences on southern Hall Peninsula, Baffin Island, Nunavut, showing stations **a)** 12MBC-B045 (aerial view approximately 600 m wide; photo by P. Budkewitsch); **b)** 12MBC-B077 (CNGO-HPIGP photo no. 12MBC-B077P02[1]); **c)** 12MBC-B080 (CNGO-HPIGP photo no. 12MBC-B080P01); **d)** 12MBC-B115 (CNGO-HPIGP photo no. 12MBC-B115P01); **e)** 12MBC-K074 (dark rock in foreground approximately 2.5 m in width; CNGO-HPIGP photo no. 12MBC-K074P01).

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[1] *Unless otherwise indicated, all numbered photos are from the Canada-Nunavut Geoscience Office Hall Peninsula Integrated Geoscience Program database.*

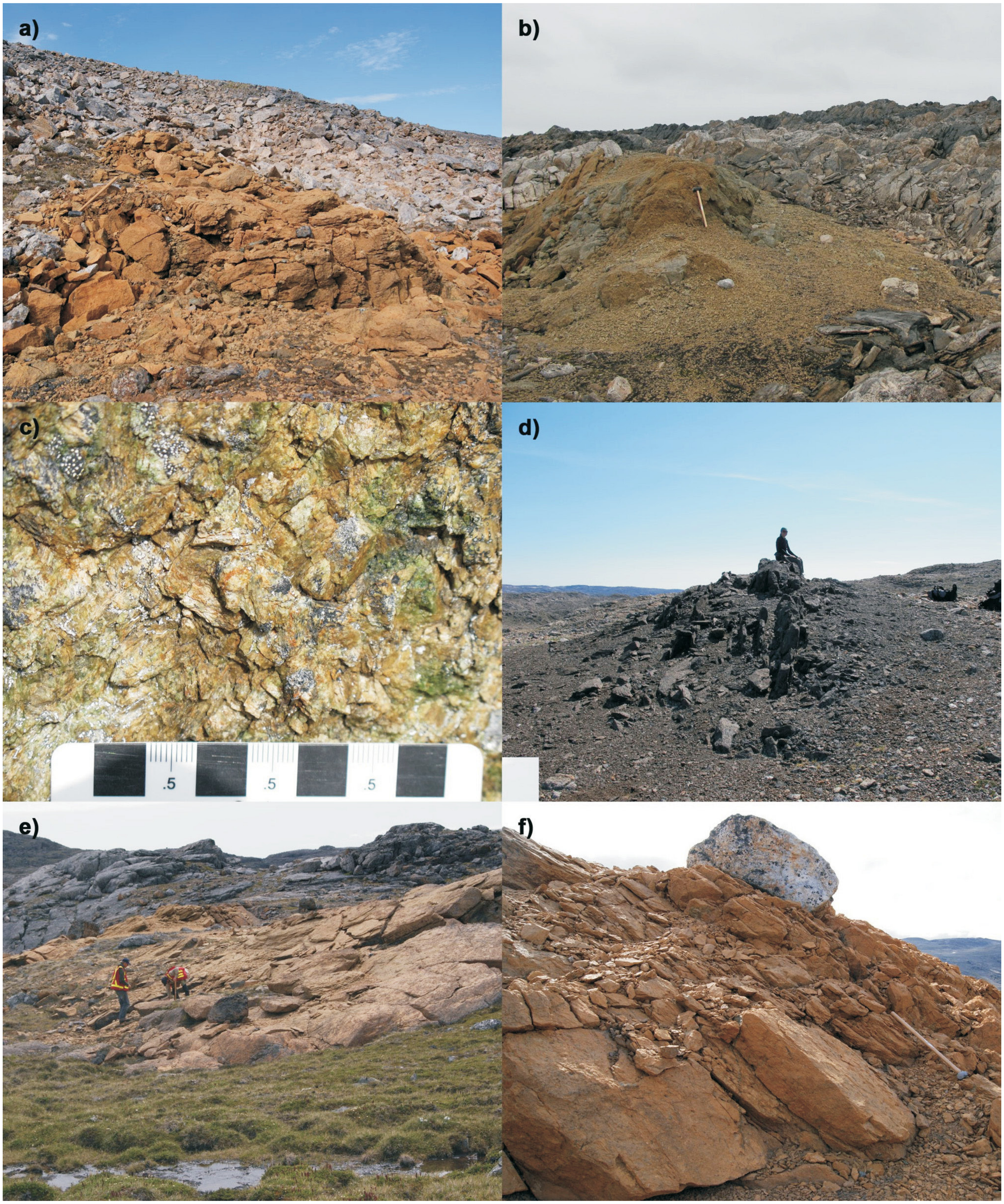

Figure 3. Photographs of ultramafic occurrences on southern Hall Peninsula, Baffin Island, Nunavut, showing stations **a)** 12MBC-M067 (CNGO-HPIGP photo no. 12MBC-W005P02); **b)** 12MBC-K099 (CNGO-HPIGP photo no. 12MBC-K099P03); **c)** 12MBC-R023 (CNGO-HPIGP photo no. 12MBC-R023P06); **d)** 12MBC-S083 (CNGO-HPIGP photo no. 12MBC-S083P01); **e)** 12MBC-W001 (CNGO-HPIGP photo no. 12MBC-W002P11); **f)** 12MBC-W003 (photo by M. Senkow). Hammer in photographs is approximately 1 m long.

Table 1. Ultramafic occurrences on southern Hall Peninsula, Baffin Island, Nunavut.

Station ID	Longitude	Latitude	Estimated size[1]	Estimated volume (t)
12MBC-B045	65° 22' 37.200" W	62° 58' 08.250" N	Large	500 000
12MBC-B077	64° 26' 09.260" W	63° 38' 14.220" N	Modest	2 500
12MBC-B080	64° 30' 43.453" W	63° 50' 14.790" N	Modest	5 000
12MBC-B115	65° 06' 36.468" W	63° 55' 18.816" N	Large	12 500
12MBC-K074	65° 59' 37.151" W	63° 18' 25.422" N	Small	Unknown
12MBC-K099	65° 54' 35.399" W	63° 12' 14.748" N	Small	100
12MBC-M067	66° 21' 29.512" W	63° 13' 51.654" N	Small	500
12MBC-R023	66° 53' 08.901" W	63° 29' 47.916" N	Modest	1 000
12MBC-S083	66° 50' 57.478" W	63° 18' 05.586" N	Small	100
12MBC-W001	66° 06' 41.300" W	62° 58' 16.920" N	Large	12 500
12MBC-W003	65° 53' 17.600" W	63° 05' 51.500" N	Small	500

[1] Nunavut Carving Stone Deposit Evaluation Program classification

metrically insignificant and are therefore not the subject of further discussion. Four of the 11 occurrences identified were examined as part of this study; the other occurrences either were not logistically reachable within the time available or were discovered later in the field season.

Description of occurrences

Station 12MBC-B045

Station 12MBC-B045 is a lozenge-shaped outcrop (Figure 2a) approximately 250 m wide by 500 m long with significant relief (estimated 75 m from base to peak). The composition varies from dunite to pyroxenite, with amphibole phenocrysts. Both serpentine and talc are found in certain areas of the outcrop. The unit weathers red-brown to mustard-brown to green; it is not clear what causes the differential weathering, as the units appear compositionally similar.

Station 12MBC-M067

This station includes three ultramafic outcrops each approximately 3 to 5 m wide by 8 to 10 m long (Figure 3a). Similarly to station 12MBC-W001 discussed below, two compositional variations were observed at this station: the lower phase is fine-grained and homogeneous, whereas the upper phase is medium- to coarse-grained, with amphibole and serpentine phenocrysts. Both phases are olivine-rich and are intruded by amphibole veins, which range in size from centimetres to decimetres. This unit weathers mustard-brown and features an anastomosing texture on the weathered surface (Figure 4).

Station 12MBC-W001

Station 12MBC-W001 consists of a cliff of ultramafic rock approximately 100 m long by 15 m high exposed on a hillside. This occurrence is divided into two distinct, mustard-brown weathering phases: the lower 8 to 10 m is a strongly foliated (065°/53°), fine-grained and olivine-rich unit, with some alteration to serpentine, and has been identified in the field as dunite; the upper 5 to 7 m unit is coarse-grained, has an anastomosing texture, which includes amphibole phenocrysts, and is intruded by veins up to 10 cm wide consisting of coarse phlogopite and serpentine. The ultramafic unit is overlain by a unit of monzogranite gneiss intruded by rafts of garnet-bearing psammite, which is itself overlain by massive tonalite.

A unit of similar composition is found approximately 200 m from station 12MBC-W001, consisting of a flat-lying pod of ultramafic rock approximately 30 m wide (Figure 3e). The unit is primarily composed of olivine and includes coarse amphibole phenocrysts as well as veins of phlogopite and serpentine, as discussed above; these veins may be a late feature, as evidenced by the lack of deformation of the phlogopite crystals.

Station 12MBC-W003

Station 12MBC-W003 comprises several pods of olivine-rich ultramafic rock (Figure 3f) with an anastomosing texture, common amphibole phenocrysts and some olivine altered to serpentine. The outcrops weather mustard-brown, similarly to the outcrops described at the previous station.

Discussion

Characterization of the ultramafic occurrences examined during the field season is still at the preliminary stage. Sam-

Figure 4. Anastomosing texture on the weathered surface of ultramafic occurrence 12MBC-M067 on Hall Peninsula, Baffin Island, Nunavut (CNGO-HPIGP photo no. 12MBC-W006P06).

ples will be sent for thin-section preparation and geochemical analysis of major, trace and rare earth elements. The occurrences will also be examined in the context of the regional geological data, including other known ultramafic bodies outside the project area. Questions to be answered include resolution of the approximate age of the occurrences (Archean or Proterozoic?) as well as the nature of their mode of emplacement. The potential of these occurrences to be used as a source of carving stone will be evaluated by

- the quality of the stone, in terms of hardness, grain size, homogeneity and other features; and
- the relative ease of access to each location by travel overland or by sea.

Economic considerations

Because of their potential as sources of raw material for carving, the ultramafic occurrences identified during the HPIGP are of chief interest to the Inuit of Nunavut. Inuit artists rely on dependable sources of carving stone to allow them to continue to produce and sell carvings. This study will help determine the quality of stone at each deposit visited. Table 1 lists the estimated size of each station identified during the field season, using the classification system established by the Nunavut Carving Stone Deposit Evaluation Program (NCSDEP; Beauregard et al., 2013). A volumetric estimate for each station based on field notes is also given in the same table; these numbers are tentative and are intended only to give a relative idea of the size of each occurrence.

Using the NCSDEP classification system, the deposits with the most potential for quarrying are those of modest size or larger located near tidewater. Five of the 11 sites meet these criteria: stations 12MBC-B045, -B077, -B080, -B115 and -W001. Station 12MBC-B045 is located on southern Hall Peninsula, approximately 5 km inland of Napoleon Bay. Stations 12MBC-B077 and -B080 are both located on the Lemieux Islands; the former is a short distance from the water, whereas station 12MBC-B080 is directly on shore. Station 12MBC-B115 is located on eastern Hall Peninsula, less than 10 km inland of Okalik Bay and station 12MBC-W001 is located on Barrow Peninsula, within 3 km of the coast. However, of these five occurrences, only two (stations 12MBC-B045 and -W001) were visited by the author and will be assessed in greater detail in the course of this study.

At this point, it is premature to state whether any of the sites examined possess the correct combination of quality stone and ease of access to be considered suitable for quarrying. Moreover, analysis for the asbestos-bearing mineral chrysotile should be conducted before using carving stone from any of these sites.

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