Natural Resources Canada / Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8104

NATMAP – Canada's National Geoscience Mapping Program: 1991–2002

B. Robertson

2017

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8104

NATMAP – Canada's National Geoscience Mapping Program: 1991–2002

B. Robertson

2017

doi:10.4095/299022

This publication is available for free download through GEOSCAN (http://geoscan.nrcan.gc.ca/).

Recommended citation
Robertson, B., 2017. NATMAP – Canada's National Geoscience Mapping Program: 1991–2002; Geological Survey of Canada, Open File 8104, 94 p. doi:10.4095/299022

Publications in this series have not been edited; they are released as submitted by the author.

FOREWORD

"A comprehensive knowledge of the geoscience of the Canadian landmass and its offshore is fundamental to economic development, public safety, environmental protection and national sovereignty" (Vodden, 1992).

"Geoscience knowledge, provided by governments as a public good, is the basis upon which the private sector plans and conducts its activities. The mining industry has identified this publicly accessible geoscience knowledge as one of Canada's key advantages in attracting investment in the increasingly competitive global mineral exploration market." (Intergovernmental Working Group on the Mineral Industry, 1999)

The National Geoscience Mapping Program (NATMAP) was developed by the Geological Survey of Canada (GSC) in 1991 to support Canada's natural resources industry by filling gaps in the fundamental geoscience database, and to respond to emerging environmental and societal issues. The 12-year, multi-million dollar program operated through close collaboration between GSC and the provincial and territorial geoscience agencies, with participation from universities and some support from industry. Projects ranged from mapping and assessing the surficial geology of the Oak Ridges Moraine in Greater Toronto, documenting the geological framework of the Slave Province in the Northwest Territories, to research on the evolution of oil and gas in the Magdalen Basin of Canada's east coast. The program, whose thirteen projects included components in nine provinces and three territories, came to a successful end in 2003. Now, almost twenty years since fieldwork began on the first of the NATMAP projects, impacts of this major contribution to Canada's geoscience realm have been recognized from several perspectives.

As expected, a wealth of new, high quality geoscience knowledge was acquired for various areas across Canada, knowledge that became and remained readily accessible, and the early socio-economic impacts from applying this knowledge are being recognized and documented. But NATMAP'S legacy must also include recognition of how it led to establishing an important and effective framework under which cooperative and collaborative geoscience is designed and conducted by GSC and provincial and territorial geoscience agencies, and also how the organization of NATMAP became the first step in the evolution of the way in which GSC plans and undertakes the whole of its geoscience program in response to meeting the varied geoscience needs of Canadians. And, finally, many of this country's young geologists, now following professional careers in the public and private sectors, received invaluable training as student participants in one or another of the NATMAP projects.

CONTENTS

Figures

Abstract

The National Geoscience Mapping Program (NATMAP) was launched by the Geological Survey of Canada in 1991 in response to a concern of the country's mineral exploration community that the level of geological mapping by Canada's federal and provincial/territorial surveys was no longer adequate to assist companies in new exploration ventures into more remote or poorly understood regions. The principles and practices of the NATMAP Program were developed in GSC-led deliberations with its counterpart surveys and industry representatives. For the first time, major geological mapping projects would be formally coordinated and collaborated studies by the public geosciences agencies, utilizing their resident and relevant expertise and funds to produce a new era of geological maps incorporating data from several geosciences disciplines and in digital formats. The thirteen NATMAP projects undertaken over the Program's thirteen-year span were proposed, reviewed, funded and renewed by management and advisory panels according to a series of criteria for project suitability and operations – a process that has since become the standard for GSC project management.

The success of NATMAP undoubtedly lies in the important advances in Canada's geosciences database and integrated knowledge. The scientific results of the individual NATMAP projects, covering one million km^2 *across nine provinces and three territories, have been published and communicated elsewhere in well over 500 maps and 1500 reports. This compilation provides information for each project's rationale, component studies and methodologies, some high-level findings and their implications, plus impacts attributable to acceptance of the results by the resource exploration and public policy sectors, perhaps a decade or more later.*

In general terms, NATMAP accomplished its original goal of providing the new geoscience required by the private sector to refine its exploration strategies in areas of previous interest and to advance with some confidence into regions that were formerly considered too uncertain because of the poor quality of the extant geological knowledge. Virtually all of the projects targeted at this industry have seen new claims, staking and detailed surveys and exploration over the newly mapped terranes. In some instances, follow up of geophysical or geochemical anomalies identified during the NATMAP investigations have led to the discovery of potential economic deposits. NATMAP projects over portions of sedimentary basins in western and eastern Canada helped define the 3-dimensional extent of suitable lithologies and structures for oil and gas deposits have seen the immediate drilling of significant numbers of exploratory wells. This latter activity, plus the mineral exploration ventures, have already contributed hundreds of millions of dollars to the Canadian economy. Important results were also achieved in the NATMAP projects that addressed issues of groundwater source recognition and protection, terrain stability and aggregate resource potential, contributing to new, related public policy debates and regulations.

It is unlikely that the total contribution of the NATMAP geosciences, in terms of providing the knowledge upon which future resource discoveries will be made, will be compiled or calculated. Nonetheless, the role played by Canada's geological surveys in NATMAP and its successor projects and programs, will continue to support a broad spectrum of issues for which geoscience knowledge is fundamental.

SUMMARY

The National Geoscience Mapping Program (NATMAP) was developed by the Geological Survey of Canada (GSC) in 1991 to support Canada's natural resources industry by filling gaps in the fundamental geoscience knowledge of selected regions of the country to aid in new exploration ventures and, in other areas, to respond to emerging environmental and societal issues.

The principal source of geoscience knowledge, whether to aid in the exploration for mineral deposits, determination of terrain stability for construction projects or for assessment of the supply and security of an important groundwater source has been, for almost two centuries, a geological map portraying the various rock units and their distribution. The most recent geological compilation map of Canada, published in 1996 by the Geological Survey of Canada (GSC), seems to indicate that all of Canada has been geologically mapped, leading to the possible belief that geological mapping of this country has been completed. From one standpoint, this is true. There are no areas of Canada where at least a 'regional-scale' investigation of the *bedrock* geology has not been carried out and maps published. However, a geological map produced as recently as twenty years ago could now be considered obsolete, or at least incomplete, in terms of the level of information it furnishes for current day ventures and decision making. In particular, there are significant areas in Canada's northern territories where the existing 1:250,000 scale maps were compiled from observations and samples taken tens of kilometres apart to provide simply a first-order portrayal of the nature and structure of the region's bedrock. Mapping Canada's geology is actually an ongoing process, adding more detailed information on the nature and distribution of a region's bedrock and surficial deposits, and incorporating complementary information from other research, such as geochemical and geophysical studies, as examples. Revisions to the three-dimensional description of a region's geological framework are necessitated, as new tools and understandings allow, and as the more remote regions gain new importance in the search for natural resources. This does not mean that terrains must be remapped in their entirety to bring them up to current standards; a new map can be developed through the addition of 'layers' of digital data for newly acquired geological parameters - geochemistry, for example - to an otherwise complete and adequate map. The new generation of digital, interactive, GIS-based maps also allows the users to add and merge their own specific data to assist their interpretations and help guide their ventures.

In a large and incompletely explored country like Canada, it is beyond the scope of even the major exploration companies to undertake the mapping of any sizeable region and well beyond the competitive nature of their business to make this information generally available. As a result, this task is carried out by publicly-funded geological surveys which provide the knowledge as a public good in support of the nation's resource-based economy. For over a century, the members of Canada's mineral exploration industry have recognized the value of geological maps produced by Canada's federal, provincial and territorial geoscience agencies - a geological map has been considered by all users as the single most useful type of product and is irreplaceable. Specific studies carried out in Australia, United States, Ontario, Quebec and Canada countrywide, to quantify the value of geological mapping concluded, without exception, that the public costs of producing a geological map are returned to the country's economy at least five-fold in terms of expenditures by resource companies as they use these maps to focus their exploration programs and, ultimately, open new mines or producing oilfields.

Mineral exploration levels follow the changing world prices of metal commodities. Sharp increases in the prices of gold and silver between 1978 and 1980 were reflected in a dramatic rise in exploration expenditures in Canada in 1980 and 1981. But an almost immediate drop in the price for nearly all metals caused exploration levels to fall sharply. To offset the decline in this sector of the economy, Canada introduced an exploration tax incentive for the period 1983 to 1988 so both major and junior exploration companies could be more speculative by venturing into unknown or poorly explored regions. The Prospectors and Developers Association recognized, however, that map coverage for these regions wasn't keeping up with their needs and that the level of mapping by Canada's geological surveys wasn't adequate to close the widening gap.

As a result, GSC management and scientists embarked on a series of internal, in-depth discussions with the aim of defining and implementing a new National Geoscience Mapping Program that would incorporate the modern concept of geological maps, data standardization and best policies and practices used in other countries for improving mapping. Following discussions with other mapping agencies in Canada, and a workshop involving the Canadian geosciences community, GSC officially announced a revised program "much broader in scope and potentially involving all mapping agencies in *Canada, titled Canada's National Geoscience Mapping Program (NATMAP)*." NATMAP elements were defined (in part) as follows:

- NATMAP encourages coordinated projects by all agencies to reduce operating expenses and produce integrated projects and products that combine the skills and results of the different agencies, capturing new data in digital format and maximizing the application of computer technology.
- NATMAP projects should be multi-disciplinary, incorporating other disciplines (*e.g.* geophysics, engineering geology, geochronology, geochemistry, stratigraphy, paleontology, structural geology) as required, producing geoscientific maps as major outputs.

- Projects should involve undergraduate and graduate students from Canadian universities in their field components.

To help ensure adherence to these principles and other recommendations, NATMAP was to be controlled by a National Steering Committee (renamed National Coordination Committee in 1995) representing all participating agencies. The Steering Committee stressed that the NATMAP Program was not a granting agency to provide total funding for a project; NATMAP would provide supplementary funding to expand and enhance mapping programs that were largely funded from other sources. Projects would be GSC-led, but technical and academic expertise could be drawn from the appropriate source, whether GSC, provincial or territorial survey or university. Project plans would include both the research period plus the time to properly complete the scientific outputs. Milestones and budgets for each year of the 3- to 5-year duration would be detailed at the outset. Project proposals and the details of budgets, methods, timetable and expected outcomes and outputs would require review and approval by a panel convened from Canada' geoscience community. Progress would be assessed annually by the same panel to determine whether the project would continue.

Two NATMAP 'pilot' projects were launched in the summer of 1991 - the Shield Margin NATMAP and the Slave Province NATMAP. Both areas were already the site of GSC geoscience projects whose goals were largely those of the NATMAP aim of enhancing Canada's geological map coverage and associated geoscience knowledge.

Over the twelve years of the NATMAP Program, thirteen projects, resident in all parts of Canada, were approved and funded, generally for a 3- or 4-year lifetime. The majority focused on improving the knowledge of a region's bedrock or surficial geology, or both in several cases, to support resource exploration. The Shield Margin project, for example, would enhance geoscience knowledge of the Flin Flon – Snow Lake – Hanson Lake greenstone belt across the Manitoba-Saskatchewan northern boundary to help direct exploration for new copper-zinc deposits to strengthen the region's mining economy. Similarly, the production of modern bedrock and surficial geology maps across a 375-kilometre transect from northeastern B.C. to southern Yukon and Northwest Territories under the Central Foreland project would yield a better understanding of the likelihood of new oil and gas deposits and their potential economic development. Other NATMAP projects were built around an environmental focus. The objective of the Oak Ridges Moraine project was to understand the geomorphology of this feature to direct its preservation and management as a critical groundwater source for the greater Toronto region. Also, components of the Greater Winnipeg project addressed human and natural influences on Lake Winnipeg's continuing evolution, plus afforded a better understanding of flooding of the Red River from a long term perspective. The principal achievement of these two studies has been an increased awareness of the need by government, industry and environmental groups to incorporate geosciences in their planning.

The scientific results of the NATMAP projects were recorded, synthesized, archived, interpreted and communicated in an estimated 3000 geological maps and reports, supplemented by numerous consultations and presentations, released during and after a project's term. Accumulating large amounts of new geoscience information necessitated development of a range of new techniques and tools for data acquisition, its standardization, archiving, manipulation and dissemination. Many of the data management tools developed under NATMAP are standard components of today's geoscience 'toolbox'.

The NATMAP scientific advances are simply summarized or highlighted in this compendium, which is intended to present a higher-level view of the various studies. Why was a project undertaken, what were its goals, how could they be achieved and, perhaps most importantly, what were the impacts and consequences that derived from the understanding and use of the new geoscience knowledge? Many such influences weren't, or won't be, completely evident for many years after a project's completion. Nonetheless, examples can be cited from virtually all projects where incorporating the new NATMAP geoscience into exploration strategies has had immediate results.

At its conclusion in 2003, Canada's NATMAP Program was one of the most heavily-funded geological mapping programs in the history of the GSC, calculated at $115 million from all contributors. Just over half came from GSC's A-Base and NATMAP budgets, another third from provincial and territorial partners, with lesser, but important, funding from Canada's universities, exploration industry and other government departments.

The legacy of the NATMAP Program extends beyond the new geoscience knowledge acquired through the various field and laboratory studies and its contribution to new economic ventures by Canada's exploration industry, and to improvements in the environmental management of important features of the country's landscape. The federal-provincial geoscience collaboration fostered under the NATMAP projects - collaboration that required a major culture shift by the management of the two spheres of government - is now commonplace, expected and valued in providing the range of public geoscience information routinely used by stakeholders in both government and private sectors.

While the Program overall and its collaborative project ventures in particular were generally regarded in a very positive light, as with all multi-agency, multi-discipline initiatives, some deficiencies were also noted. The original NATMAP goals, objectives and expected science components, spelled out at its inception, were interpreted to mean that regional geophysical and geochemical studies, both invaluable adjuncts to regional-scale geological mapping *per se* , should not be formal facets in a NATMAP project proposal. Fortunately, many projects benefitted significantly by the existence of parallel projects in these two disciplines in the same map area. As well, despite the government and industry consultations and focus groups leading to formulation of the need, intent and operations of NATMAP, and the undeniable success of the scientific undertakings, the opinion was expressed that the program lacked a strategic vision for mapping across Canada in the longer term.

The rigorous proposal, review, approval and renewal principles and processes established under NATMAP became the core of all GSC project management and, in effect, constitute another significant legacy of this milestone program.

The author was not directly involved with the NATMAP Program as a whole, nor with any of the mapping projects, and so has relied entirely on a variety of written sources and very many individuals who led, or were integral parts of, the thirteen projects to furnish the information for this compilation of the history and accomplishments of NATMAP.

The Shield Margin NATMAP project was undertaken to enhance the geoscience knowledge of the Flin Flon - Snow Lake - Hanson Lake greenstone belt, a broad swath of complexly deformed Precambrian age rocks extending east-west across the central part of Manitoba into Saskatchewan. The terrane was already an important producer of base metals but, without the discovery of new, economic deposits, the region's future might be in jeopardy. A better knowledge of the geology and deformational history of the greenstone belt to direct renewed mineral exploration could increase the likelihood of discovering such deposits to preserve and prolong the mining economy of the region in both provinces. To this end, bedrock and surficial mapping activities by GSC and the geological surveys of Manitoba and Saskatchewan under the 1991-1996 NATMAP project were supported by thematic geophysical, geochemical, geochronological and mineral deposit studies. The new, high-quality NATMAP data helped initiate the LITHOPROBE Trans-Hudson Transect, which added seismic and other geophysical data to the three-dimensional picture of the region.

The NATMAP Shield Margin bedrock studies concluded that the Flin Flon belt is an intraoceanic accretionary collage marked by a diverse and complex tectonostratigraphy and protracted deformation and metamorphic history. Since all the local ore deposits are associated with the island arc rocks, the newly understood tectonic framework provided a predictive context for mineral exploration. As a result of the new tectonic model, base metal exploration levels showed a significant and steady increase during the NATMAP project rising from approximately five claims before the project in 1990, to thirty-five in 1997. Although lowered base metal prices have generally limited exploration since the project was completed, the ideas, reports, maps, and databases are in place as commodity prices strengthen.

Ccomprehensive knowledge of the region's Quaternary geology was generated by the project's surficial geology component, including reconstruction of the area's glacial and deglacial history. The recognition of at least nine distinct ice flow events has profound implications for understanding the glacial dispersal of minerals indicative of various buried mineral deposits and the consequent ability to trace these indicator minerals back to their pre-glaciation source.

The Slave Province NATMAP project was formulated to upgrade the geoscience knowledge of a large part of the Slave craton, one of the oldest and most distinct building blocks of the North American continent, where mineral exploration activities and mining are vital to a healthy NWT economy. Gold mining had been the region's economic backbone since 1937 but several smaller mines had closed in the 1990s. Even if the Giant, Con, Ptarmigan and Colomac mines around Yellowknife, and the Lupin mine to the north could remain viable for another decade, the opening of new mines elsewhere across NWT was essential to the territory's economic health. Ongoing exploration for base metals to diversify the mining industry hadn't proved successful and, while the first diamond exploration ventures were underway, there was little expectation of these gems making a significant contribution to the region's mining industry. Before the NATMAP project, knowledge of the Slave Province bedrock and surficial geology was inadequate for mounting cost-effective exploration programs. The Slave NATMAP project was built around bedrock mapping of targeted areas along a north-south corridor from Coronation Gulf to Yellowknife, complemented by regional Quaternary geology studies. However, discovery of the Lac de Gras diamondiferous kimberlites east of the mapping corridor meant the Quaternary studies would also study the nature and distribution of the kimberlite pipes, kimberlite indicator minerals in the glacial drift, and ice flow history to provide a regional framework for geological interpretation and drift prospecting.

The NATMAP project made significant advances in revealing the character of the Slave province, especially that of its Mesoarchean basement, and recognition of ten distinct events in the craton's evolution. In part, the revelation that many supracrustal rocks are not even braoadly correlative has profound significance on metallogenic evaluations. Detailed bedrock mapping discovered two new kimberlites in the core area of diamond exploration, and a possible mechanical control by mafic dykes on kimberlite emplacement was established. From an environmental standpoint, results from detailed till geochemical surveys are actively being used by mining companies and government to determine pre-mining, natural metal concentrations in soil to aid in environment assessment work.

The Eastern Cordillera NATMAP project remappped the geology of part of the Outer Foothills region of the Canadian Cordillera, along a swath 50-100 km wide extending 200 km north-northwest from the Alberta-U.S. boundary. The map area contains significant reserves of oil and natural gas and has important potential for sulphur, thermal coal and coal bed methane. The NATMAP map areas were selected to upgrade GSC bedrock maps dating from the 1930s to the 1950s, especially those produced prior to recognition of the so-called Triangle Zone structure, a region of increasing industry activity. The project also included a component to remap surficial deposits to try to resolve divergent views of the roles and timing of montane vs continental glacial advances leading to contemporary glacial sedimentary environments. The new bedrock maps and digital databases were intended to assist in petroleum exploration, hydrogeology studies and engineering and land use projects. Field work was begun by GSC in 1993 with main collaboration from the University of Calgary and the Alberta Geological Survey. Advances were made in terms of new recognition and understanding of regional and local stratigraphy and structural factors controlling petroleum reservoir units and leading to improved 3-dimensional models and ideas for new hydrocarbon exploration targets, both in the mapped areas and, by extrapolation, beyond. As well, bedrock mapping provided new data related to anomalous gold occurrences that defined a new exploration target for this metal. Release of the new geoscience data during and following the NATMAP project prompted the drilling of more than 55 new wells in the Triangle Zone, the discovery of 974 million m^3 of gas reserves and the construction of at least one new gas plant. The surficial geology studies led to the conclusion that the region was subjected to just one advance of a single Wisconsinan age continental ice sheet – the Laurentide ice sheet – with a much lower profile than was assumed previously. Evidence for several montane glacial advances preceding this ice sheet was corroborated. The late Wisconsinan age for the Foothills erratic train, however, negates the belief that an ice-free corridor existed between the western limit of the ice sheet and the Rocky Mountain glaciers, so that the first humans could not have entered North America until well into the deglacial phase.

The Southern Prairies NATMAP project was conducted over two separate areas of the Interior Plains region of southern Saskatchewan and Manitoba, a region considered typical of the entire southern Prairies Provinces, by the GSC and the respective, provincial geological surveys. Studies would develop field and laboratory protocols and GIS and computer database handling as standards for future surficial geology studies over the entire region, and would produce an integrated model for Quaternary deposits for the southern Prairies. The area is mostly covered by a thick blanket of drift, but the influence of the bedrock geology and pre-glaciation physiography is evident in small variations of topographic relief. At the project's inception in 1992, extant geoscience information was inadequate to address emerging problems of understanding groundwater resources in order to allow development of the petroleum industry while preserving them for urban and agricultural growth. Surficial geology maps were more than thirty years old and, although a substantial geological database was available, it wasn't widely used because the several geosciences agencies – federal, provincial and private sector – that contributed data had employed different methodologies and the results were commonly fragmented and disseminated among these organizations. The NATMAP results at the end of each season's mapping were released as 1:50,000 or 1:100,000 Open File maps and at the project's completion as eight, final 1:100,000 surficial materials maps and a 1:250,000 A-Series map. The mapping data was augmented by subsurface information from 27 new drillholes, seismic and ground probing radar profiling and compilation of 20,000 borehole records to provide an improved knowledge of the region's surficial geological makeup and history. Sspecial maps were also developed; a well driller can now examine maps showing the proportion of aquifer-quality materials in 10m-depth slices in the Virden area to determine where such materials would be encountered. The new NATMAP results afford an improved understanding of glacial flow in southeastern Manitoba and, thereby, clarified the geology affecting groundwater aquifer recharge. Release of till characterization data that revealed gold, base metal and kimberlite anomalies, led to immediate staking of the entire region of this same segment, with an investment of $5-$10 million.

The Oak Ridges Moraine (ORM) is one of the largest aquifer systems of southern Ontario. The hummocky ridge of sandy hills is the primary groundwater source for the Greater Toronto Area and 33 other municipalities. Continued expansion of the use of this resource and decisions related to land use management require a complete understanding of the region's hydrogeological system, an understanding that was inadequate at the project's outset in 1993. The principal objective of the ORM NATMAP project was to clarify and comprehend the moraine's geomorphology and interior structure to identify the geologic elements controlling groundwater recharge, flow and discharge. This was accomplished through the production of an extensive suite of digital surficial geology maps, supplemented by drilling and geophysics studies. An associated geochemical survey provided critical baseline environmental data for assessments of waste remediation sites and siting of waste disposal facilities. Based on this new geoscience data, the newly developed regional stratigraphic framework and regional geological model have revealed the area's structural and process complexities. As one example, recognition of large subsurface channels, including at the site of a proposed landfill in Vaughan, has economic significance regarding new aquifer targets, watershed management and landfill siting. The pressing environmental and planning concerns dictated that the project feature rapid and timely communication of new information to stakeholder forums during the project's operation, a feature that was one of the most successful aspects of the ORM project. As a result of the communication program the ORM Conservation Act was enacted in 2001 to protect the moraine and its groundwaters, and afforded guidance for implementing the provincial Clean Water Act in 2005. The ORM project demonstrated that scientific research within the public sector can effectively raise awareness of environmental issues, both within governments and the concerned public, to impact policy and legislation.

Canada's **Magdalen Basin**, some 600km by 300km centred roughly on the Magdalen Islands of the Gulf of St. Lawrence, is underlain by a 12km-thick sedimentary sequence known to host important deposits of salt, potash gypsum and coal. There was an unproven expectation that hydrocarbon reserves, notably coal-bed methane deposits, could also exist, but the measure of the basin's economic potential required an understanding of its origins and tectonic history. While rocks of the sedimentary sequence lie largely submerged under the Gulf of St. Lawrence, outcroppings of strata deposited near the basin's margin are well exposed in all Atlantic Region provinces. Yet, despite a history of geological investigation since the mid 1800s, large areas remained poorly mapped and the region's geosciences databases were still inadequate. The Magdalen Basin NATMAP project, undertaken between 1993 and 1998 by the GSC and the provincial surveys of New Brunswick and Nova Scotia, focused on geological mapping of the basin's southern margin, building on reflection and refraction seismic studies of the early 1990s that had defined the basin's deep structure. Bedrock mapping, compiled at 1:50,000 and 1:250, 000 scales, was supplemented by diamond drilling in selected areas. The new geoscience knowledge provided a record and an understanding of the relative importance of tectonic and depositional processes operating on a local scale, plus those much larger processes operating at crustal scales far-removed from the present basin. For example, across the region, a complete cycle of orogenic buildup, extensional collapse and successor basin formation is recorded. The new 1:250,000 scale compilations in digital format has allowed advanced spatial analysis of geological data with geophysical data to greatly assist resource exploration. While the geological mapping and interchange of ideas among the Magdalen Basin NATMAP participants and stakeholders provided a much better understanding of the region's stratigraphy and structure, socio-economic impacts resulting from use of the new knowledge are difficult to quantify in the short term. The new geoscience is being used, however, by those involved in assessing groundwater for municipal water supplies, in formulating exploration strategies for oil, gas and a variety of metallic minerals across the Atlantic Region.

The Nechako NATMAP project was designed to improve understanding of the rock assemblages and various tectonic events of the past 400 million years in the Intermontane Belt of central British Columbia to stimulate mineral exploration and support sustainable development. The new geosciences knowledge would also be valuable for land-use decisions related to reservoir siting and the impact of logging on the terrain, and for aboriginal land-claim negotiations. Extant geological maps from 1949 and 1962 had led to the discovery and mining of copper, gold, molybdenum, mercury and silver. More recent mapping revealed problems with the earlier maps and reports, including the new recognition of still unmapped rock suites and tectonic events and the existence of large areas covered by extensive drift, deficiencies that were contributing to a poorly tested mineral and hydrocarbon potential. Under the NATMAP project, from 1995-2000, geoscientists from the GSC and the BC Geological Survey combined resources and expertise to produce 37 new regional and detailed geological and geophysical maps, applying modern mapping techniques that included isotopic and geochronologic and detailed aeromagnetic surveys to 'see through' the surficial deposits to the bedrock beneath. In particular, the NATMAP studies tested, and added new knowledge to, scientific hypotheses related to the nature, age and deformational history of four enigmatic geological terranes and a fifth hypothesis related to ice flow during regional glaciations. Among the discoveries was the clear definition of the Eocence age range for mineralized host rocks of the Babine mining district and determination of the most prospective areas for new exploration. Biogeochemical surveys over the Endako batholiths revealed the world's largest known biogeochemical anomaly for molybdenum, strengthening the potential for a new and expanded ore deposit. Scientifically, the Nechako project resulted in extensive re-interpretations in understanding 350 million years of geological history. From a more practical standpoint, the new geoscience fostered renewed confidence in the area's mineral potential, a confidence that translated into new investor capital to advance private sector mineral exploration and evaluation of the hydrocarbon potential of the Necahko Basin. While no major mineral discoveries could be attributed to the Nechako geosciences in the years immediately following the project's completion and release of new maps and syntheses of the region's geology, it is fully expected that rising mineral and hydrocarbon prices and BC governmental support for these industries will stimulate successful exploration for these commodities.

Prior to **the Western Churchill NATMAP project** (1997-2002), the WCP was one of the largest and most poorly known fragments of Archean crust in the world. It was known to contain an extraordinary diversity of gold, base metal and uranium resources, as well as diamond prospects, but a lack of comprehensive geoscience knowledge, particularly in key areas, hampered mineral exploration and effective land use management. Thus, the WCP project was undertaken to provide modern geological maps of late Archean and Paleoproterozoic supracrustal belts in five areas of that part of the province west of Hudson Bay, straddling the Rae (northwest) – Hearne (southeast) domains. At the outset, the Northwest Territories included what is Nunavut today, so the project was a collaboration between GSC, Government of NWT and Indian and Northern Affairs Canada. The main scientific objectives included establishing teconostratigraphic and tectonic settings of the late Archean supracrustal belts, understanding Paleoproterozoic tectonothermal events and tracking the Quaternary history of the Keewatin Ice Divide. The project mapped the equivalent of 75 1:50K NTS sheets, published as 19 bedrock maps, with new information communicated at the end of each field season through helicopter-supported field workshops directed at the exploration industry. The project significantly impacted the understanding of the geological origins and evolution of the central part of the WCP. It laid out a working hypothesis for the Archean development of the main supracrustal belts and highlighted the extent and complexity of Proterozoic reworking with significant significance for mineral exploration. As examples; distinct deformational histories were recognized in the central and northwestern Hearne subdomains and in the Rae domain; the complex, multiphase Paleoproterozoic reworking of the central WCP was recognized and characterized; the ice flow history of the Keewatin Ice Divide was revised significantly. The project's metallogenetic studies identified new targets for gold exploration in several greenstone belts of the WCP, and the new geoscience has broadened the region of mineral potential from the Hearne domain into the Rae domain. Using the updated geoscience knowledge, several companies expanded their exploration programs, leading to new or renewed staking activities in the search for gold. As well, the discovery of kimberlite indicator minerals, plus discrete fragments of kimberlite in glacial deposits in the Rankin Inlet area, provided the impetus and critical knowledge for industry to undertake a major diamond exploration program in the WCP.

The Western Superior NATMAP project was conceived to provide an up to date characterization and understanding of the tectonic framework of a region, approximately 500,000km^2, straddling the northwestern Ontario-Manitoba boundary. The targeted geoscience studies were carried out by GSC, in partnership with the geological surveys of Ontario and Manitoba, supported by the geophysical program of the concurrent Western Superior Lithoprobe transect. The region is characterized by east-west trending greenstone belts that commonly host gold and base metal deposits. Geological maps were available for most of the region's greenstone belts but interpretations varied vastly from belt to belt, limiting the effectiveness of exploration models for these commodities. Thus, the project aimed to improve understanding of the depositional setting and structural history of large crustal blocks of the western Superior province, to determine their age, affinity (continental vs oceanic) and to re-assess their mineral potential to help guide new exploration strategies. The NATMAP results were integrated with Lithoprobe observations to present a comprehensive, four-dimensional view of crustal evolution of the western Superior lithosphere. The new geoscience knowledge provides a modified regional framework that emphasizes the tectonic setting of volcanic, sedimentary and plutonic rocks and their mineral potential. From this new understanding, the most favourable environment for volcanogenic massive sulphide (VMS) deposits appears to have been areas of the continental margin related to subduction of the oceanic plate. Also, the deformed Mesoarchean-Neoarchean unconformity in the Red Lake belt appears to have had an important role in gold localization and this feature provides a guide for exploration in this belt, in rocks of similar age elsewhere in the Uchi subprovince and similar settings elsewhere in the Canadian Shield. Because the region maintains a high, but variable, level of exploration activity dependent on commodity prices, it is somewhat difficult to demonstrate the incremental impact of the NATMAP project results. Nonetheless, as a consequence of the new understandings gained from the project's multi-disciplinary undertakings, companies have now focused VMS exploration efforts in certain areas of the Uchi subprovince. Major and junior companies have adapted their gold exploration strategies to target ultramafic rocks in proximity to the unconformity within the Red Lake belt. Investment for gold exploration in the Rice Lake – Lake Winnipeg corridor doubled. Diamond explorers have focused their efforts in an area now suspected to be underlain by ancient, thick cold lithosphere, prospective for diamonds.

The Winnipeg Region NATMAP project encompassed the city of Winnipeg and contiguous tracts beyond in all four directions. Combined with the earlier Southern Prairies project, the two NATMAP projects provided new geoscience for roughly 30,000km^2 of southeast Manitoba. In the mid 1990s, it was recognized that updated, 3-dimensional geoscience knowledge of the Winnipeg region was essential to understanding and addressing several economic and environmental issues. Geological mapping of industrial mineral resources would help ensure that such commodities would be protected and available for future use. Increasingly intensive management of groundwater quantity and quality called for a better definition and understanding of aquifer geology. Perceived conflicts between hydroelectric power generation and shoreline erosion, and between waste disposal and water quality in the Lake Winnipeg Basin drew attention to an urgent need for enhanced knowledge of the basin's natural history. Between 1997 and 2001, the NATMAP project was jointly led by GSC and the Manitoba Geological Survey, with important contributions from Agriculture Canada and the Manitoba Water Resources Branch. As well, the NATMAP project assisted ongoing regional hydrogeology and Lake Winnipeg coastal studies projects by these agencies by adding an essential, fully-developed mapping component. The new 3D geology compilations provided a three-dimensional density dependent flow and transport model for the important carbonate and sandstone aquifers and the resulting model has been used to evaluate several water resource scenarios within the province. Through analysis of alluvial sediments mapped along the Red River, construction of a complete and informative tree-ring record, by analysis of cores from Lake Winnipeg, by modeling of the impact of the uplift and through several associated investigations, a picture developed of a river that naturally undergoes extensive flooding once or twice a century, in a manner that has worsened very gradually due to loss of gradient to uplift. The new knowledge demonstrated that slope stability problems along the Red and Assiniboine Rivers are a function of higher moisture content of the Lake Agassiz clays in the 'unconfined' environments along the river banks, compared with the 'drier' clays and alluvium found in the rivers' outer meanders or at a distance from the major channels. The improved understanding of geological influences on Red River flooding assisted the engineering design of flood protection works. Lake Winnipeg cottage owners dropped their suit against Manitoba Hydro with the realization that geological factors were responsible for shoreline erosion. Results of studies for the clarification of groundwater stability are now incorporated and fundamental to designing waste disposal and groundwater protection facilities. New geochemical and indicator mineral studies over several promising areas will continue to influence mineral exploration. Of at least equal importance to the geoscientific results presented in new geological maps, 3D models and associated databases, the Winnipeg project enabled implementation of highly influential new capabilities and inter-agency collaborations in Manitoba that are models for similar initiatives worldwide. The NATMAP activities and products that resulted in an improved understanding of the surficial and bedrock geology of the region will also provide a knowledge legacy to be consulted over coming decades in support of a variety of new land use, environmental and economic applications and issues that will require a geoscience input.

The Ancient Pacific Margin NATMAP project has provided a comprehensive analysis of a belt of complexly deformed and metamorphosed rocks that extends roughly 2000 kilometres north-northwest from southern British Columbia through Yukon Territory into east-central Alaska. The project was a response to demands of the mineral industry for new mapping, new geophysics, new metallogenic studies and new syntheses of the belt's poorly understood component terranes, spurred by discoveries in the mid-1990s of high-grade volcanogenic massive sulphides deposits near Finlayson Lake, Yukon. The NATMAP project brought up to modern standards all or part of several key 1:250,000-scale bedrock maps along the belt. In addition, the project included more detailed (1:50,000) mapping in parts of Yukon known to be prospective for massive sulphides, metallogenic studies along the belt and studies of the surficial deposits to identify favourable areas for placer gold exploration. The five year venture (1999-2004) coordinated resources of the GSC, the BC Geological Survey and the Yukon Geology Program within three separate project areas along the pericratonic belt: southeastern B.C.; areas straddling the B.C./Yukon boundary and in southern Yukon; abutting the Alaska boundary in central Yukon. Many of the new geoscience insights are related, on the one hand, to recognition of distinct components within major assemblages which were believed to be homogeneous or too complexly deformed to be subdivided. On the other hand, units and assemblages in different parts of the belt that were considered distinct are now shown to be correlative over considerable distances. Surficial deposit studies revealed that glacial ice advance down the Stewart River valley stopped well short of the limit previously believed. Thus, basins beyond the confluences of Rosebud and Black Hills Creeks with the Stewart were never disturbed by glaciation or glaciofluvial flushing so their Tertiary-age placers have remained in place. The new NATMAP geoscience information provides a greater level of confidence for the discovery of new mineral occurrences of potential economic significance. New mapping in the Finlayson Lake district provided a stratigraphic context for the known occurrences and new discoveries in that area – and outline the spatial extents of the prospective stratigraphic horizons. Follow up exploration in the Stewart River area by the private sector over a significant magnetic signature defined by an airborne magnetic survey complementing the NATMAP bedrock mapping demonstrated that a copper-gold-molydenum metal signature is coincident with the geophysical anomaly. The property - known as the Lucky Joe copper-gold occurrence – has been a major focus of additional exploration, drilling and testing in the subsequent years. The discovery of some remarkable paleoenvironmental records, particularly in placer exposures of Thistle Creek where fossil permafrost dates back more than 600,000 years and numerous tephras are exposed, has greatly improved knowledge of the area's paleoecology and climate history.

The Eastern Canada Appalachian Forelands and Platform NATMAP project (also known as the 'Bridges' project) was designed to upgrade our knowledge of the complex assemblage of Early Paleozoic age platform sedimentary rocks and coeval, but deformed, Appalachian volcanic and sedimentary rocks that are exposed on the northern and southern shores of the St. Lawrence system, between southern Quebec, northern New Brunswick and western Newfoundland. Incomplete knowledge of the region's tectono-stratigraphic history had created several challenges for the resource industry when it initiated a new cycle of oil and gas exploration in the Canadian Appalachian Region in the early 1990's. The new geoscience data would provide oil and gas, mining and groundwater ventures with modern information and models to help plan and carry out future exploration. To achieve these objectives, diverse geoscience studies were undertaken from 1999 to 2004 by the GSC and its provincial partners in Quebec, New Brunswick and Newfoundland and Labrador. Conventional bedrock and Quaternary mapping was effected at 1:20 000 to 1:50 000 scales; a wide range of thematic geoscience studies included lithostratigraphy, biostratigraphy, palynology, thermal maturation, geophysics, geochronology, diagenesis and geochemistry; 4 regional (1:125 000 and 1: 250 000) geological strip-maps and cross-sections were synthesized across five narrow corridors from southern Quebec to western Newfoundland. The Bridges NATMAP project resulted in a new synergy of geoscience efforts during an overall period of declining public geoscience funding and the associated reduction in expertise; these collaborative models are still used in ongoing, broader geoscience initiatives in eastern Canada. The project made major contributions to our knowledge of the fundamental geological architecture and evolution of the Lower Paleozoic rocks in eastern Canada. The various local and regional maps and cross-sections, reports and databases are playing an unequivocal role in the ongoing major hydrocarbon exploration activities in the Paleozoic rocks of eastern Canada and some of the new data and findings are recognized as major elements in the development of producing hydrocarbon fields in Gaspé.

Although one might wish to measure the "success" of NATMAP in largely economic terms – increased spending on exploration and discovery of new ore bodies, and contributions to Canada's GNP from new mines brought into production, both those who compile the 'maps' and the industry users fully recognize that the ultimate value of publicly-funded base level geoscience lies in the longer term. As an industry representative noted, "NATMAP projects do not by themselves drive discoveries – economics plays a huge role. It is really the building of information that started generations before – the work to improve the data base and to get it into the public domain – that allows timely economic decisions to capitalize on markets. NATMAP and the work of all geological surveys, deserve credit for improving the base data. It is up to industry to take it to the next step and do the discovering."

INTRODUCTION

Geological Mapping in Canada

Planning and conducting a wide range of undertakings requires specific knowledge of the bedrock of the region in question and/or its overlying, unconsolidated deposits. The source of this knowledge, whether to aid in the exploration for mineral deposits, determination of terrain stability for construction projects or for assessment of the supply and security of an important groundwater source has been, for almost two centuries, a geological map portraying the various rock units and their distribution. The knowledge on these two-dimensional maps is almost always augmented by descriptive notes and interpretation of aspects of the region's geology that cannot be adequately described by the graphic depictions on the map alone.

This country's first geological maps were based on the 1843 field studies of Sir William Logan, the first director of the newly founded Geological Survey of Canada, and his associate Alexander Murray, and covered areas of New Brunswick and the Gaspé, and the region between Lake Erie and Lake Huron, respectively. These investigations supported the mandate of the GSC to determine whether Britain's new Province of Canada would furnish the coal and mineral resources required to support its settlement and development. In the years following, adjacent and intervening areas were systematically mapped by Logan and his GSC colleagues, gradually piecing together the broad geological framework of eastern Canada and its natural resource potential and resulting in the publication of the *Geology of Canada*, in 1863 (Logan, 1863). One prominent reviewer – Sir William Dawson - recognized not only the scientific importance of the work, but also the value of public geoscience knowledge when he wrote "The practical man has all that is known of what our country produces in every description of mineral wealth; and thus has a reliable guide to mining enterprise, and a protection against imposture." (Dawson, 1864) And, with remarkable insight into the longer-term legacy of geological maps and reports, he remarked that "Even in the case of new discoveries of useful minerals which may be made, or may be claimed to be made after the publication of this Report, it gives the means of testing their probable nature and values, as compared with those previously known." Logan, himself, had earlier proclaimed on the economic value of public geological surveys in an anonymous article on the history of the fledgling GSC published in 1851. According to C.H. Smith (1999), ". . . . Logan was a master in generating public awareness of the benefits of geological surveys in Canada . . "

Despite its gradually evolving mandate over 168 years, geological mapping to provide the fundamental geoscience knowledge in unmapped, or undermapped regions to encourage and support resource development has remained at the core of GSC's mandate and activities. Over the decades since the various stages of Confederation, the geoscience agencies - geological surveys - of Canada's provincial and territorial governments have joined and shared in this role, albeit with slightly different focus. These complementary roles were eventually formally defined in the first Intergovernmental Geoscience Accord (1996) as follows. "The Geological Survey of Canada carries out national geoscience programs to define the geology and resources of Canada. These programs are typically thematically based, and national or broadly regional in scope or significance." Whereas, "The provincial and territorial geological survey organizations carry out programs . . . at a scale appropriate to addressing provincial or territorial responsibilities . . . largely directed towards sustainable development and are closely linked to the needs of local clients." The most recent Intergovernmental Geoscience Accord – IGA3 2007 – generally restates these distinctions, but acknowledges that the GSC's programs are typically thematic based and are intended to provide a comprehensive geoscience knowledge base to also address public safety and environmental protection, rather than simply defining the nation's geology and its resources, while the work of the provinces and territories is increasingly used to resolve land use and address public health and safety issues.

Periodically - roughly every twenty-five years - the Geological Survey of Canada produces an updated geology map of the entire country, working with the provinces and territories to incorporate new geoscience data for all regions of Canada. The most recent compilation, published in 1996, just as for the 1968 version, seems to indicate that all of Canada has been geologically mapped - there are no gaps - leading to the possible supposition that geological mapping of this country has been completed. From one standpoint, this is true. There are no areas of Canada where at least a 'regional-scale' investigation of the *bedrock* geology has not been carried out and maps published. (But there are still large areas of Canada lacking even regional documentation of the *surficial* geology, and similar gaps exist with regional *surficial geochemical* mapping and *geophysical* mapping.) However, a geological map of a given area produced even as recently as twenty years ago could likely now be considered obsolete, or at least incomplete, in terms of the level of information it furnishes for current day ventures and decision making. As well, there are significant areas in Canada's northern territories where the existing 1:250,000 scale maps were compiled three and four decades ago, from observations and samples taken no closer than tens of kilometres apart, simply to provide a first-order portrayal of the nature and structure of the region's bedrock. While such reconnaissance maps and their accompanying reports were initially suitable to construct and depict the broad geological framework of Canada's north, they have proven entirely inadequate in offering the level of geoscience knowledge required to undertake cost-effective resource exploration in this remote region. In Nunavut, for example, where reconnaissance geological maps cover the entire region, almost one third of the terrain is now considered inadequately mapped to aid this new Territory in effectively managing its land and resources.

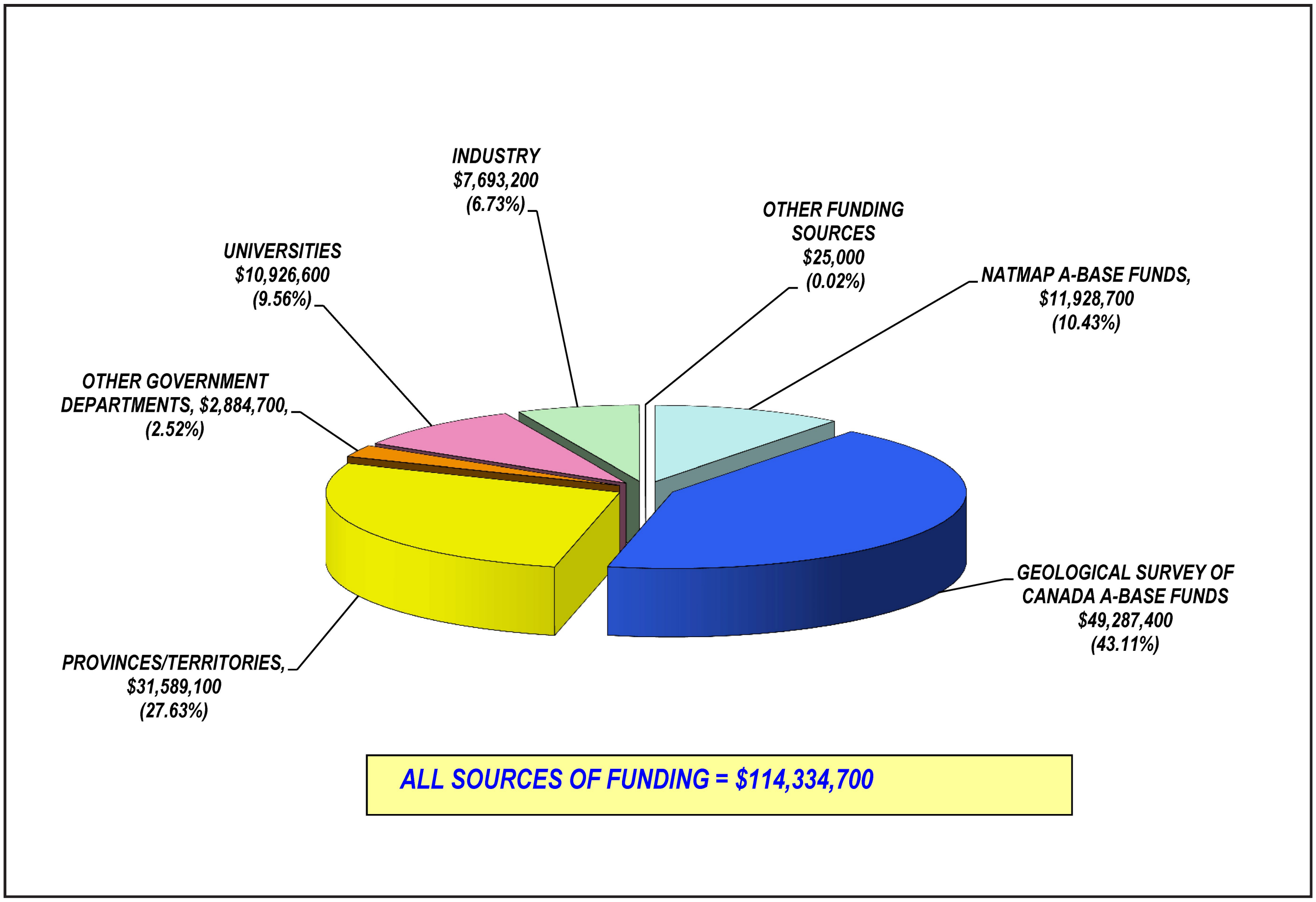

Fig.I-1: Breakdown of NATMAP Initiative funding sources. (courtesy of D. Richardson, GSC)

The scale of mapping is not the only factor limiting the current-day usefulness of a geological map. Many techniques, technologies and concepts that are an integral part of today's mapping 'toolbox', and which contribute a critical level of understanding of the nature and evolutionary history of a region's geology, were either unavailable twenty years ago, or in the early stages of development. While it is still absolutely critical in today's mapping projects that the fundamental geoscience knowledge of a map area be obtained by a skilled geologist on the ground through observations, measurements and sampling at strategically selected intervals, this knowledge is now routinely supplemented by a range of other information gained from airborne and satellite measurements and observations and sophisticated laboratory studies. As a result, mapping Canada's geology must be an ongoing process, with revisions incorporated as new tools and understandings are brought to the task and as the more remote regions gain new importance in the search for natural resources.

This does not mean that terrains must be remapped in their entirety to bring them up to current standards. Today's geological map is no longer simply a graphic representation of bedrock and surficial deposits, but might be better defined as a geospatial distribution of thematic geoscience information. Geoscience information that, besides the standard nomenclature and two-dimensional portrayal of the various rock types plus the region's structural elements, could include knowledge of chemical, magnetic, gravitational and radiometric properties of the rocks and their precise age of formation, all tied to specific and accurate geographical localities. These several components constitute a digital geoscience database, from which one or more knowledge 'layers' can be extracted, combined, correlated and extended into adjacent terrains to provide a more complete picture of the geology and geological history of the area in question, and provide the means for assessing its economic potential. Whereas the basis for producing new or revised maps can simply be gathering data at more closely-spaced geological outcrops over targeted parts of an area previously mapped in reconnaissance fashion, such as for many of the northern map areas, a new map can also be developed through the addition of another data 'layer' for a newly acquired geological parameter - geochemistry, for example - to an otherwise complete and adequate map. This new generation of digital, interactive, GIS-based maps also allows the users to add and merge their own specific data to assist their interpretations and help guide their ventures. (It should be noted that, while maps of bedrock and surficial deposits and their structural elements are still the

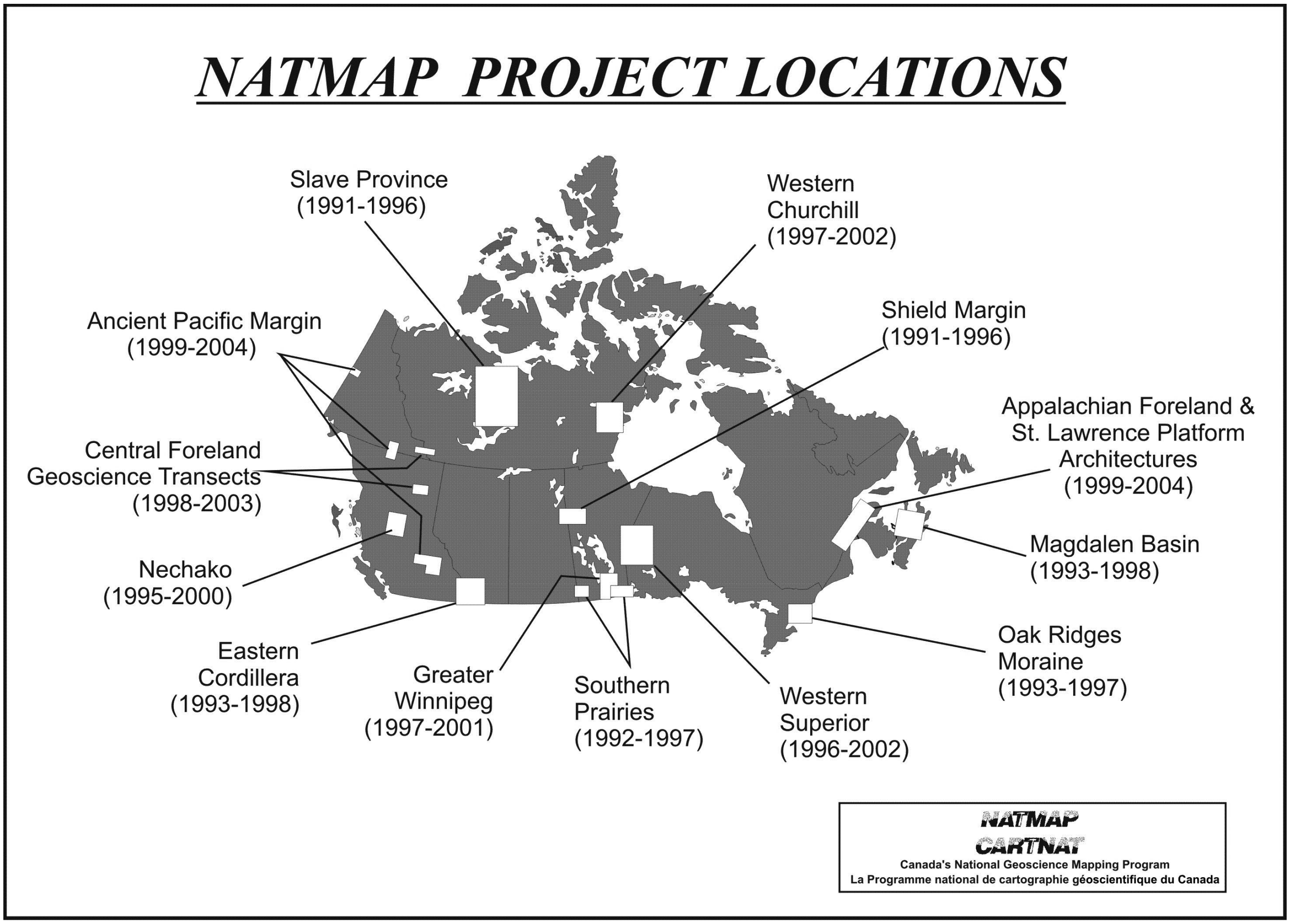

Fig. I-2: Location of the thirteen NATMAP project areas and years of operation. (courtesy of D. Richardson, GSC)

principal products of geological mapping and were largely the focus of the NATMAP program, they are not the only category of geological maps. There is an increasing variety of other maps that document specific geoscience properties to either augment knowledge of the physico-chemical nature of the rocks on the 'traditional' maps, or to delineate structural parameters whose existence could be supportive of, or hazardous to, environmental and development issues. Typical examples of the former group are maps of a region's geochemical or magnetic signatures, while maps of terrain stability as influenced by landslide potential or permafrost degradation would typify the latter).

The Value of Geological Maps

While geological maps support an expanding range of uses, including environmental impact assessments, hazard evaluation and urban land use planning for groundwater and aggregate resources, their primary value in Canada remains in providing the fundamental knowledge of a region's bedrock to direct mineral resource exploration. In a large and incompletely explored country like Canada, it is beyond the scope of even the major exploration companies to undertake the mapping of any sizeable region and well beyond the competitive nature of their business to make this information generally available. As a result, here and in many other countries this task is carried out by publicly-funded geoscience agencies - geological surveys - who provide the knowledge as a public good in support of the nation's resource-based sector of the economy. And, as is necessary with expenditures from the public purse, the questions related to public funding of geological mapping must be asked on a recurring basis. Is the information being used? Must the information be periodically updated? Is it the right information in the right format? Is there a strategy in selecting the areas being mapped or remapped? And, most importantly, are the exploration expenditures stemming from the new geoscience, and thus the contribution to the nation's economy, meaningfully greater than the cost of providing the new maps?

For over a century, the members of Canada's mineral exploration industry have recognized the value of geological maps produced by Canada's federal, provincial and territorial geoscience agencies. Having reviewed the scientific output of the GSC and its use in 1982, the resultant report of the Canadian Geoscience Council (Coope et al, 1983) concluded that a geological map was considered by all users as the single most useful type of product and that this product is irreplaceable. A similar review of the work of the Ontario Geological Survey (OGS) a year later reached the same conclusion. The Prospectors and Developers Association of Canada (PDAC) has, on several occasions, publicly acknowledged the key role that Canada's government geological surveys play in attracting mineral exploration by providing the up-to-date, comprehensive geoscience information and knowledge required by the mineral industry, and the competitive advantage that this knowledge base provides.

A number of studies to assess the value of geological mapping have been carried out in the recent past, requesting qualitative responses by the users of the geoscience information on their satisfaction with the maps and related products. Without exception, those users in the mineral exploration industry continue to indicate that geological maps, in their modern guises, are still an important factor in planning their exploration activities. A study in Australia, for example, concluded that "The modest expenditure by governments on pre-competitive geoscience has been very important to Australia's development. It has greatly stimulated private investment by reducing the commercial risk in mineral exploration and greatly improving the overall efficiency of exploration" (Lambert, 1999).

Some studies have attempted a more quantitative analysis. It is generally accepted that the ultimate impact of a geological map likely won't be realized for a decade or more after its completion, and so an evaluation of its usefulness in the few years immediately after its release would be incomplete, and perhaps misleading. In the United States, Kentucky is the only state that has completed and published maps for all its quadrangles, at a cost of $90 million, and seen at least two decades of map use. Analysis of responses by users of these maps in several fields, including exploration, indicated "the value of geologic maps to the users was at least 25 to 38 times higher than the cost of the mapping program" (Bhagwat and Ipe, 2000). Focusing specifically on the value of public geoscience to the resource exploration industries in Canada, a somewhat more involved study by Boulton (1999) found that "every $1 million of government investment to enhance the geoscience knowledge base will likely stimulate $5 million of private sector exploration expenditures . . ." , a more modest, but still appreciable, factor of 5:1. Boulton extended this analysis to conclude that this initial $1 million investment resulted, perhaps years or decades later, in the discovery of new resources with an average in situ value of $125 million.

A more recent study by Bernknopf et al. (2006) incorporated efficiency, productivity, effectiveness and risk considerations of the exploration industry users to analyse the value of government geological map information for mineral exploration. Their analysis was founded on exploration in the Flin Flon Belt of Manitoba and Saskatchewan and the South Baffin Island area of Nunavut, a mature mining district and a frontier region, respectively, and both mapped by the GSC. A calculation of the economic value of exploration activities resulting from publication of the updated Baffin Island maps ranges from $2.28 to $15.21 million. And, when compared to the $1.86 million for the cost of the mapping, results in a multiplier effect of 8 to 1. Just as importantly, the study concluded that "updated and finer resolution maps provide more detailed and accurate information than older coarser resolution maps when used as a guide for mineral exploration", and that use of the upgraded geological maps "provided more exploration options, reduced exploration risk and improved efficiency and productivity" - a confirmation of the need to periodically remap a region using the newest technologies and concepts and focusing on more promising areas delineated in the earlier mapping.

In an even more recent review (Maurice and Roy, 2009), Géologie Québec tracked the evolution of investments by the mineral industry in two large, underexplored regions where that agency had conducted major mapping projects. In northern Québec, covered by the Far North program, exploration expenditures increased almost continually from virtually zero in 1988, at the outset of the mapping program, to over $25 million by 2007. A more dramatic experience was documented over the ten years of the Baie-James region program where industry expenditures rose annually from less than $20 million in 1997 to nearly $100 million over the 10-year span of the mapping program.

From a mutual understanding of the regional priorities for upgrading our geological 'maps', and by sharing local and regional expertise and employing specialized techniques and technologies to accomplish this, GSC and the provincial and territorial surveys are continuing to keep Canada's geoscience knowledge at the high level required for socio-economic growth. Canada's NATMAP program was a major contributor to this endeavour.

The Origins of NATMAP

Mineral exploration levels generally follow the changing world prices of metal commodities. Sharp increases in the prices of gold and silver between 1978 and 1980 were reflected in a dramatic rise in exploration expenditures in Canada in 1980 and 1981 (Cranstone, 2002). However, with the almost immediate drop in the price for these precious metals in 1981, followed by the decrease in the price of nearly all base metals a year later, exploration levels fell off steeply. To offset the decline in this sector of the economy, an exploration incentive was introduced to the Canadian income tax system for the period 1983 to 1988. This meant that both major and junior exploration companies could now be more speculative in their exploration activities by venturing into unknown or poorly explored regions. However, from a survey of its members, PDAC concluded that map coverage for these regions wasn't keeping up with industry needs and that the level of geological mapping by Canada's geological surveys had declined to a level inadequate to close the widening gap (Andrews and Lawton, 1987). (The perceived problem wasn't unique to Canada; the U.S. Geological

Survey had also recognized that "current geologic mapping in the United States . . . is inadequate to meet current needs" [USGS, 1987], and the situation was similar in Australia.)

GSC acknowledged an apparent decline in traditional, systematic map coverage, but this had been paralleled by publication of more detailed, non-traditional maps and data sets resulting from various specialized research and surveys. Even though these latter products were becoming more important to the more sophisticated elements of the exploration community, the attention of the junior mining and exploration community was still focused on traditional and systematic areal geologic map coverage. GSC recognized that the PDAC concern could provide a special opportunity to propose a national review of the current-day status plus the future requirements for geological mapping in Canada. Not only was the production of new maps apparently inadequate, the ever increasing volume and complexity of geoscience data and the expanding uses to which it was being applied demanded new ways of managing and distributing this knowledge. Therefore, in 1988, as part of a periodic review of the activities of the Geological Survey of Canada, the Canadian Geoscience Council (Mossop, 1989) recommended that "creation of a modern computerized database system that incorporates all relevant existing data should be one of the highest priorities of the GSC, in collaboration with provincial surveys and industry."

To address these issues, GSC management and scientists embarked on a series of internal, in-depth discussions on the modern concept of geological maps and data standardization to define and implement a new National Geoscience Mapping Program. The latest policies and practices for improving mapping in other countries facing the same problems of inadequate geological maps, most notably the United States, were examined as part of these discussions. The timing of this exercise, while driven by the CGC and PDAC concerns, was propitious for other reasons. The current phase of Canada's Mineral Development Agreements (MDAs) was drawing to a close, prompting the need to consider future mechanisms for geoscience program delivery in the provinces and territories. As well, the Geographic Information System (GIS) was emerging as a new and essential component of all geological field observations and data analysis locations to permit better merging and comparison through computer technology of a variety of geoscience parameters over a map area.

The result of GSC's deliberations was an internal document in early 1989 outlining a potential GSC national mapping program to fill this 'map gap'. Later that year, as a result of discussions with other mapping agencies in Canada, GSC prepared a revised program "much broader in scope and potentially involving all mapping agencies in Canada, titled *Canada's National Geoscience Mapping Program (NATMAP)*." The revised NATMAP program was then presented to the Canadian geoscience community at a workshop in early 1990, attended by representatives of provincial/territorial geological surveys, industry, academia, other federal agencies and professional associations. Workshop participants reached substantive agreement on the concept of NATMAP as a cooperative, multidisciplinary program, and a number of important guiding principles were defined (St-Onge, 1990). Principal among these were that NATMAP would (1) foster coordination of mapping activities among federal, provincial and territorial surveys and Canada's universities, (2) employ all available and developing computer technologies for digital mapping and geoscience data management, and (3) contribute to the development of the next generation of skilled field geologists by employing and training undergraduate and graduate students in the various mapping projects. To help ensure adherence to these principles and other recommendations, NATMAP was to be controlled by a National Steering Committee (renamed National Coordination Committee in 1995) representing all participating agencies. (Introduction Appendix A)

The workshop participants recognized that development of these guiding principles was only the first step in addressing the growing demand for new geological maps, and that the next challenges would be to identify projects for an expanded mapping program and to confirm and allocate the resources to carry them out. These tasks were undertaken by the newly constituted NATMAP Steering Committee, led by GSC- and provincial (Manitoba) co-chairs and composed of eleven representatives of the GSC, provincial surveys, industry and universities, served by a GSC-based Secretariat whose manager was seconded from the Ontario survey for two years.

The Steering Committee stressed to all potential participants that the NATMAP Program was not a granting agency to provide total funding for a project. Rather, NATMAP would provide supplementary funding to expand and enhance mapping programs that were largely funded from other sources - the annual financial appropriations to the federal and provincial/territorial surveys by their respective governments, Natural Science and Engineering Council (NSERC) Research Grants and provincial Geoscience Research funds. NATMAP's fundamental principles were firmly enough established to allow the launch of two 'pilot' projects in the summer of 1991 - the Shield Margin NATMAP and the Slave Province NATMAP. Both areas were already the site of GSC geoscience projects whose goals were largely those of the NATMAP aim of enhancing Canada's geological map coverage and associated geoscience knowledge. The Steering Committee notionally identified a reallocation of $500,000 of GSC funding for this first set of GSC-led projects, divided almost equally between field operational costs and salary and laboratory support costs. The expectation was that this would be at least matched by other GSC funding related to the projects.

The new NATMAP Program was officially announced in a fan-fold pamphlet (NATMAP, 1992) in early 1992, and widely disseminated to the Canadian geoscience community. NATMAP elements were defined (in part) as follows:

- What is NATMAP?: NATMAP is an initiative of the Geological Survey of Canada to increase the level of geoscience mapping in Canada. NATMAP encourages coordinated projects by all agencies with an interest in the geosciences to reduce operating expenses and duplication of effort, and produce integrated projects. NATMAP supports projects that maximize the application of computer technology. NATMAP will contribute to the development of the next generation of skilled field geologists in Canada by supporting projects that provide opportunities for students to obtain practical training in mapping disciplines.
- What makes a NATMAP project?: NATMAP projects must meet the following criteria:
- What makes a NATMAP project?: NATMAP projects must meet the following criteria:
- projects must produce geoscientific maps as major outputs.
- projects should be multi-disciplinary. Mapping must be the principal component, but projects should incorporate other disciplines (*e.g.* geophysics, engineering geology, geochronology, hydrogeology, geochemistry, stratigraphy, paleontology, structural geology) as required.
- projects should be cooperative (i.e. involve more than one agency) and, where possible, should result in integrated products that combine the results of different agencies and different disciplines.
- projects should involve undergraduate and graduate students from Canadian universities in their field components.
- projects should capture new data in digital format.

NATMAP - A Major Change in Geological Mapping

Before 1990, GSC's mapping projects had been carried out by its several Divisions, based on the expertise and responsibility of that Division: the crystalline rocks of the Precambrian Shield, the sedimentary rocks of the large sedimentary basins, the unconsolidated overlying deposits, or the geophysical parameters of these lithologies. Bedrock mapping projects were defined by a senior geologist, based on matching the training, experience and interests of the mapper to a particular region's scientific potential. The project's rationale was that the area was unmapped or insufficiently mapped, a premise that served the nation well for the first century of the GSC's existence. Project proposals that stated objectives, method, budget, milestones and participants were remarkably brief and general and were usually approved and annually renewed with limited discussion. A regional mapping project would be carried out at 1:250,000 scale over a three-year period, moving the field operations each successive year to an adjacent quarter-million map sheet. Little regard was paid in advance of the field activities to any existing maps, likely at 1:1million scale and compiled twenty or thirty years beforehand, nor to the samples from these earlier efforts archived in the GSC sample repository. Although preliminary results were released every year, as no time schedule for compiling and publishing the maps and reports was formally built into the project plans, commonly the final publications weren't produced until several years afterwards. Bedrock mapping meant simply that - examinations on the outcrop and in the laboratory to produce a map and report of a region's bedrock lithologies and structural relationships. Projects didn't include airborne geophysical, or ground-based geochemical surveys that could help understand an area's mineral potential. The nature and extent of surficial deposits and the region's glacial landforms and history were similarly not considered. Studies of these complementary geoscience elements weren't ignored, but commonly weren't undertaken for several years afterward, or over areas whose boundaries or mapping scale might not correspond to those of the bedrock map. As a result, clients who were interested in learning the total geoscience story of a region to help assess its mineral potential were obliged to assemble the several component maps and reports and to devise the relevant correlations and economic implications on their own before planning and executing an exploration venture.

Acceptance of the NATMAP concept, principles and practices meant a significant and necessary shift in how the GSC proposed, planned and carried out its major geoscience mapping projects. NATMAP projects had to have a defined, defensible and timely rationale. Each scientific endeavour would need to bring together all the tools and expertise necessary to provide the complete geoscience story. NATMAP projects were both multi-disciplinary (geology, geophysics, geochemistry) and interdisciplinary, with the experts in each aspect integral to the project's planning and execution. (Now, for example, airborne geophysics is routinely the first step in bedrock mapping, with its data and interpretation essential in guiding the field mapping in following years.) Projects would be GSC-led, but the requisite technical and academic expertise could be drawn from the appropriate source, whether GSC, provincial or territorial survey or university. The planning for each project would include both the research period plus the time to properly complete the scientific outputs. Milestones and budgets for each year of the 3- to 5-year duration would be detailed at the outset. Project proposals and the details of budgets, methods, timetable and expected outcomes and outputs would require review and approval by a panel whose members were drawn from appropriate facets of Canada' geoscience community. Progress would be assessed annually by the same panel to determine whether the project would proceed. Although these ideals and principles were not always realized during NATMAP, with modifications over the succeeding years these elements of relevance, accountability, collaboration and an interdisciplinary approach have largely become the standard requirement for all of GSC's scientific endeavours.

Before roughly 1974, Canada's federal and provincial public geoscience agencies generally carried out their geological mapping without collaborating on projects that overlapped or abutted their political jurisdictions, or taking advantage of expertise extant in another agency. Some provinces were wary of allowing GSC to infringe on their territory and GSC felt that the work carried out by some provincial surveys focussed on the mineral industry and economic development, whereas it took a broader and longer-term approach. Although individual scientists in GSC and the provincial surveys occasionally collaborated for specific and limited projects, the two spheres officially, and contentedly, worked independently.

But the seeds for a spirit and environment of formal collaboration between GSC and its provincial/territorial counterparts that became the strength of NATMAP had been sowed under two earlier federal, regional economic development initiatives in the 1970s and 1980s. Under the General Development Agreement (GDA), managed by the Department of Regional and Economic Expansion (DREE) from1974 to 1984, federal funding was allotted to provinces for a variety of initiatives to help stimulate economic development, initiatives that included attempts to expand and prolong the mining and minerals industry through geoscience studies geared to improving the knowledge of a region's mineral potential. Under the GDA initiative, the provincial surveys could call upon GSC to assist in specific aspects of the various geoscience projects using GDA funds to contract unique GSC expertise, airborne geophysics and mineral deposits knowledge were common examples, to compliment the skills of the resident provincial geoscientists. GSC had no official role, however, in the selection of the project area or studies to be undertaken, nor in the management of the project.

The following decade (1984-94) saw GDA succeeded by the Economic and Regional Development Agreement (ERDA). Again, an important component of this new federal initiative was maintaining the viability of Canada's mineral industry. The federal Department of Energy, Mines and Resources (succeeded by Natural Resources Canada) was assigned responsibility for the minerals component of ERDA under the several Federal-Provincial Mineral Development Sub agreements (MDAs) that were negotiated between EMR and each province and territory (Prince Edward Island, without important mineral resources, didn't participate). Under the MDAs, GSC undertook to work with each province to develop geoscience projects to address each region's particular minerals potential, and to ***jointly*** determine how the strengths of the federal and provincial geological surveys could be cooperatively employed to prioritize and deliver relevant projects. Although both federal and provincial geoscience agencies participated in a province's MDA endeavours, and thereby operated in a collaborative manner, scientists of the two agencies still commonly operated in different areas and on different themes, rather than being intermeshed in a larger, cohesive project that required continual consultation, interaction and review. (Sadly, from a provincial geological survey point of view, the demise of the MDA agreements drastically affected geological mapping by these agencies. That, combined with government funding cutbacks in various jurisdictions, forced a reduction in the geoscience programs of several provinces. While NATMAP funds certainly helped keep some activity going, in Newfoundland and Labrador, for example, it was only a minor positive note in a climate where geological mapping had declined to half what it was during the 1980s.)

One purpose of both the GDA and MDA initiatives was to assist the respective provincial and territorial geoscience organizations in developing their staff complements and expertise to enable an expanded and more effective capability in the management, encouragement and provision of geoscience data to its industry. Another, unstated, hope of the initiative was that by the GSC working cooperatively and collaboratively with these agencies, the federal organization would be treated with less suspicion in their jurisdictions and, where appropriate, welcomed in projects within their borders. Nonetheless, under GDA and the MDAs, Canada's geological survey organizations were becoming more accepting of one another's expertise and more understanding of their mutual roles in delivering the fundamental geoscience required to further this country's minerals industry. It was this new appreciation of the federal and provincial/territorial mandates and abilities that encouraged GSC to embark on Canada's National Mapping Program (NATMAP), and to expand the nature of the collaboration beyond the traditional bedrock mapping to the various studies of Quaternary geology and the environment that were a major part of several NATMAP projects.

Funding NATMAP

At its formal conclusion in 2003, Canada's NATMAP Program had been one of the most heavily-funded geological mapping programs in the history of the Geological Survey of Canada, calculated at approximately $115 million from all contributors (Table 1). Funding sources included the GSC's NATMAP Program and A-Base budgets, nine provincial and three territorial geoscience agencies, a dozen or so other federal and provincial government departments or agencies, a score of universities and as many exploration and consulting companies.

Guidelines for the NATMAP Program included the proviso that NATMAP would provide supplementary funding to expand and enhance mapping programs that were largely funded from other sources. GSC management took supplementary funding to mean, as a rule of thumb, no more than twenty percent of the project costs. 1 clearly indicates that

Table 1. NATMAP funding summarized by sources of funds

Funding Source	$K	%
NATMAP	12028.7*	9.9
Geological Survey of Canada	50415.8	41.6
Provinces/Territories	38894.9	32.1
Other Government Depts	1104.2	1.0
Universities	10926.6	9.0
Industry	7693.2	6.3
Other	25.0	0.1
Totals	121088.4	100.0
* Includes $200K to support the NATMAP Secretariat function		

this goal was achieved and provides a graphical representation of the relative contributions from the main funding sources.

While every attempt has been made to identify all sources and to compile exact figures, with such a wide range of contributors and type of support it is certain that some have been unavoidably overlooked or imprecisely valued. The yearly NATMAP Report of Activities documents, prepared by the GSC NATMAP Secretariat, contain excellent summaries of the annual GSC NATMAP budget assignments to each project, plus funding and expenditure/budget summaries for each project submitted by the respective project leaders. Unfortunately, not only did this series of reports not commence until 1993-94, but detailed funding information wasn't a requirement for the project reports until the following year. Thus, only some components of the financial accounting could be discovered for the projects operating in 1991-92 and 1992-93. As well, a complete report for the Slave NATMAP project wasn't available for either 94-95 or 95-96. Other difficulties in reporting funding arose from the type of support. Much of the contribution from industry, for example, was of the 'in-kind' category where companies provided logistical support for field operations, or data and samples from their archives. While extremely valuable, the true dollar values are difficult to determine. In addition, inconsistencies in identifying total dollar contributions likely arose due to different accounting practices among the various major contributors, especially where salaries of participants might or might not have been included as part of the support. In some instances, funds from other organizations were transferred to the GSC NATMAP project, and are readily calculable. In many other cases, however, support from an outside organization was used by that organization solely in support of its specific research activity and exact figures might not have been accounted for under the project summary. It is certain, therefore, that the calculated figure of $114.3 million (Table 1) has underestimated the total expenditures, and that a total of $116 – $120 million would more realistically approximate the total funding contributions.

Using the information available, a breakdown of funding by project and funding source is presented in Tables 1-8 of Appendix B. NATMAP funding ceased in 2003-04, but a few of the mapping projects still had loose ends to tidy up at that point and these components were funded in the following year under the GSC's Proposal Approval System (PAS).

Despite the difficulties encountered in compiling these figures, the calculated $114 million contributed from a broad range of sources and used to undertake an even greater spectrum of research and publication activities is an impressive testament to the effective management of the NATMAP Program.

The NATMAP Projects

NATMAP projects were conceived, proposed and developed by one or more GSC scientists, commonly with consultation and input from provincial/territorial colleagues who, in turn, sought guidance from their respective mineral industry associations regarding their particular exploration interests and how they thought such interests could be addressed by the acquisition of new geoscience knowledge. Thirteen geological mapping projects were approved and undertaken under the NATMAP banner, and details of each are presented in the chapters that follow. At least four additional projects were proposed and reviewed, but did not receive approval for NATMAP support. Nonetheless, most of these projects were of value and were undertaken, at least in part, funded through the GSC A-Base or other non-NATMAP budgets. It is true that most of the projects were located in the western half of Canada, but the geographical (and political) distribution of the thirteen mapping projects (Figure 2, Table 1) is, nonetheless, a validation of NATMAP as a "national" mapping program. The NATMAP projects produced new geoscience knowledge for an area of roughly 1 million km^2, or an impressive 10% of Canada's landmass.[1]

The results of the individual NATMAP projects have been synthesized, archived, interpreted, published and communicated in a wide variety of forms and in countless scientific reports, maps, databases, theses, posters, field trips and oral presentations. By 2000, in a report commissioned by GSC as an outside evaluation of NATMAP (Gartner, 2000), it was estimated that the program had resulted in the publication of more than 500 geological maps and more than 1500 reports. It is probably fair to say that similar products appearing in the three succeeding years of NATMAP, plus those completed and published in the few years afterward, increased the total NATMAP by an additional 50%. The purpose of this report, however, is not to try to present comprehensive, or even extensive, details of, or references to, this immense volume of new geoscience knowledge, and so the reader interested in this level of information is advised to conduct a literature search using standard methods.

[1] It could be argued that a large part of these areas would have been mapped by the GSC and provincial surveys anyway, regardless of the NATMAP Program and funding

Table 2: Summary of NATMAP projects by years of operation

Project	91-92	92-93	93-94	94-95	95-96	96-97	97-98	98-99	99-00	00-01	01-02	02-03	03-04	Total
Shield Margin	250.0	250.0	350.0	255.0	180.0									1285.0
Slave Province	220.0	350.0	350.0	300.0	100.0									1320.0
Quaternary of Southern Prairies		118.0	210.0	217.0	200.0	150.0	7.5							902.5
Eastern Cordilleran			148.0	184.0	184.0	189.0	133.0							838.0
Oak Ridges Moraine			117.5	175.0	175.0	215.0	10.0							692.5
Magdalen Basin			85.0	220.0	245.0	200.0	82.5							832.5
Nechako					181.0	300.0	265.0	232.0	112.0					1090.0
Western Churchill							315.0	300.0	200.0	180.0	143.6			1138.6
Western Superior						10.0	250.0	250.0	225.0	225.0	171.6	8.4		1140.0*
Greater Winnipeg							165.0	165.0	150.0	50.0				530.0
Central Foreland Geoscience Transect								250.0	203.0	225.0	202.5	225.0		1105.5*
Ancient Pacific Margin								20.0	202.5	225.0	202.5	225.0	225.0	1100.0*
Appalachian Foreland & St. Lawrence Platform Architectures									110.0	225.0	202.5	225.0	220.0	982.5*
TOTALS	470.0	718.0	1260.5	1351.0	1265.0	1064.0	1228.0	1217.0	1202.5	1130.0	922.7	683.4	445.0	12957.1**

* The NATMAP Program formally ended in FY2001-02. The four projects that continued in 2002-03 and 2003-04 had been notionally approved to receive NATMAP funds in those years, so were then funded under the GSC's PAS (Program Approval System) to enable their completion. The totals presented above, therefore, represent the total GSC NATMAP project costs. Annual funding support provided for the NATMAP Secretariat function from 1991-92 to 2001-01 (~$20K per year) is not included

The chapters that follow, however, try to present a higher-level view of each project. What were the circumstances that suggested the need for particular geoscience knowledge? What were the constraints on the extant knowledge? What were the goals of the NATMAP project? How would the new knowledge to achieve these goals best be gained in terms of areas to be researched, necessary expertise, sharing of duties and techniques and technologies to be employed.

The Success and Legacy of NATMAP

As was its intent, the primary legacy of NATMAP is the important advances in Canada's geoscience database and interpreted knowledge made in each of the thirteen project areas, advances that have been documented, portrayed, manipulated and communicated in a variety of ways for use by a range of stakeholders. By 2000, it was estimated that the program had resulted in the publication of more than 500 geological maps and more than 1500 reports. Similar products appearing in the three succeeding years of NATMAP, plus those completed and published in the few years afterward, increased the total NATMAP by an additional 50%. Maps and potential economic implications were presented to the resource exploration sectors at gatherings of this industry. Field trips, guided by the NATMAP geoscientists to significant newly mapped areas, provided on-site interpretations for industry colleagues with an interest in the areas in question. Databases of geology, geochemistry and geochronology parameters, GIS-referenced to field localities, are accessible for application in a wide range of issues - economic, environmental, societal - where geoscience makes an essential contribution. The acquisition of large amounts of new geoscience data, and the requirement to make it easily accessible and applicable in the emerging digital data world, necessitated development of a range of new and readily usable techniques and tools for data acquisition, standardization, archiving, manipulation and dissemination, often specific to a particular project's needs. Many of these, or their derivatives, have become standard components of today's geoscience 'toolbox'.

Although one might wish to measure the "success" of NATMAP in largely economic terms – increased spending on exploration and discovery of new ore bodies, and contributions to Canada's GNP from new mines brought into production, both those who compile the 'maps' and the industry users fully recognize that the ultimate value of publicly-funded, base level geoscience lies in the longer term. As Dirk Templeman-Kluit, VP Exploration, Richfield Ventures Corp, stated (pers comm.), referring to the results of the Nechako NATMAP project, "NATMAP [projects] do not by themselves drive discoveries – economics plays a huge role. It is really the building of information that started generations before – the work to improve the data base and to get it into the public domain – that allows timely economic decisions to capitalize on markets. NATMAP and all geological surveys deserve credit for improving the base data. That is the proper role – it is up to industry to take it to the next step and do the discovering." Nonetheless, examples can be cited from virtually all projects that focussed on improving knowledge for resource exploration where incorporating the new NATMAP geoscience into exploration strategies has had immediate results.

- The Lucky Joe copper-gold occurrence in the Stewart River, Yukon, region was recognized following staking and sampling of a significant geophysical signature revealed in airborne magnetic surveys as part of the Ancient Pacific Margin project.
- The expansion of known reserves at the Endako molybdenum mine, B.C. used the new Nechako project geoscience as it was released to target new prospects, and new claims were staked over a molybdenum anomaly discovered by the NATMAP geochemical survey data.
- The new geoscience knowledge from the Central Foreland project (Alberta) contributed to resource exploration expenditures on the order of $400 million and the drilling of 48 new wells, including 17 successful gas producers between 1998 and 2006.
- New geological maps and structural cross sections from the Eastern Cordilleran project (Alberta) greatly assisted industry in developing and successfully exploring new plays for oil and gas; in the Triangle Zone, 55 new wells, at an average cost of $2.3 million, resulted in the discovery of 974 million m^3 of gas reserves.
- The release of till characterization data for the southeast Manitoba segment of the Southern Prairies project, that revealed gold, base metal and kimberlite anomalies, immediately led to the largest mining claim staking in the province's history, with a corresponding investment of $5-$10 million.
- Western Superior project results, that provided a westward correlation of geologic units of the Red Lake Belt, Ontario, led to redoubled gold exploration investment, while southeastward correlation prompted new staking of 24,000 acres.
- Hydrocarbon exploration expenditures in Quebec, virtually nil before the initiation of the Appalachian Forelands NATMAP project in 1999, reached a record $24 million in 2004, the final year of the project.

Not all of the thirteen NATMAP projects, however, were designed to acquire new understandings of a region's geology to aid the mineral and petroleum exploration industries. In particular, the principal aim of the multifaceted Oak Ridges Moraine project was to understand the geomorphology of this feature and, thereby, to aid in establishing principles and practices to preserve this critical source of groundwater for the greater Toronto region. As one result of this NATMAP project, the Oak Ridges Moraine Conservation Act was enacted by the Government of Ontario in 2001. Groundwater sustainability was similarly a major focus of the Greater Winnipeg project, but other components addressed human and natural influences on Lake Winnipeg evolution and a better understanding of Red River flooding from a long term prospective. The principal success of these latter studies has been a dramatically increased awareness by various government, industrial and environmental communities of the need to incorporate geoscience in their planning.

The legacy of the NATMAP program, however, extends beyond the actual new geoscience knowledge gained from diligent field and laboratory studies, and how this knowledge has contributed to new economic ventures or environmental management practices. The federal-provincial geoscience collaboration that became a cornerstone of NATMAP's success and is commonplace, expected and valued today, required a major culture shift that was generally accepted by management of all organizations. The willingness at senior leadership levels to venture into collaborative projects translated into a changed culture of acceptance at the scientist level on both sides. In his report on the evaluation of the NATMAP Program, Gartner (2000) partially quoted a respondent from a provincial survey. "NATMAP stands out as the most cost-effective, pragmatic, inspirational and productive model for co-operation between geoscientists in Canada . . . . it has left a lasting legacy of goodwill between all who have shared the co-operative experience." To also quote (pers.comm.) the head of one of the provincial surveys who was involved throughout the Program span, "One of the greatest inter-organizational outcomes of NATMAP was a very clear understanding gained by all federal, provincial and territorial players on expectations, management and operational processes and responsibilities, collaborative project management practices and resultant colleague-to-colleague relationships that enhanced the post-NATMAP science collaboration at the technical level. We learned what worked and what didn't work. [NATMAP] afforded an opportunity for federal, provincial and territorial collaboration that was a milestone in helping to guide future science collaborations."

The new spirit of federal-provincial collaboration was generally welcomed also at the individual scientist level from both sides. As a member of the Manitoba Geological Survey expressed, not only was it invaluable to be able to combine the talents of MGS, GSC and OGS geoscientists in the Western Superior NATMAP project, it was "exciting" to be part of a dynamic team proposing and discussing ideas and concepts whose validity would be researched in the field studies. And, from a member of the Newfoundland and Labrador Survey involved in the "Bridges" project, "the NATMAP project brought me into much closer contact with the excellent group of scientists at the GSC Quebec office, whom I came to hold in very high regard both on a professional and a personal level", a connection that had practical and positive implications for other projects where the two organizations shared an interest.

But it is important also to note that the NATMAP Program had its flaws and criticisms, many of which were pointed out in the evaluation survey report. As Gartner initially noted, "Weaknesses of the program that were reported by respondents [GSC, provincial surveys and industry] were often perceived or related to human factors and not really program weaknesses." But a more encompassing problem was that "there was not a rigorously unbiased process built into NATMAP to determine mapping priorities for the future, say 5 to 10 years. In other words, lack of a strategic vision." As well, the goals and objectives of the program meant, generally, that only larger projects were proposed, considered and funded so that large dollar resources were focused on relatively few -13 - projects. "Funds that could and maybe should have been spent in other projects and programs were designated as NATMAP funds", and it was observed that "an inordinate amount of money was actually controlled by the Co-ordination Committee" which, from GSC's standpoint, "negatively impacted GSC management's control of much of its budget".

Another weakness, this from an operational point of view, stemmed from the original goals and objectives of NATMAP that stated NATMAP *should not undertake systematic regional geophysical or geochemical mapping, although available information will obviously be used, and new information may be generated if essential*. According to Gartner, "this was interpreted that geophysics and geochemistry should not be considered on NATMAP projects." For some of the projects, other parallel projects in geophysics, geochemistry and hydrogeology in the same areas could be linked to the NATMAP project to augment and support the geological mapping efforts, but not in a true interdisciplinary sense. While not in Gartner's summary, it is worth noting that many members of provincial surveys and industry believed that the GSC's rigid management, reporting and renewal processes meant that the GSC projects leaders were obliged to spend too much time on these aspects, which reduced their time spent mapping.

The new geoscience knowledge gained under NATMAP projects was meant, for the most part, to assist the exploration industry in assessing the potential for economic opportunities in the regions mapped and formulating their exploration strategies. NATMAP consultation with industry stakeholders about what type of program or priorities they would like addressed, didn't always translate into the areas or activities that industry considered the most useful at the time for their needs. As these consultations commonly occurred through the established provincial-territorial client networks, it was these agencies, not the GSC, who received the annoyance of these companies.

From a project delivery standpoint, there were differing perceptions about how rapidly the NATMAP results were disseminated, at least for some projects. At one annual NATMAP review meeting, for example, an influential industry member took NATMAP to task for the slow to non-existent release of some data.

Nonetheless, the environment of cooperation generated largely under NATMAP has continued well beyond the original program. It has become an invaluable part of today's major geoscience programs carried out by the GSC with its provincial and territorial counterparts. As a prime example, the three phases of GSC's highly successful Targeted Geoscience Initiative (TGI), commenced in 2000 and re-funded through 2012, planned and carried out in collaboration with provincial surveys, universities and industry, were a direct result of the successful interaction realized under NATMAP. Recognition of the value of sharing geoscience expertise in collaborative geological mapping projects took time to develop, however.

The Geological Survey of Canada has always managed its scientific projects through some form of approval and review system for the work undertaken and the funding required. In the era before NATMAP, most projects were each carried out by just one, or a few, GSC scientists. The approval and review steps largely involved completing relatively brief, standard forms and one-on-one discussions between the lead scientist and the responsible division director. It was common for projects to run for several years, with annual modifications incorporated to reflect the previous summer's findings that might shift the research for the subsequent field season. NATMAP projects were generally on a much different scale, however, in terms of the larger budgets required, the greater number of scientists involved from various agencies, and the associated need to demonstrate that the substantial dollars and human resources allocated would provide the desired results within a realistic time frame. Assigning up to $250,000 of NATMAP funds annually and competitively to a geological mapping project required that the goals were worthwhile and well understood, that definable progress was made and documented each year and that value was being received for the research undertaken. This strict set of principles applied, however, only to projects seeking NATMAP funding - those competing for a share of the roughly $1.2 million of the GSC's operating (as opposed to salaries) budget set aside for NATMAP. The remainder of the operating budget, roughly 95%, continued to be apportioned among GSC divisions and assigned by each division to its respective suite of projects as before.

It became apparent that the NATMAP format and process of project submission, review, selection and funding provided a rigorous new system of accountability whose practices and benefits should be applied more widely across the scientific program. As a result, for its operations in 2000-2001, GSC instituted the Proposal-Driven System (PDS). Proposals for all scientific projects were scrutinized by selected subject experts, within and outside GSC, whose recommendations were the basis for GSC management decisions regarding the approval and receipt of funds for meritorious projects. Like most new management systems, PDS experienced difficulties with its implementation. Nevertheless, its principles were sound, so the problem elements were modified and it was reborn the following year as the Proposal Approval System (PAS). The main change was that now there was no requirement for project proposals to be reviewed by experts outside the GSC, although this option could be exercised if management believed a broader-based opinion would be of benefit. Despite the improvements, PAS, too, was just as short-lived, being in effect only for 2001-2002. The following year, the Earth Sciences Sector, of which GSC was a part, instituted the results-based, issues-driven regime that has continued, with modifications, to the time of writing. But the NATMAP principles of rigorous project review and evaluation and continuous accountability have remained at the core of the issues-driven system, and the milestone of the NATMAP style of project management remains as another significant legacy of this important GSC program.

An essential part of the education and training of students undertaking geology studies in Canada's universities has always been the practical training gained from participating in, and being educated by, the summer field programs of the GSC and provincial surveys. This aspect is almost unique in the world and attracts geology students, from abroad as well as Canadian universities, who wish to gain field experience by working with Canada's geoscience agencies. In recognition of the benefits of this type of training in preparing the next generation of geologists, one of the five stipulations of the NATMAP program was that "projects should involve undergraduate and graduate students from Canadian universities in their field components, and in other activities where possible." To this end, roughly 250-300 undergraduate and graduate students were integral members of the NATMAP project field mapping teams. (The actual numbers of participating students was likely lower than had been working with the various geoscience agencies in the 1980s, a function of the strong economic climate of that decade.) The value of this participation was described by one of the GSC project leaders, whose project benefited from 51 student assistants over the five-year investigation. "Mentorship is a major collaborative effort and is a key factor in the breadth of participation, providing field experience for undergraduate and graduate students and young researchers. Many individuals were employed over several summers and part-time through the winter. This allowed the project to make more efficient use of the time invested in training them. It also expanded the students' work experience. The Geological Survey of Canada benefits because training young Canadian geoscientists for the future benefit of Canada is part of its mandate; and a few of them come back to grace its halls eventually. Provincial surveys have a similar mandate and experience. In a time when scientific research, and particularly government science, is not considered a priority to Canadians, it is increasingly difficult to finance our mandate. This collaboration helps us to carry out a vital part of our mandate while, at the same time, extending our limited operating resources." No attempt has been made to systematically document the education or career paths of the scores of students who participated in the NATMAP program. There is, however, enough anecdotal evidence to indicate that many of Canada's young professional geoscientists of a decade later were among those who gained at least part of their training and experience in this national geological mapping program, and so the legacy of NATMAP lives on in the careers of these individuals.

Acknowledgements:

The author was not directly involved with the NATMAP Program as a whole, nor with any of the mapping projects, and so has had to rely entirely on a variety of written sources and very many individuals to furnish the information for this compilation of the history and accomplishments of NATMAP. Here, I wish to acknowledge the contributions that have helped immensely in understanding and documenting the overall NATMAP Program, whereas, at the end of each project chapter in the section that follows, I acknowledge those whose help has been invaluable in preparing the detailed information for the respective projects. In the latter case, since all of the projects ended some years ago, I am especially grateful to many former NATMAP Project Leaders, all of whom have moved on to other major research interests or to positions outside the GSC, for taking time from their current responsibilities to assist in this compilation. This assistance ranged from entire writing of the first draft of a chapter, editing of the author's drafts, suggestions for written reports to reference, provision of illustrations, plus recommendations for contacts in other organizations. I also wish to thank the heads of all the provincial and territorial geological surveys in 2005 who, at the inception of this undertaking, provided the names of members of their staffs whom I could contact to learn more about the specific NATMAP projects carried out cooperatively within their respective jurisdictions. Many of them, or their successors, also read a draft of the Introduction, and offered valuable insights and comments on the successes and shortcomings of the NATMAP concept, its management and implementation, opinions I've tried to reflect in the final manuscript. In this regard, I'd particularly like to acknowledge Dr. Andy Fyon, Ontario Geological Survey, Dr. David Liverman, Geological Survey of Newfoundland and Labrador, Dr. Carolyn Relf, Yukon Geological Survey, Dr. Les Fyffe, New Brunswick Geological Surveys Branch and Dr. Dave Lefebure, British Columbia Geological Survey. Other useful comments on the overall NATMAP Program from the provincial and territorial standpoint were received from Dr. Steve Colman-Sadd (Nfld),

During the "NATMAP years", the program was managed effectively in the GSC by the two-person NATMAP Secretariat - Dr. Michael Cherry (NATMAP Coordinator) and Dan Richardson (NATMAP Secretary). For the years 1993-94 through the program's conclusion in 2002-03, they prepared an invaluable series of annual reports (Review of Activities) which were the author's primary source of information on project objectives, progress and products, funding and partnerships and collaborations. Both have also provided insightful comments on NATMAP. I am particularly grateful to Dan whose daily work I continually interrupted while he graciously explained (or re-explained) some aspect of the program, either from his remarkable memory or reference to documents in his legendary library of files, and for providing Figure 2. Dr. Bill Poole (GSC) kindly educated me on the Mineral Development Agreements, while Dr. Marc St-Onge (GSC) offered insights on the way GSC geological mapping projects were planned and undertaken before NATMAP, and provided valuable suggestions for improving the final manuscript. I wish also extend my thanks to Dr. Daniel Lebel who, when a member of the GSC, first suggested that a NATMAP compilation would be valuable as a future reference to this important GSC initiative, and to Dr. Murray Duke and Dr. David Boerner who supported this project through advice, encouragement and the opportunity for me to undertake and see this project through as an Emeritus Scientist in the GSC.

II - SHIELD MARGIN NATMAP PROJECT

Rationale and Geologic Setting

The Shield Margin NATMAP project was undertaken to enhance the geoscience knowledge of a broad swath, some 100km wide, of complexly deformed Precambrian age rocks extending east-west across the central part of Manitoba into Saskatchewan. This terrane, known as the Flin Flon - Snow Lake - Hanson Lake greenstone belt (here abbreviated to Flin Flon belt), lies at the southern margin of the Canadian Shield in these provinces, hence the name Shield Margin project. Greenstone belts are elongate areas of metamorphosed and deformed volcanic and sedimentary rocks that commonly host gold and base-metal deposits, and this greenstone belt was already an important producer of base metals. At the inception of the NATMAP project, Hudson Bay Mining and Smelting was producing copper and zinc from nine mines in Manitoba: six in the Snow Lake camp and three in the Flin Flon camp. Several other deposits were also known, some with the potential to become producers. Nonetheless, the futures of these two mining camps and, consequently, the Flin Flon smelter, were uncertain in the early 1990s due to a lack of defined long-term ore bodies. An improved knowledge of the geology and deformational history of the greenstone belt to direct renewed mineral exploration could be expected to increase the likelihood of discovering additional important deposits to strengthen the mining economy of the region, both in Manitoba and Saskatchewan.

The Flin Flon belt is a relatively small part of the Trans-Hudson Orogen of Paleoproterozoic (1.9 - 1.8 billion years old; or 1.9-1.8 Ga) rocks that extends from South Dakota northward through Saskatchewan and Manitoba and across Hudson Bay to northern Quebec. The main lithologies of the Flin Flon Belt comprise oceanic volcanic rocks, plutons and sedimentary rocks emplaced in an intra-oceanic setting between, and on the margins of, two ancient Archean cratons, and that subsequently were deformed by events associated with the collision of the two cratons at the end of this period.

Regional mapping of the Flin Flon region began just prior to the end of the 19th century, but the discovery of gold in 1913 led to a flurry of more detailed mapping, which continued intermittently in Saskatchewan until the mid-1960s. At that time, a major report and map was published by the Saskatchewan government that came to be known as the bible of Flin Flon geology in Saskatchewan for the next 30 years. The report was quickly joined by the results of a symposium on the geology of the Coronation base metal mine. Over the next two decades, some property-scale studies were conducted in Saskatchewan but most mapping tended to focus on the more highly metamorphosed rocks north and west of the immediate Flin Flon area. A new generation of superb detailed geological mapping on the Manitoba side of the immediate Flin Flon area from 1979-1983 was released in 1989 and led to a renewed mapping effort on the Saskatchewan side that same year. Due to the overlapping nature of the Flin Flon Belt, it was quickly recognized that much more meaningful results could be obtained from a collaborative, multi-disciplinary approach involving the Saskatchewan and Manitoba provincial governments and the federal Geological Survey of Canada.

The principal activities of the multi-disciplinary Shield Margin NATMAP project would be mapping, using modern tools and concepts, of bedrock and surficial geology, supported by thematic geophysical, geochemical, geochronological and mineral deposit studies. The new geoscience knowledge would be compiled for segments of the project area and released primarily at scales ranging from 1:20,000 to 1:250,000. As the greenstone belt is continuous southward, lying beneath and obscured by up to 125m of the younger Paleozoic sedimentary rocks, an additional important component of the NATMAP project would be an interpretive map of the sub-Paleozoic geology, developed from geophysics, drilling and interpretation from knowledge of the exposed Precambrian lithologies and structural elements. All the extensive new knowledge would be merged with existing data in the development of a digital geoscience data base that would include regional compilation maps for the entire area.

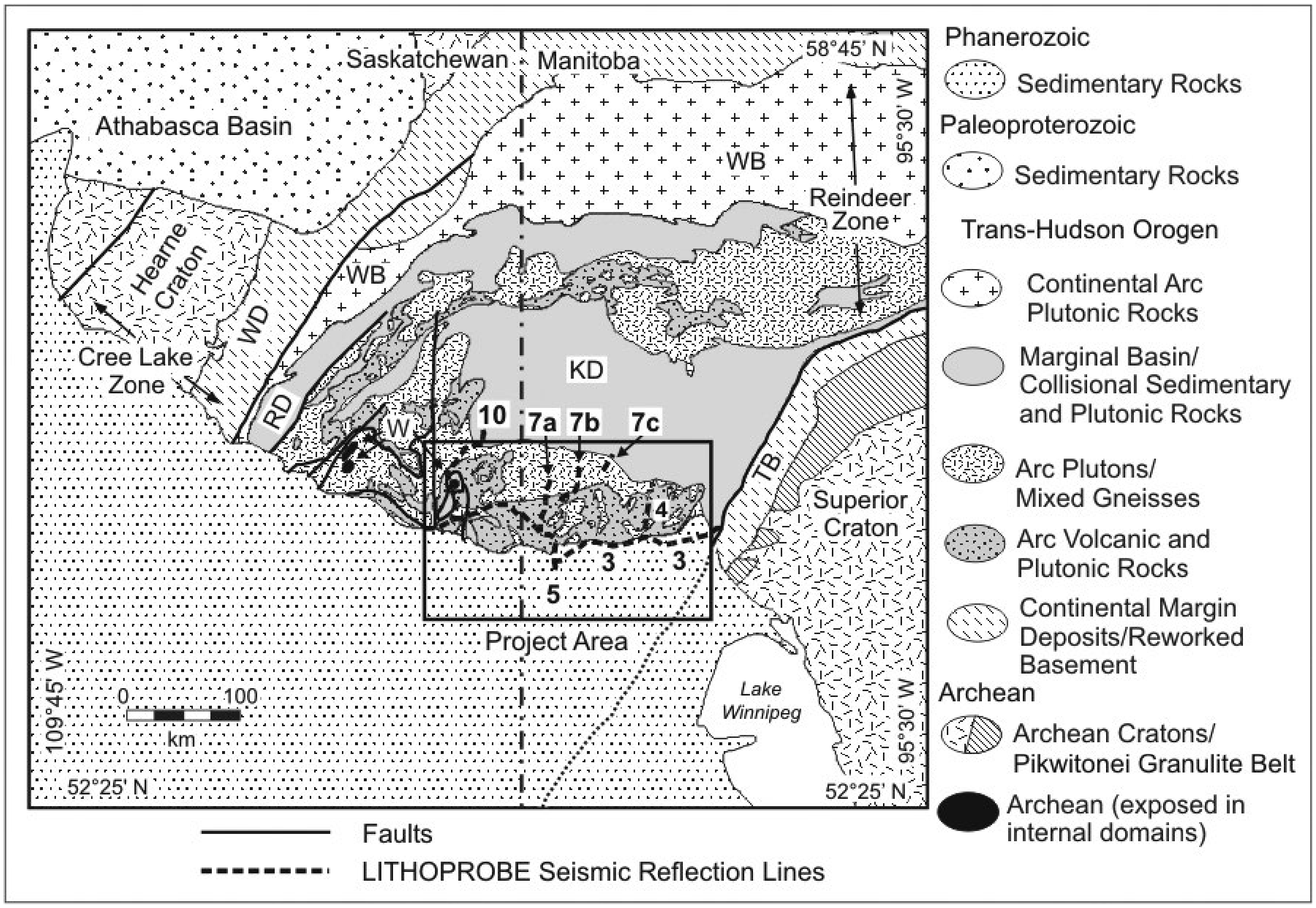

Fig. II-1. Location of the Shield Margin NATMAP project straddling the Manitoba-Saskatchewan boundary. Major units of the region's geological framework on the southern margin of the Canadian Shield are shown, together with the locations of several transects of the Lithoprobe Trans-Hudson Transect. (courtesy of Ric Syme, Manitoba Geological Survey)

Project Delivery

The collaborative work to unravel the Flin Flon Belt began with the Partnership Agreement on Mineral Development (1990-95) but was quickly followed by the NATMAP Shield Margin Project. Because the Flin Flon Belt extends across parts of two provinces, the elements of NATMAP - cooperative planning and collaborative project delivery by several geoscience organizations - were brought to bear during the life of the project from 1991-1996. Led by the Geological Survey of Canada (GSC), the NATMAP project involved a partnership between this federal geoscience agency, the Manitoba Geological Surveys Branch and the Saskatchewan Geological Survey. The enhanced funding opportunities under NATMAP facilitated the involvement of several universities, which in turn facilitated detailed scientific theme studies that had not previously been practical within the provincial surveys. As well, extensive partnerships with the Saskatchewan Research Council, university researchers and students across Canada and the U.S.A., and collaboration with the Flin Flon - Snow Lake area mineral exploration industry contributed significantly to the success of the project. The new generation of high-quality scientific data coming out of the NATMAP Project also attracted the attention of the LITHOPROBE Project and helped to initiate the 1991-1998 Trans-Hudson Transect, which then added seismic and other geophysical data as well as further collaborators and scientific studies to those already ongoing through NATMAP.

Most of the bedrock and sub-Phanerozoic maps were released with accompanying notes in 1998. Data bases were released on a CD-ROM in 1999, an innovative mode of product delivery for this era. Saskatchewan published two 1:20 000 scale maps with accompanying preliminary geological reports in 1989, 3 in 1990, 4 in 1991, 5 in 1992, 6 in 1993, 4 in 1994 and 2 in 1995 for a total of 21 between 1989 and 1995. These were incorporated into the 1:100,000 and 1:325,000 scale NATMAP compilations.

- In addition to the publication of these maps, reports and databases, the main scientific conclusions were synthesized and presented in several forums: The Canadian Journal of Earth Sciences, volume 36 special issues of February and November, 1999 were devoted to the results from a total of nineteen studies ranging from bedrock and surficial geology to the volcanic-hosted massive sulphide deposits in the Flin Flon and Snow Lake camps;

- A special meeting of the Flin Flon - Creighton CIMM Branch in June 1993 entitled ANew perspectives on the Flin Flon - Snow Lake - Hanson Lake Belt from the NATMAP Shield Margin Project, that featured the release of bedrock and gravity maps and a preview of the CD-ROM digital geoscience data release, drew over 180 registrants from the mineral exploration industry, government and academia. Registrants were guided by NATMAP scientists in two days of field trips over the project area;
- The Shield Margin project was the focus of a two-day symposium at the 1996 annual meeting of the Geological Association of Canada - Mineralogical Association of Canada (GAC-MAC), plus a post-meeting, four-day field trip to the project area.
- The final 1:1,000,000 -scale compilation maps were highlighted at the 1997 GAC-MAC meeting.

Scientific Results and Implications

A major outcome of the NATMAP Shield Margin bedrock mapping project has been to change the perception of the Flin Flon belt from that of a Precambrian greenstone belt to that of an intraoceanic accretionary collage marked by a diverse and complex tectonostratigraphy and protracted deformation and metamorphic history. The Flin Flon greenstone belt is now recognized as comprising tectonostratigraphic assemblages that were derived from a variety of tectonic environments over the period 1.92-1.88 Ga, amalgamated to form an accretionary collage prior to the emplacement of granitoid plutons from 1.87-1.83 Ga. These plutons and coeval volcanic rocks are associated with younger arcs imposed on the collage, which resulted in the emergence of a micro-continent by 1.85-1.84 Ga. Subsequent deformation from 1.83-1.69 Ga, recognized in the LITHOPROBE seismic reflection profiles, served to dismember this microcontinent. As it is recognized that all the local ore deposits are associated with the island arc rocks, the newly understood tectonic framework for the Flin Flon Belt provides a predictive context for mineral exploration.

Mapping beneath the Phanerozoic cover has demonstrated that the tectonostratigraphic assemblages trend north-south for more than150 km. As a consequence, this knowledge has more than doubled the target range for copper-zinc deposit exploration and, using the predictive context developed for the exposed shield, has focused exploration along high potential corridors.

The work of the NATMAP Shield Margin project, which focused on the early tectonic history of the belt, when complemented by the LITHOPROBE transect seismic reflection studies on the crustal architecture, provided one of the most comprehensive knowledge bases for orogens in Canada resulting in several fundamental breakthroughs in understanding the processes and outcomes of collisional tectonics.

The settings of mineral deposits were recast in this new tectonic framework. Their differences and diversity became more obvious and the search for specific types of deposits was focused in tectonically fertile assemblages within the Flin Flon belt. As well, new insights were gained on the extent of the belt. Prior to the NATMAP project it was believed that the volcanic massive sulphide (VMS) - rich Flin Flon belt rocks were restricted to the weakly metamorphosed rocks in the immediate vicinity of the town of Flin Flon. Other areas mapped outside the belt to the north that display a higher grade of metamorphism and structural complexities were considered as separate, and likely non-prospective, domains. However, re-mapping during the Shield Margin project demonstrated the continuity of Flin Flon belt rocks into these areas and led to integration of the so called Hanson Lake and Attitti Blocks into the Flin Flon domain. It was further shown that rocks of the Glennie domain were also continuous with the northern Flin Flon domain. These discoveries have effectively expanded the extent of Flin Flon belt rocks, thereby greatly increasing its VMS potential. Also, since the Glennie domain hosts the significant Seabee gold mine, this new knowledge can also be viewed as increasing the gold potential of the Flin Flon belt.

The surficial geology component of the NATMAP project generated a comprehensive knowledge base of the region's Quaternary (<2.5 million years ago) geology. Regional mapping of surficial deposits has led to reconstruction of the area's glacial and deglacial history. A fundamental advance has been the recognition of at least nine distinct ice flow events, a realization that has profound implications for drift prospecting - understanding the glacial dispersal of minerals indicative of various buried mineral deposits and the consequent ability to trace these indicator minerals back to their pre-glaciation source.

The Flin Flon smelter complex has been processing sulphide ores from local mines since 1930 - ores that yield zinc, copper and cadmium metals, lead concentrates and gold, silver, selenium and tellurium byproducts. The atmospheric emissions escaping from the smelter's central chimney, as at other smelters, and the related ore processing activities, consisting of gases and particulates, are dispersed by the prevailing winds and then deposited in a broad area surrounding the complex. This results in heavy-metal contamination of the regional soils and potential health hazards related to their uptake in vegetation of the food chain. Soil contamination by these same metals also results from natural processes as, for example, when naturally occurring metals such as lead and mercury are concentrated in humus through long-term, upward translocation from the underlying bedrock by plant roots or accumulation through plant litter decay. Efforts and actions to try to mitigate the deleterious effects must identify and distinguish the natural contribution of the contamination and the anthropogenic contribution. Studies undertaken in the NATMAP project to assess these contributions revealed the expected heavy metal concentrations in the humus layer. These concentrations decline radially outward, stretching farthest in the prevailing, southeast downwind direction. Variation in the distance to where the anthropogenic contribution disappears for six metals ranges from 104 km for arsenic to 70 km for cadmium, and is influenced by a number of geological and biogeochemical factors.

In addition to the mapping, the collaboration led to more detailed theme studies including geochronology, P-T work, and isotopic and geochemical analyses. Many of these studies provided the first tests of models that had been previously generated in the provinces, whereas others formed the basis for new models. Together, these studies helped to evolve a model relating both the rocks and the mineralization of the Flin Flon Belt to the plate tectonic model.

Recognized Impacts

The Shield Margin NATMAP Project left both companies and prospectors with a far better understanding of volcanic processes, primary stratigraphy, and the temporal framework. Together these were fashioned into a tectonic model for the Shield Margin area that forms a regional context for the known mineral deposits and focuses exploration activity on the most fertile ground. In addition, structural studies shed light on the complicated deformational history that has resulted in the present map configuration and produced significant modifications to mineral deposits. The correlation of several lithotectonic domains has greatly increased the area of inferred high mineral potential.

The new tectonic ideas emerging out of the Shield Margin NATMAP Project were variably received by industry, which included many geologists who'd spent most of their careers working in the Flin Flon belt. With time, these ideas have become more generally accepted and integrated into exploration models.

Base metal exploration levels, based on the number and areal extent of active claims, showed a significant and steady increase during the NATMAP project rising from approximately five claims before the project in 1990, to thirty-five in 1997. This was followed by a brief drop off, which likely reflected the sudden decrease in the release of new papers, maps, talks etc. immediately after the project's completion. Exploration has since rebounded to levels higher than those prior to the project as the new geoscience knowledge becomes part of industry's strategies to discover new mineral deposits.

Exploration levels would undoubtedly be even higher but for two reasons. First, metal prices, which are the prime motivating factor driving exploration, have generally been low, which has, in turn, contributed towards the departure of most exploration companies from the general area. Second, while Hudson Bay Mining and Smelting and its exploration and development wing continues to be the main player in the camp, it was recently taken over by OntZinc Corporation, which has focussed on production from existing deposits rather than embarking on a robust new exploration program.

In a survey conducted as part of Saskatchewan's Mineral Incentive Program, clients rated metal prices and perceived mineral potential as the main reasons for exploring a given area. It is noteworthy that the perception of high mineral potential must be based on a solid understanding of the geology. The availability of up-to-date geoscience data, including geophysical data and maps and reports, was generally considered to be moderate to high motivation for exploring an area, with most prospectors rating it even higher. Thus, a prime legacy from the NATMAP project in the Shield Margin area is that all of these new, up-to-date data, maps, and models are ready and waiting for the time when the metal prices and business climate are more favourable for investment in exploration.

The Shield Margin NATMAP Project coincided with a re-evaluation of the project area for several mineral commodities other than base metals, including gold (e.g. Laurel Lake), beryllium and other rare earth elements (e.g. Hanson Lake area), silica sand (Hanson-Deschambault Lake area), and building stone (e.g. Sahli Granite).

One very worthwhile spin-off from the Shield Margin NATMAP Project has been the new interest generated from academia that has initiated detailed physical volcanology studies in 2000 that have continued to the present. The resulting information and ideas are being fed back to industry and into government databases.

Conclusions

The success of the Shield Margin NATMAP project has been built on the substantial, multi-faceted efforts of participants from various organizations who cooperated and collaborated on studies across traditional disciplinary, institutional and program boundaries. The Shield Margin project revolutionized geological thought in the Flin Flon Belt. It provided a new tectonic context for the known VMS mineralization and helped focus new exploration activity towards the discovery of future deposits. Although base metal prices have generally worked to limit exploration since the project was completed, the ideas, reports, maps, and databases are in place for when commodity prices turn around.

Acknowledgements:

The Shield Margin NATMAP project was jointly developed by the Geological Survey of Canada and the geological surveys of Manitoba and Saskatchewan. Overall project coordination was by Stephen Lucas, GSC, with leadership from the Manitoba Geological Services Branch by Paul Lenton, and from the Saskatchewan Geological Survey by Brian Reilly. Some of the background information used to compile this chapter was taken from the annual NATMAP Reports of Activities prepared by Lucas. I also used the

summary papers in the special issues of the Canadian Journal of Earth Sciences (Lucas et al., 1999a, 1999b) as valuable references to some of the scientific accomplishments of the project. At the time of this compilation, Lucas had moved on to another organization and other duties, so I am especially grateful to the considerable help provided by Ken Ashton, Saskatchewan Geological Survey, in filling gaps left by the above noted references, and particularly on the impacts that the new geoscience knowledge had on exploration in the area. Some parts of the text are taken directly from Ashton's communications. I also wish to thank Ric Syme, Director, Manitoba Geological Survey, for kindly providing the figure, which was published originally in the CJES issues.

III - SLAVE PROVINCE NATMAP PROJECT

Rationale and Geological Setting

The Slave Province, or the Slave craton, of the northwestern Canadian Shield is one of the oldest and most distinct building blocks of the North American continent. It hosts the Acasta gneisses, which, at almost four billion years in age, are almost the oldest intact rocks on Earth. Stretching north from Great Slave Lake to the shores of Coronation Gulf and west to Great Bear Lake, its roughly 180,000 km^2 area is roughly bisected by the northwest-trending border of the Northwest Territories and Nunavut. The highly folded bedrock geology is reflected in the sinuous pattern of the myriad small lakes that typify the region. The Slave Province is an important economic and scientific entity of the Canadian Shield, and the exploration activities and mining industry of this region are vital to a healthy NWT economy. The Slave Province NATMAP project was formulated to update and upgrade the map-based geoscience knowledge of a large part of the region, and the consequent advanced understanding of the Slave Province as a whole would provide information useful for mineral exploration activities.

Gold mining had been the region's economic backbone since 1937. By the early 1990s some smaller mines had begun to close, but the large Giant and Con mines and the smaller Ptarmigan and Colomac mines around the City of Yellowknife, and the large Lupin mine 400km to the north were expected to remain viable for another decade or more. There were even hopes for extending this lifespan by the discovery of additional ore reserves on or near these properties. Regardless of the success in achieving this aim, the need for the discovery of new deposits and new mines in other greenstone belts elsewhere across the Territory was thought to be essential to maintaining a critical element in the economic health of the NWT. While no base metal mines were in operation at this time, nor major deposits known to exist, exploration for these metals was continuing in a number of belts across the Slave Province in hopes of diversifying the region's mining industry. As well, the first ventures into diamond exploration were underway but, except for the hopes of the couple of small exploration companies involved, there was little expectation of these gems making a significant contribution to the region's, much less Canada's, mining industry.

Before the NATMAP project, the extant knowledge of the Slave Province bedrock and surficial geology was inadequate for undertaking cost-effective exploration ventures necessary to try to expand the minerals economy of the NWT. In the early 1990s, there were many circumstantial indications for the presence of very ancient crust, mostly in the western half of the Salve craton. If this proved correct, this ancient crust had almost certainly played a critical role in the evolution of the craton and its mantle root. The early 1990s was also the time that indicator minerals and diamonds were finally traced back to the core of the Slave craton, specifically the Lac de Gras area, and it seemed likely that the presence or absence of crustal rocks older than 3 billion years and the distribution of kimberlite pipes and their diamonds might somehow be related. The Geological Survey of Canada (GSC) had been carrying out bedrock mapping of the Slave craton at intervals for more than forty years, almost entirely at reconnaissance scales. Adding a more recent contribution by the Northwest Territories Geology Division (INAC) and the Canada-NWT Minerals Initiative Office (MIO), by 1990, still only half the central part of the area had been mapped, and this on a reconnaissance basis, and major gaps remained to the north and south. The only work on the surficial geology had been territorial-wide, reconnaissance mapping by GSC in the late 1960s that provided preliminary information on regional ice-flow history. GSC's systematic airborne mapping of Canada's bedrock magnetic character had reached the Slave Province by the late 1960s, and 1:250,000 and 1:50,000 scale maps of the northeastern quadrant of the region were available by 1980. While these aeromagnetic surveys had covered the Lac de Gras area and recorded the anomalies associated with kimberlite pipes, the significance of the anomalies and the recognition of the diamond-producing bodies wouldn't take place for another eleven years.

Even a cursory glance at the geological map of Canada is enough to convey the complexity of the region's geology, especially when contrasted with the majority of the rest of the Canadian Shield. The craton comprises interspersed Archean granitoid intrusions, supracrustal sequences and basement core complexes predating 2.6 billion years ago. In addition to large-scale tectonic deformation and modification of these components, several swarms of Proterozoic diabase dykes sliced through the Slave over the ensuing 2 billion years. And, as is known now, but only since the early1990s, the latest magmatic episodes saw the emplacement of kimberlite intrusions, the source of diamonds that now

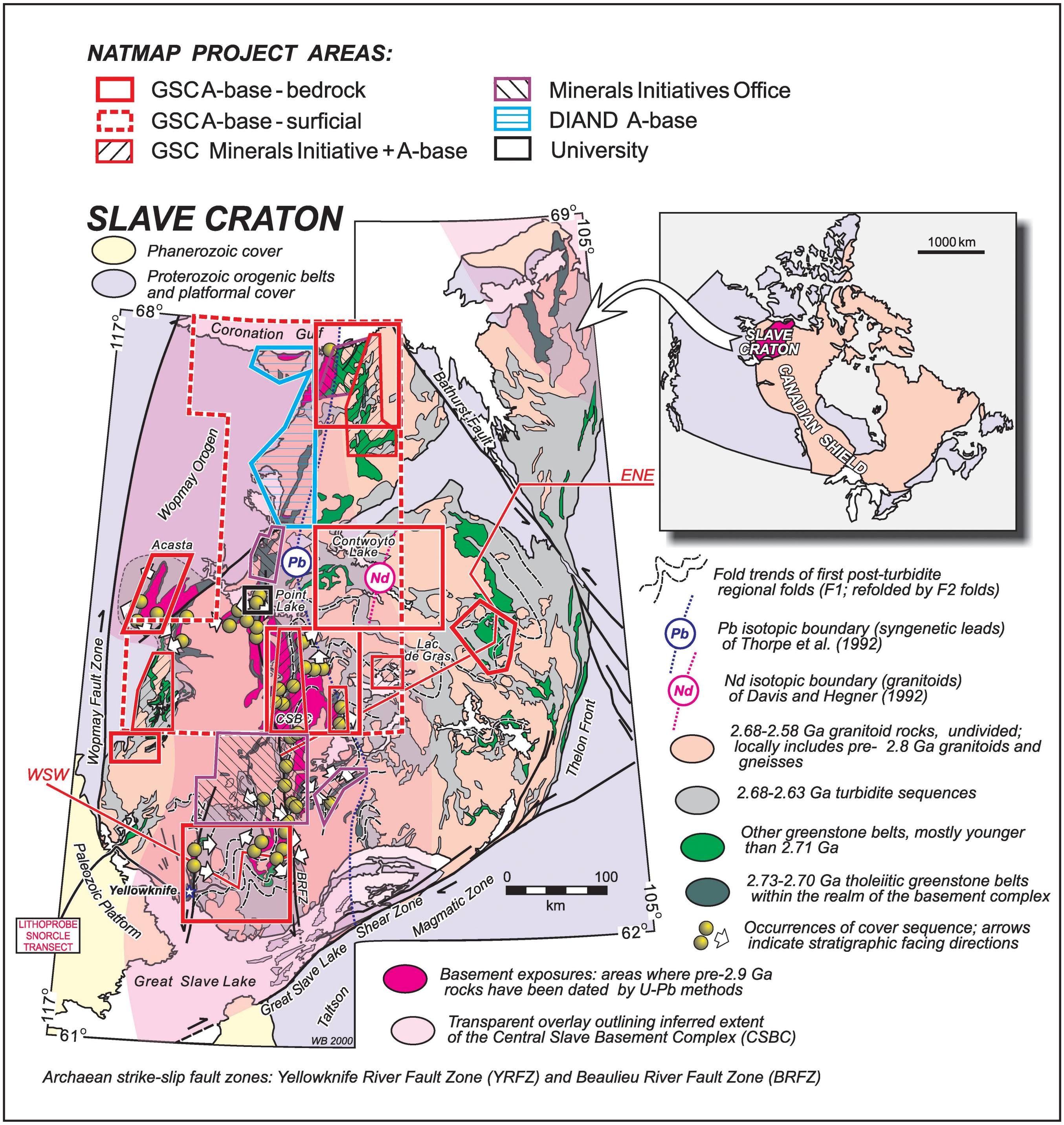

Fig. III-1: Location of the Slave Province NATMAP project within the Slave Craton of the Canadian Shield. The several components of the NATMAP project, and the agency responsible for their delivery, are outlined and superimposed on the Slave Craton's general geology. (courtesy of W. Bleeker, GSC)

Fig. III-2: Typical terrain in the Acasta Gneiss outcrop region of the Slave Province NATMAP project. (courtesy of J. Ketchum, NWT Geoscience Office)

make Canada a world class producer of these gems.[2] It's not surprising, then, that this complexity had spawned a number of fundamental questions in the late 1980s related to characterization and understanding of the Slave Province geology. At that time, however, at the current and planned levels of geoscience activity, these problems wouldn't be addressed adequately for at least another decade.

Thus, in a general sense, area selection for NATMAP and related projects was guided by three main considerations: 1) developing a better understanding of the nature and distribution of the ancient crust; 2) mapping (or remapping) of a number of greenstone belts with active mineral exploration (gold or base metals); and 3) thematic studies to resolve key stratigraphic questions.

The Slave NATMAP project was originally designed to address these considerations through a program of bedrock mapping along a north-south corridor from Yellowknife to Coronation Gulf. The large size of the province, together with its inadequate geoscientific coverage, required that a number of target areas be chosen based on a high mineral potential combined with the possibility of significant advancement in the scientific understanding of the Slave Province. The proposed program would also examine the Quaternary geology through regional mapping and studies of the stratigraphy, mineralogy and geochemistry of the surficial deposits. The surficial studies were to coincide with an area identified by the Government of the Northwest Territories as a possible transportation corridor linking Yellowknife, and mining operations along the route, with tidewater on Coronation Gulf. The new geoscience would provide information essential for infrastructure development. The discovery, however, in 1991 of diamondiferous kimberlites in the Lac de Gras region, east of the NATMAP mapping corridor and almost 300 km north-northeast of Yellowknife, meant that the original plan for the Quaternary studies would be re-prioritized to provide scientific support for the massive exploration rush spawned immediately by this discovery. Slave NATMAP would now also support studies on the nature and distribution of the kimberlite pipes, sampling and analysis of kimberlite indicator minerals in the glacial drift and ice flow history. The modified goal was to provide a regional framework for geological interpretation and drift prospecting. The advent of a vibrant diamond industry in the Slave Province placed an emphasis on understanding geological evolution of the province for the first time at a lithospheric scale.

Project Delivery

The Slave Province NATMAP project was one of the two projects that inaugurated GSC's new NATMAP Program. Undertaken between 1991 and 1996, Slave NATMAP was led by GSC, in collaboration with Canada-NWT Minerals Initiatives Office (MIO) and the Yellowknife Geology Division of the Department of Indian Affairs and Northern Development (now Indian and Northern Affairs Canada). Scientists of these geoscience agencies each took responsibility for the mapping of specific areas within the map corridor, each area contributing to the overall project goals. The NATMAP financial support also significantly enhanced other geoscientific mapping underway or planned, and enabled other related GSC projects, such as the geochronological studies that provided the 'glue' to link the various individual bedrock projects, to be integrated into the larger picture. The bedrock and surficial geology studies also drew on the collaborative expertise of geoscientists from six Canadian and US universities and, in turn, provided field training and the basis for BSc, MSc and PhD theses for students at these institutions. Extensive collaboration with numerous exploration companies active in the area provided valuable logistic support and site-specific information. In the latter years of the NATMAP project, an important synergy developed, particularly at the GSC, between mapping and research projects in the Slave and activities related to LITHOPROBE's SNORCLE Transect (Slave-Northern Cordillera Lithosphere Evolution) that commenced in 1994 using geophysics (reflection seismics) to characterize and understand the region's deep-seated geology and structure. The critical mass of expertise brought to bear on the Slave Province geoscience, combined with the momentum generated by the NATMAP mechanism, led to rapid and successful development of ideas and scientific products. Many of these were compiled in a special issue of the Canadian Journal of Earth Sciences (Bleeker and Davis, 1999).

[2] It is interesting to note that an early project proposed for consideration for NATMAP funding was to improve mapping in the Lac de Gras area because of the "potential for base metals and gold." - no hint of diamonds!

Scientific Results and Implications

At the time of conception of the project, a number of important geological problems or goals were highlighted related to the potential for, and the emplacement and evolution of, economic mineral deposits of the bedrock. These included:

- Defining and understanding the tectono-stratigraphy of key greenstone belts throughout the craton and their relationship to the Mesoarchean basement;
- Defining the characteristics and extent of preserved basement;
- Studies of the geochemistry and isotope systematics of granitoid rocks as a probe to the deep crust;
- Understanding the nature and tectonic significance of regional high-strain zones.
- Developing tectonic models linking the different tectono-stratigraphic elements of the craton.

The discovery of diamondiferous kimberlites in 1991 meant that the original plans for broad studies of the Quaternary geology and surficial deposits were modified to focus on:

- Mapping-based characterization and spatial analysis of kimberlite pipes in the Lac de Gras region
- Sampling and analysis procedures for kimberlite indicator minerals in the glacial drift.

The considerable advances in knowledge gained from the NATMAP studies have been extensively documented and reported in many scientific publications and theses and so are only briefly noted here.

- A significant advance in understanding the character and evolution of the Slave Province from the NATMAP research was the recognition of the nature and distribution of Mesoarchean basement rocks.
- Bedrock mapping, supported by extensive geochronology studies, recognized ten distinct events in the evolution of the Slave craton, events ranging from the growth of juvenile crust at ~ 4.0 billion years, followed by numerous magmatic or tectonic events that emplaced and deformed a succession of lithologies, culminating in the emplacement of voluminous granitic magma at 2.6 billion years, and subsequent uplift.
- A significant, and previously unknown, deformation event, younger than 2.6 billion years before present, was identified and characterized.
- A number of previously unrecognized and unsuspected supracrustal units associated with volcanic belts were identified and their distribution and stratigraphic relationships defined.
- It was established that the map patterns of several large greenstone belts are dominated by regional-scale fold interference patterns.
- The basic geometry of the major, N-S fault system and unique tectono-stratigraphic assemblages contained therein were established and defined.
- Several lithologies previously not known in the Slave Province, including komatiitic basalts and late Archean carbonatites, were discovered.
- Detailed bedrock mapping in the core area of diamond exploration discovered two additional kimberlites.
- The possible mechanical control of emplacement of kimberlites by mafic dykes was established.
- From the mapping and understanding of the region's Quaternary geology, a 3-component ice-flow history was established for the Lac de Gras region, with minor local variations. Glacial striations indicate that glaciers have transported material southwest, west, and northwest of kimberlite sources. A major glacial dispersal train trends northwestward for more than 100 km from the Lac de Gras kimberlite cluster, but smaller dispersal trains and isolated indicators suggest that kimberlite sources are present at several other locations. The data reveal that indicators are more abundant in the 0.25-0.5 mm size fraction than in coarser sizes, and that pyrope is typically the most abundant indicator, although some locales with no pyropes also have been identified as potential kimberlite sources.

As with all the NATMAP projects, the intent was not to uncover new mineral showings but to provide new knowledge about the geological environment and its evolutionary history that would aid the mineral industry in focusing and implementing its exploration ventures in an effective manner. Thus, in contrast to the situation generally accepted from1970, NATMAP determined that many supracrustal rocks in the Slave Province are not even broadly correlative, a revelation that has profound significance on metallogenic evaluations. An example would be the metallogenic implications of BIF (banded iron formation)-bearing *versus* BIF-absent turbidite sequences. While this latter revelation was actually a post-NATMAP discovery, the NATMAP framework provided the basis for its examination.

Another example stems from a gravity survey of the Indin Lake greenstone belt that led to the recognition that prospective stratigraphy hosting the Colomac gold mine heads shallowly under younger sediments. Although the company holding this property at the time of release of this information ceased operations, whenever exploration does resume at this property, this new information is certain to direct activities.

The new Slave Province NATAMP bedrock geoscience at the surface, linked with the SNORCLE understandings of the deeper-seated lithologies and structure, advanced the general knowledge of the generation and emplacement of mineral deposits. An improved understanding of the processes that generate metallic mineral deposits, the emplacement of kimberlites and the preservation of diamonds will present new exploration opportunities and provide a better assessment of the Slave Province's mineral potential.

In the Yellowknife Greenstone Belt, gold grain counts in till, conducted for the first time, have proven particularly useful in identifying areas of gold mineralization. High gold counts are derived from erosion of local bedrock by glaciers and *in-situ* weathering and suggest a nearby, rather than remote, source.

Recognized Impacts

Economic

The new knowledge of the region's glacial history, gained under the NATMAP project, and subsequent tracing of kimberlite indicator minerals (KIMs) with this knowledge have been of paramount importance in the discovery by industry exploration programs of many kimberlites in the Slave Province. The detailed mapping of glacial geology, ice flow features and till sampling in the Slave by the GSC under the NATMAP project demonstrated the utility of drift prospecting techniques in glaciated terrain. Published surficial maps and reports of till geochemistry and KIMs have stimulated mineral exploration throughout the entire Slave Province and beyond its borders west towards the McKenzie Delta, east to Nunavut and, eventually, south of 60 degrees latitude. GSC mappers undertaking fieldwork were often approached by exploration companies seeking advice on ice flow directions, in some cases undertaking cooperative studies, and Slave till geochemical survey data and surficial maps were used by many exploration companies as soon as the new data were released.

A very active gold exploration program was underway in the Indin Lake area at the commencement of the NATMAP studies. The NATMAP results provided an important contribution to unravelling the geometry of the deposit through sorting out the complex interference fold pattern at Damoti and Fishhook banded iron formation (BIF) gold properties, results that significantly influenced the exploration model for this deposit.

On the basis of the new NATMAP geoscience information that indicated a greater potential for BIF gold than previously thought, Royal Oak Mines took out new property leases in another part of the belt.

Partnership staking of the Greys Bay alkaline complex in the Anialik area was a direct result of its discovery during mapping of the area by a NWT geoscience component of the Slave Province NATMAP. Focusing of additional new exploration on Inuit-owned lands in the Anialik belt was made possible because of the maps and new geoscience knowledge generated under NATMAP, that included highlighting the locations of interesting 'showings' discovered and sampled as part of the project.

Environmental

The detailed GSC till geochemical surveys in the Slave Province identified numerous anomalous gold, base metal and kimberlite indicator minerals anomalies, some in under-explored parts of the Province. This new geoscience knowledge and database is actively being used by mining companies and government agencies as a basis to determine pre-mining natural levels of elemental concentrations in soil as an aid in their environmental assessment studies.

The new geoscience knowledge obtained from surficial maps and published reports is valuable for land-use planning decisions, such as those associated with the impact of land disturbance by construction and mining. Quaternary stratigraphic and permafrost studies have demonstrated the existence of buried massive ground ice in some glaciofluvial and till deposits. These have the potential to affect the short and long term stability of roads, open pit and underground mines, and other building structures such as dykes used to hold back water or tailings at mine sites. Permafrost is a critical element of the tailings design and management plan of the Ekati and Diavik diamond mines at Lac de Gras and frozen core dams have been used at the mines both for drainage diversion and tailings containment. GSC expertise gained in the Slave NATMAP project and provided to federal and territorial governments was critical to the review of permafrost aspects related to the assessment and mitigation of environmental impacts for both of these projects.

Conclusions

The new Slave NATMAP project geoscience has made a significant contribution towards addressing many of the important geological questions posed in formulating the various facet's of the project's scientific endeavours. In particular, a better understanding now exists of the tectonostratigraphy of several greenstone sequences and their relationships to Mesoarchaean basement. As well, the extent and nature of the Mesoarchean crust are better defined and understood, as is the Neoarchean structural evolution. The newly-emerged, vibrant diamond industry in the Slave Province will continue to rely heavily on the new geoscience to support this industry's need for an improved knowledge of the geological evolution of the Province at a lithospheric scale.

Acknowledgements

The Slave Province NATMAP project was developed and carried out for the GSC under the leadership of Janet King, Continental Geoscience Division, Ottawa. Leadership for

components carried out by the Geology Office of DIAND and by the Canada-NWT Minerals initiative office was by William Padgham and Carolyn Relf, respectively. Much of the background information contained in this chapter was gleaned from the NATMAP annual Review of Activities summaries prepared by King. Highlights of the geoscience were taken from the Introduction chapter of a special issue of the Canadian Journal of Earth Sciences (Bleeker and Davis, 1999), and from the Preface prepared by King. Wouter Bleeker, GSC, one of the authors of this cited volume, provided the location map figure, while John Ketchum, Senior geologist for the NWT Geoscience Office, furnished the terrain photo. I wish to thank Dan Kerr, GSC, for his contribution to the surficial geology studies that he carried out as part of the Slave NATMAP team. As well, I appreciate the helpful contributions of Relf and Sally Pehrsson, GSC, regarding the impacts of the new geoscience knowledge on exploration in the Slave craton. Relf also provided useful comments to correct and improve the final draft of the text. Also, I thank Valerie Jackson, NWT Geoscience Office, who suggested additional references to consult related to the Slave Province geoscience.

IV - EASTERN CORDILLERAN GEOLOGIC MAPPING IN SOUTHERN ALBERTA NATMAP PROJECT

Rationale and Geological Setting

The purpose of the Eastern Cordilleran NATMAP project was to remap the geology of a portion of the southeastern edge of the Canadian Cordillera - the name for the mountains of western Canada - in southern Alberta. The area of study, a swath in the Rocky Mountain Foothills some 50-100 km in width extending north-northwest 200 km from the Canada-US boundary, is an important geological province with significant reserves and resource potential for natural gas, oil, sulphur, thermal coal, and coal bed methane and significant groundwater concerns.

The Rocky Mountain Foothills lie between the structurally undeformed Interior Plains of western Canada and the topographically high-relief Rocky Mountains. The deformed sediments comprising the Rocky Mountains and Foothills have a cumulative stratigraphic thickness of up to 20 km or more, and encompass rocks deposited on the western passive margin of the ancient North American craton prior to mountain-building events, as well as those deposited in the Alberta foreland basin, which formed adjacent to the evolving mountain belt. The relatively subdued relief of the Foothills, in comparison to that of the adjacent Mountains, is due to the relative erosional resistance of the underlying bedrock. Whereas the bedrock of the Rocky Mountains is dominated by resistant Paleozoic carbonates and Proterozoic to earliest Paleozoic quartzites of the ancient passive margin, the Foothills are generally underlain by relatively recessive Cretaceous to Paleocene sandstones and shales of the foreland basin succession.

The Foothills are a prolific structural province for petroleum exploration, principally natural gas. Updated estimates by the Geological Survey of Canada (GSC) indicate that approximately 2.33 x 10^{12} m^3 (82.4 TCF) of gas remains to be discovered in the deformed Cordilleran foreland, or 41.6% of the total initial resource. Gas pools lie in structural traps formed by the faults and associated folds of the deformed sedimentary rocks. Reservoir rocks lie in both the Paleozoic carbonates and the Cretaceous siliciclastics. Although the largest discovered pools lie in thrust-repeated carbonate slices, new plays in the Cretaceous sandstones, developed in part because of this NATMAP project, are being actively explored and developed, especially in the area known as the “Triangle Zone” that forms the eastern edge of the Foothills belt.

The NATMAP project area lies within the Outer Foothills (the eastern half of the Foothills Belt), and encompasses the Triangle Zone. The NATMAP map areas were selected to replace the oldest GSC maps in a region with increasing industry activity. The area between the international border and the Turner Valley region (the location of the 1914 discovery oil well that led the rush to Foothills exploration) contained nine full and three half 1:50,000 scale map sheets that required remapping. Most of the southern Alberta Foothills were mapped at a scale of 1 inch to 1 mile (1:63,360) in the 1930s through 1950s, although some of the NATMAP map areas had only been mapped at a much larger, regional scale.

Critical elements in our geological understanding of the area that impelled the need to remap these sheets include recognition of the Triangle Zone structure, and improvements in the stratigraphic subdivision within the Cretaceous foreland basin clastic units. Bedrock exposures within the Outer Foothills are very good to excellent along the major rivers and creeks, but only good to poor through the intervening ridges and rangelands where generally only the more resistant sandstones crop out.

Comparable to the bedrock studies under the NATMAP project was a component to remap surficial deposits to try to resolve two divergent views of the region’s glacial history. Previous studies of the surficial deposits largely predated the explosion of research in contemporary glacial sedimentary environments that began in the early 1970s, as well as the development of new dating techniques. Also, as this early work was generally based on the interpretation of stratigraphic sections with reference to only reconnaissance-scale mapping, by the 1990s, this important area required re-examination.

The Eastern Cordilleran NATMAP project brought together the disciplines of both bedrock and surficial mapping, using modern techniques and concepts to provide the surface picture of the region’s geology at 1:50,000 scale.

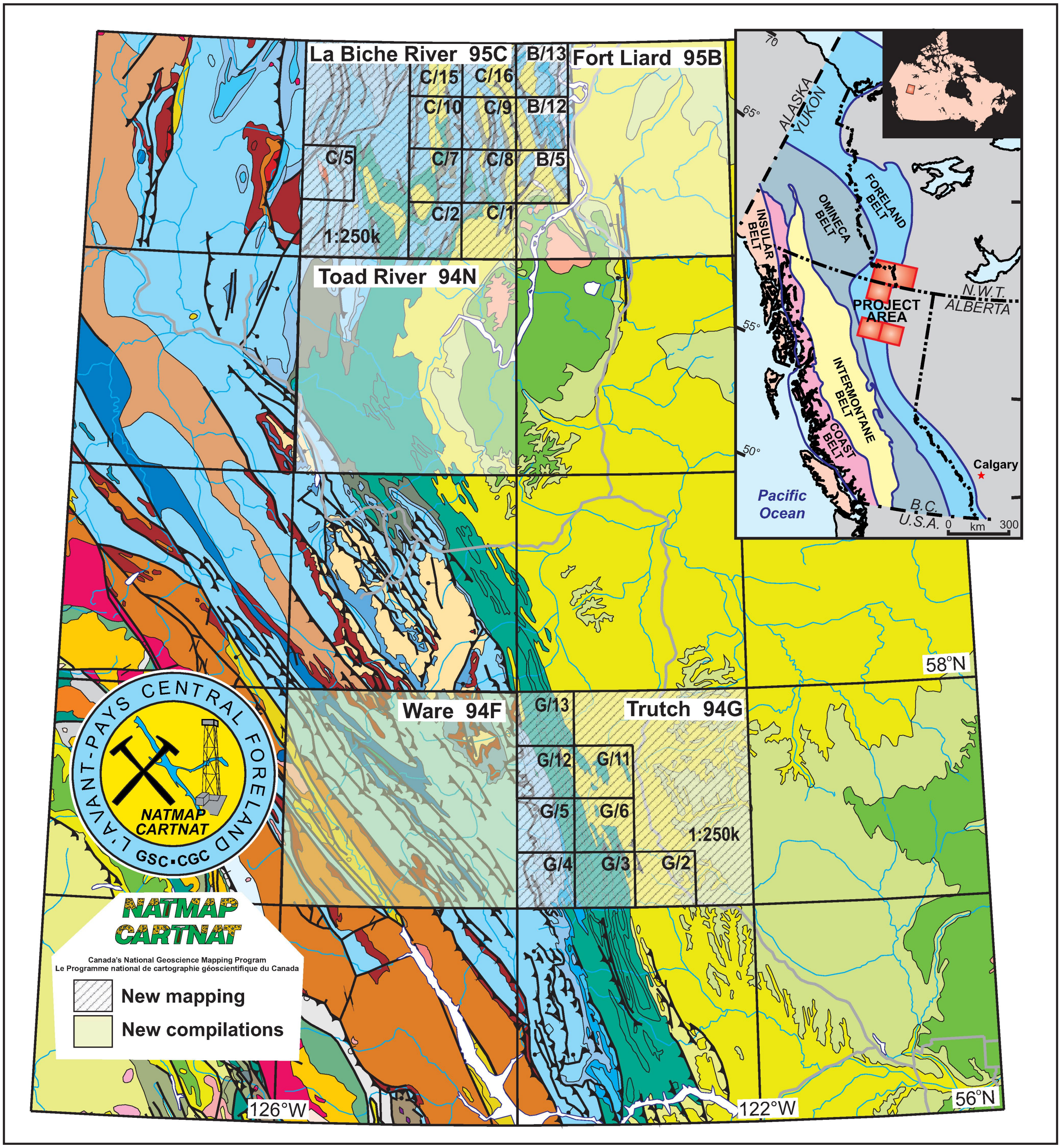

Fig. IV-1: Location of the Eastern Cordillera NATMAP project in the Rocky Mountain Foothills of southeastern Alberta. Areas mapped in the NATMAP project are outlined in yellow and superimposed on the regional geology of the southeastern Canadian Cordillera physiographic region.

Fig. IV-2: Major structural elements of the eastern Cordillera NATMAP project region.

This knowledge was combined with available detailed reflection seismic data, reprocessed using modern techniques, plus drill hole samples and electric logs from hydrocarbon resource industry collaborators, to construct cross-sections of the region's sub-surface structures. Development of a digital database was planned to facilitate the creation and publication of derivative maps involving a variety of data, including distribution of potential aquifers, potential sources of aggregate, level of thermal maturation in petroleum evaluation, as well as stratigraphic, structural and natural hazard information. The maps and databases would be useful to petroleum explorationists, hydrogeologists, engineering geologists, land use planners, resource assessment agencies, academia and the public.

Project Delivery

The Eastern Cordilleran NATMAP project was principally coordinated and largely funded by GSC, with its main collaborators the University of Calgary and the Alberta Geological Survey. Additional participation was by the University of Western Ontario, the University of Lethbridge, Simon Fraser University, Dalhousie University, the National Museum of Canada and the Royal Tyrell Museum of Paleontology. Ten petroleum companies made critical contributions to the project through their provision of proprietary seismic information. The Eastern Cordilleran project was among the first of the NATMAP projects, with bedrock and surficial mapping commencing in 1993 with completion of the project planned for 1998. In the case of surficial geology mapping, it was among the first to bring computers into the field so that digital manuscript maps were produced as the surficial geology information was being gathered.

The project produced both GSC A-series (12 in total - all Quaternary) and Open File maps (14 in total - 10 bedrock and 4 Quaternary), as well as one GSC Bulletin, 16 GSC Current Research papers, 9 articles in outside refereed scientific journals, 5 geological guidebooks, and 27 published abstracts of formal presentations, both oral and poster.

Scientific Results and Implications

Bedrock geology mapping:

- Recognition and mapping of a new stratigraphic subdivision for Upper Cretaceous (Santonian and Campanian) rocks in the NATMAP area was greatly aided by new biostratigraphic data gathered through palynological analyses.
- Subdivision of the former Belly River Formation into as many as seven recognizable and mappable units has greatly increased resolution of previously poorly understood, or even unrecognized, structures, leading to a deeper understanding of structural styles present in petroleum reservoir units.
- Representation of the bedrock expression of the triangle zone, a near-ubiquitous complex structure at the leading edge of Cordilleran deformation, is leading to better delineation of subsurface exploration targets and aiding petroleum exploration companies in choosing seismic acquisition locations.
- Elucidation of important structures unrecognized in mapping decades ago, such as folded thrusts, roof thrusts to large duplex structures, and so-called "pop-up" structures. The subsurface analogues of many of these features are current exploration targets (forming structural traps); therefore, an improved understanding of their configurations improves exploration success.
- In the Maycroft area, mapping of complex structures, combined with seismic information, has resulted not only in a clear picture of the Triangle Zone, but one involving two nested wedges and significant hinterland-directed deformation above the upper detachment. This recognition and improved understanding can be extrapolated to similar features elsewhere along structural strike that are current exploration targets.
- In the Cardston area, mapping of numerous thrust fault repetitions imbricating the Upper Cretaceous section suggest that a triangle zone with a complex kinematic history forms the eastern boundary of the Foothills at this latitude. This triangle zone differs from that to the north, in the Maycroft area, in that the stratigraphic level of the upper detachment is significantly higher stratigraphically. The zone through which the change in level of the upper detachment occurs, in the Blairmore and Pincher Creek map areas, is currently a very active exploration region.
- Previously unrecognized, large-scale, open folded thrust faults were mapped in the Foothills portion of the Waterton map area. These features appear to be associated with large-scale duplex structures, similar in general style to those involving Paleozoic carbonate slices in the giant Waterton gas field operated by Shell Canada.
- Bedrock mapping in the Beaver Mines area established a stratigraphic control for the landslides of this area, all of which were found to be active.
- A new technique, using photogrammetry to map ridge-forming units, was developed and used in conjunction with field mapping to map the sandstone units of the Porcupine Hills.
- Completion of the 1:250,000 scale bedrock map will meet requests of industry for a tool to help visualize regional structural trends in the Alberta Foothills and Rocky Mountains in the search for deep and structurally complex gas pools.
- Bedrock mapping in the Lower Cretaceous section provided new data related to anomalous gold occurrences leading to definition of a new exploration target for gold.

Surficial geology mapping:

The southwestern foothills area of Alberta was one of the first Canadian locations where evidence of multiple glaciations was reported and debate over the number of glaciations and synchroneity of montane versus continental glacial advances has continued ever since. Mapping and understanding the region's surficial deposits under the Eastern Cordillera NATMAP project strived to resolve the situation. From the project, twelve 1,50,000 surficial geology map sheets were published along with an interactive digital 1:250 000 summary map as part of Bulletin 583 (Jackson et al., 2008). The stratigraphic aspects of the surficial geology investigations employed techniques in absolute and relative age dating including cosmogenic chlorine-36 exposure dating and paleomagnetic studies. These techniques were unavailable to investigators of the 1960s and 1970s when the area was previously mapped.

- The regional mapping of Quaternary surficial deposits revised the earlier concept that there was evidence in the Foothills of incursions of the Laurentide ice sheet and earlier continental glaciers that formed during three earlier glaciations. The region is now believed to have been subjected to just one advance of a continental ice sheet - that being the late Wisconsinan Laurentide ice sheet. However, evidence for several *montane* glacial advances preceding the Wisconsinan Glaciation was corroborated.
- Reconstruction of the glacial cover at the climax of the last glaciation indicates that the Laurentide ice sheet had a much lower profile than was previously assumed.
- Regional surficial geology mapping has also recognized and delineated many previously unknown, massive landslides within the Porcupine Hills and the Livingstone Range.

- Cosmogenic chlorine 16 dating of boulders in the Foothills erratics train demonstrated a late Wisconsinan age for the train of these glacially deposited boulders.
- The same technique demonstrated that the overlapping drift sheets along the Rocky Mountain front and adjacent Foothills are all late Wisconsinan in age.
- The timing and nature of the contact between mountain glaciers and the Laurentide ice sheet during the Wisconsinan Glaciation was extensively documented.
- Fissures were discovered across the summit of Mount Livingstone. The possibility of a rock avalanche from that peak was reported to the Alberta Geological Survey.
- Characterization by type and frequency of newly recognized landslides and others known previously, indicates that mass wasting processes along major thrust faults are progressively destabilizing slopes, making new, large scale rock avalanches on the scale of the infamous Frank Slide, likely.
- The late Wisconsinan age determined for the Foothills erratics train negates the 65-year-old hypothesis that an ice-free corridor existed between the western limit of the Laurentide ice sheet and the eastward limit of glaciers from the Rocky Mountains. Consequently, the first humans to enter North America could not have travelled through what are now the western interior plains of Canada until well into the deglacial phase of the late Wisconsinan glaciation.

Recognized Impacts

- New geological maps and structural cross sections produced by the NATMAP project have greatly assisted industry in developing and successfully exploring new plays for oil and gas in Cretaceous sandstones of the triangle zone and Foothills in southwestern Alberta.
- In the Triangle Zone, 55 wells have been drilled since the start of the NATMAP project at an average cost (2006) of $2.3 million.
- These wells resulted in the discovery of 974 million m^3 of gas reserves (Alberta EUB gas reserves 2005), leading to the construction of at least one new gas plant ($7.5 million plant and $7 million gathering system cost; Win Energy Corporation).
- Maps showing the distribution of sandstone units that function as essential aquifers are being used by ranchers to guide the location of successful water wells in this drought prone area.
- Surficial geology maps included a comprehensive map of landslide activity and other geologic hazards and potential aggregated resources.

Conclusions

The Eastern Cordilleran NATMAP project was a success, from a scientific standpoint and from its impacts on helping to direct future resource exploration, but a number of factors did intervene to require some adjustments to the initially defined goals and products. Perhaps as an omen of these difficulties, the project was approved in April, 1993 just in time for one of the wettest and coldest summers on record in southern Alberta and record flooding occurred in the Oldman River basin in the summer of 1994. Yet, despite these inclement conditions, mapping proceeded ahead of schedule in that first year and surficial geology mapping progressed normally in 1994. All surficial geology maps were complete and published by 1997 and the synthesis publication on the Quaternary geology was completed and released in 2008. However, bedrock mapping was impeded after 1994 because the primary researchers left the project, either to become managers or, being experienced mappers, through reassignment to other projects; the project inevitably fell behind schedule, and the work was not extended as a 'legacy' project following the end of the NATMAP Program in 2003. It had been hoped by the researchers that additional synthesis papers could have been written on the bedrock geology of the area and, as a testament to the commitment of its research team, several major products were completed 'after hours' without project support.

An added complication was a direct result of the new geoscience having had an immediate and significant impact in the area. As soon as each season's new mapping and stratigraphic work was released, it was used by industry in a new round of exploration in and adjacent to the Triangle Zone. A number of industry companies acquired a large amount of very high quality seismic reflection data, some 3D, and drilled new wells. As the bulk of these data are, or were, proprietary, the NATMAP project participants were reluctant to pursue additional work in the area without gaining access to some of these data, with permission to at least use this information to constrain subsequent maps and sections, if not having permission to publish it. As a result, project participants felt there was little point at that time in carrying out further studies whose synthesis and release wouldn't reflect the latest information and thinking because the proprietary data could not be incorporated.

Nonetheless, industry continued to view the GSC-led work in this area as relevant and important, as evidenced by continuing sellout enrolment in field trips offered through Canadian Society of Petroleum Geologists meetings and interest in GSC talks and publications. The primary aim of GSC geoscience mapping is to elucidate unknown or poorly known areas to allow companies to determine whether they are worth exploring and to aid in planning and natural resources management. Once the Southern Alberta Foothills area 'cools down', companies will be more willing to open up their proprietary data, and this information can be used by the GSC and the Alberta Geological Survey to make new interpretations available in advance of the next round of exploration in that area, which always comes, as the petroleum industry has demonstrated time and again.

Acknowledgements

The Eastern Cordilleran NATMAP project was carried out under the leadership of Margot McMechan, GSC Calgary, from its inception in 1993 to 1995. Daniel Lebel, then at GSC Calgary, assumed the leadership role until the project's end in 1998. Much of the information referenced for this compilation came from the annual NATMAP progress reports prepared by these project leaders. As well, I am grateful for additional project material that was prepared by McMechan and her principal research colleague on the project, Glen Stockmal, and for their insights and those of Lebel on the impacts and adjustments made to the project that ensured its success. In addition, I wish to thank Lionel Jackson, GSC Pacific Division, who led the surficial mapping component, for his careful review of the manuscript and suggestions for its improvement and for his added information on the results of the surficial mapping component and its implications.

V - SURFICIAL GEOLOGY OF THE SOUTHERN CANADIAN PRAIRIES NATMAP PROJECT

Rationale and Geological Setting

The Southern Prairies NATMAP project focussed on two separate areas in southern Saskatchewan and Manitoba that are considered typical of the entire southern Prairie Provinces. The prime objectives of this project were: to develop field and laboratory protocols and GIS and computer database handling techniques that could be used as standards for future surficial geology work in the prairie region; to develop an integrated model for the Quaternary deposits of the southern Prairie Provinces; and, at the same time, to update surficial geology information for the two parts of the study area. As well as encompassing an extensive agricultural region, the selected areas include important oil and gas, peat and aggregate industries and the thriving municipalities of Winnipeg, Brandon, Virden and Steinbach. As a result, the geoscience knowledge of the region has to address rural, industrial, and urban concerns.

The two study areas are situated in the physiographic region known as the Interior Plains, underlain by the gently-dipping sedimentary rocks that lie between the western mountains of the Cordillera and the Canadian Shield to the east. Even though most of the area is characterized by a thick blanket of drift, the influence of the bedrock geology, reflected in the pre-glaciation physiography, is evident in variations in the generally low topographic relief. The more westerly of the two areas - 'Virden' - covers approximately 10,000 km^2, extends north from the United States border to 50° N latitude and straddles the Manitoba-Saskatchewan boundary. The other - 'SE Manitoba' - covers a slightly smaller area south and east of the City of Winnipeg, also extends from 49° to 50° N latitude, and includes a sliver of western Ontario. The SE Manitoba area includes the eastern limit of sedimentary rocks, their contact with the igneous and metamorphic rocks of the Superior Province of the Precambrian Shield, and a strip of Superior Province rocks at the western margin of the Shield. This Precambrian basement, sloping gradually west-southwest, is overlain by Paleozoic and Mesozoic sedimentary strata that increase in thickness westward to 1200-1600 m in the Virden study area.

The extant geoscience knowledge for these areas was incomplete, both in the extent of the area covered and the range and currency of information available, and inadequate for current and future requirements. A substantial geological database had been amassed for some parts of the study area over the preceding four decades as a result of work by federal and provincial government agencies and the private sector. The results of that work, however, remained under utilized because each agency had developed and used its own methodologies and the results were largely fragmented and disseminated among the different organizations. Surficial geology maps for various parts of the area were the products of field mapping conducted more than thirty years previous and, in several cases, the accompanying geological reports had never been written. In certain parts of the study area, the most detailed surficial geology map was a Province of Manitoba compilation (1981) at 1:1,000,000 scale. It was based primarily on interpretation of soils mapping and some maps that had been compiled frrom air photo interpretation, with limited field work and no analyses of sediment composition. Some aggregate maps did exist, but only for scattered areas west of Winnipeg. In addition, a three-dimensional understanding of the nature and distribution of unconsolidated materials was non-existent.

None of these information sources was adequate to address emerging problems. A substantial urgency existed in provincial and municipal governments and in the petroleum and other industries to understand the groundwater resources of the Prairies to allow development of petroleum and other industrial resources while preserving water resources for urban and agricultural growth. Also at this same time, Canada and Manitoba were in the process of initiating a Red-Assiniboine Basin planning agreement as part of a Green Plan initiative that would require a regional compilation of surficial geology data and an inventory of aquifers.

The Southern Prairies NATMAP project would help close the gap in geoscience knowledge by providing an improved, up-to-date understanding of the surficial materials critical for: groundwater exploitation and protection, sustainable agriculture (soil degradation), industry (aggregate resources), urban development (land use planning),

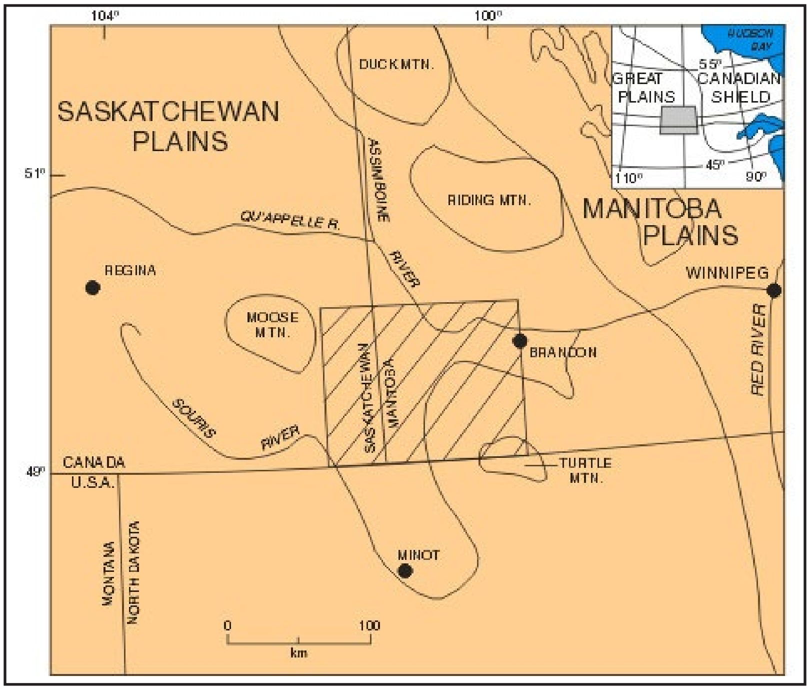

Fig. V-1: Location of the Southern Prairies NATMAP project straddling the Saskatchewan-Manitoba boundary in the Saskatchewan and Manitoba Plains physiographic region. (courtesy of A. Blais-Stevens, GSC)

Fig. V-2: Cross-section of an esker – an easily recognizable class of surficial geology landforms that characterize the Southern Prairies landscape. (courtesy of A. Blais-Stevens, GSC)

engineering (infrastructure), mineral industry (drift prospecting) and environmental (natural metal concentrations) needs. This goal would be accomplished through mapping of the surficial geology in field studies assisted by airphoto and satellite imagery. In addition, extensive effort was put into compiling existing information and developing protocols for selecting, storing, manipulating, and displaying both existing and new data. A prime goal of this work was to establish methodologies and databases that could serve as examples for additional collaborative studies of the Quaternary geology in other areas of the Prairies.

Project Delivery

The Southern Prairies NATMAP project was co-funded and jointly led by the Geological Survey of Canada and the Geological Services Branch of the Manitoba Department of Mines and Energy (MGS). GSC was responsible for all studies in the Virden project area and subsurface work in the SE Manitoba project area; MGS carried out the surficial mapping in the SE Manitoba project area. Additional contributions were made by the Water Resources Branch of Manitoba Department of Natural Resources, Manitoba Centre for Remote Sensing, Canada Centre for Remote Sensing, Manitoba Land Resource Unit of Agriculture and Agri-Food Canada, Manitoba Dept of Highways, Saskatchewan Water Corporation, Saskatchewan Research Council and the Universities of Manitoba and Regina. The urgency on the part of industry for the new geoscience knowledge was reflected in funding support provided by the Canadian Petroleum Association to the Saskatchewan Research Council for its participation in the project. The field components of the project also offered summer training opportunities for university students and the basis for graduate thesis research.

The Southern Prairies NATMAP Project, undertaken between 1992 and 1997, was among the earliest of the NATMAP projects. Whereas the preceding (and concurrent) Slave Province and Shield Margin NATMAPs were carried out in 'hardrock' shield terrain, with an emphasis on defining the potential for mineral resources, the Southern Prairies was the first NATMAP project to concentrate on surficial geology and groundwater resources for urban development. In addition to providing new geoscience knowledge for the particular study areas, it was intended to serve as a model for subsequent collaborative studies by the GSC and provincial surveys of the Quaternary geology of the southern Prairies through the development of new methodologies and databases. As a measure of its success, Southern Prairies was immediately succeeded by the Greater Winnipeg NATMAP project (1997-2001) that expanded the area of coverage of both the surficial and bedrock geology north and west to include the City of Winnipeg and Lake Winnipeg areas. Both these NATMAP projects were closely linked with, and benefited from, other concurrent geoscience studies in the region. In one case, a hydrogeological investigation was being undertaken by the GSC, Manitoba Geological Survey and the Manitoba Water Resources Board (MWRB) that was examining heavily-used bedrock aquifers and the Quaternary sediments that control their recharge. Also, GSC was examining coastal processes and crustal motion (glacial rebound) in the ongoing Lake Winnipeg Project, aided by wave monitoring and modelling studies by the University of Manitoba.

The principal objectives outlined for the NATMAP project were:

- To produce surficial geology maps, reports, and GIS databases for two typical areas of the Canadian Prairies
- To develop a unified stratigraphy for the surficial geology of the southern Prairie provinces through cross-border correlation,
- To develop standards for and to construct a digital database of surficial geology information for the program area,
- To develop, utilizing existing software wherever possible, a computer system that would allow manipulation, analysis and interpretation of observational data and production of maps and reports from the digital database.

Scientific Results and Implications

The NATMAP field and laboratory study results were compiled from each season's mapping and released initially as Open File maps at 1:50,000 scale (Virden area) or 1:100,000 scale (SE area). Mapping of the surface sediments, augmented by subsurface information from 27 new drillholes (1718 m aggregate depth), seismic and ground probing radar profiling and compilation of 20,000 borehole records, contributed to an improved knowledge of the region's surficial geological makeup and history. Eight, final 1:100,000 scale surficial materials maps were published and a 1:250,000 scale A-Series map prepared to accompany the final report for the Virden area. The maps were enhanced and supported by a digital, GIS database of surficial geology that included surficial geology, subsurface geology, aggregate information, drift composition and soils data. An excellent, easily readable summary for the Virden area, accompanied by all maps and complete databases, was published as part of the CD-ROM GSC Bulletin (Fulton et al., 2004).

Protocol and Data Handling Developments:

- *Surficial Geology Legend:* As part of developing new protocols, a map legend that could be applied to the entire Prairie Region was devised for the Virden area. This subdivided surficial deposits into major materials/genetic groups that were further subdivided in terms of texture and surface morphology. On the maps these units were labeled using a letter system that could be understood without reference to the printed legend.
- *Map and Data Viewing Software:* Special map and data viewing software was developed. This permitted viewing database information in conjunction with maps. For example, the actual material observed at the surface at each field observation site could be viewed on a map referred to as a 'Spot Surface Materials Map'. Clicking on the field data point on this map activated a view of the succession of materials observed (a stratigraphic column) and, from this, a record of the field description of each unit could be popped-up. This same software was used to display soils, aquifer, bedrock and geochemistry maps.
- *Borehole Data Compilation and Display:* Special techniques were devised for manipulating, displaying and using borehole information. Much of the data used came from drillers' logs stored in provincial water well databases. Extensive work was done to find the best way of rationalizing driller 'terminology' into a limited number of 'geological' terms. The viewing software described above was used to display the logs as stratigraphic columns. Available software used for displaying borehole logs required drawing logs individually and displaying these 'pictures' as JPEG files. The software developed by Pole Star Geomatics for this project drew the stratigraphic display log, on demand, directly from the borehole database. This permitted bypassing the onerous task of manually drawing a log for each of the 20,000 or so borehole logs.
- *Special LANDSAT Images:* Experimental work was done with snow covered LANDSAT images. These had two advantages over conventional images. First, the snow cover hides differences in vegetation which, in summer, mask subtle changes in geomorphology. Second, the low angle of the winter sun extends shadows, thus enhancing low relief features. These helped to outline the extent of certain features, such as buried valleys, and provided insight into the origin and relationship of the complex myriad of geomorphic features developed during deglaciation.

Surficial Geology:

- *Glacial Ice Flow:* Details were added, and consequent revisions made, to the history of glaciation in the study area. In particular, in the Virden area, the new interpretation that ice marginal channels may have been subglacial would indicate a largely northward ice retreat, rather than northeastward as postulated from earlier studies. Till geochemistry showed that a late push of an ice lobe from the east transported carbonate rich till into the Virden area. In the SE Manitoba area, an improved understanding of glacial flow history, gained through composition studies and striation measurements, has placed an accurate eastward limit on the dispersal of carbonate drift from the Red River Valley.
- *Catastrophic Glacial Floods:* The role of catastrophic floods in development of surficial features and aggregate resources in the Virden area was further elaborated. These floods occurred largely underneath the retreating glaciers and their effects varied from simply carving distinctive landforms in the surface of the till to depositing extensive areas of sand and gravel. In particular, the Assiniboine Flats sand and gravel deposits, which provide the area's largest aggregate source, are now interpreted as catastrophic flood, rather than normal, glaciofluvial deposits. This accounts for certain aspects of their composition and dispersal.
- *Origin of Turtle Mountain:* Digital elevation models developed from surface elevations (digital topographic data) and elevation of bedrock (from the borehole database) indicate that the relatively high peaks at the west end of Turtle Mountain Upland consist of glacially stacked thrust slices of Quaternary materials and Tertiary bedrock. This observation has important implications for correlating near-surface bedrock units in that area, exploration for coal and in explaining the origin of the Turtle Mountain Upland.
- *Quaternary Stratigraphic Correlation:* The stratigraphic scheme for Quaternary deposits used by the Saskatchewan Research Council was extended to the Virden area. This was then used in preparing a series of forty Quaternary stratigraphic cross-sections using the BORDAT database. Each can be displayed by clicking on the cross-section location on the cross-section location map. The extent and thickness of each stratigraphic unit is displayed on a series of isopach maps.
- *Deglaciation History:* A series of eight paleogeographic illustrations was drawn to depict ice retreat from the Virden area. These show separation of the main ice sheet into Assiniboine and Red River lobes, development of four glacial lakes and locations of four major scale meltwater floods. These help explain the distribution of the various deposits and landforms found in the area.

Environmental and Economic:

- *Groundwater Flow:* The improved understanding of glacial flow history in SE Manitoba has also clarified the geology affecting groundwater aquifer recharge in this region.
- *Water Well Database and Aquifer Maps:* The 'cleaning-up' and terminology standardization of water well borehole information makes this information more available and easier to interpret. In addition, the incorporation of these data into cross-sections that were based, in general, on more reliable stratigraphic information, shows the lateral extent of aquifer quality materials. Also, for the Virden area, a map was published showing the distribution of known aquifers.
- *Drift Thickness:* Drift thickness and drift surface maps were prepared for the Virden area. These help in determining potential locations of aquifers.
- *Aquifer Quality Material Depth Slices:* Special maps were developed for the Virden area showing the proportion of aquifer quality material (sand and gravel) in 10m-depth slices. These could be used in a number of ways. A well driller could look at these maps to determine the depth where aquifer quality materials could be encountered. An environmental steward concerned about aquifer contamination could use the maps to determine the approximate thickness of aquitard material above potential aquifers. The maps could be used to determine the depth, thickness and quality of materials capable of being developed as an aquifer in a particular area.
- *Aggregate Database:* A database was compiled of all aggregate related information that has been collected in the Virden area. This provides data on active and potential gravel pits, in addition to many sites that were never active pits or have been exhausted. The inclusion of information on all active, potential and exhausted sites shows where exploration or aggregate exploitation has been carried out and will help in guiding new exploration. The new interpretation that glacial ice retreat was northward, rather than to the northeast, means that efforts to locate associated sand and gravel resources in the Virden area might have to be revised accordingly.
- *Aggregate Suitability Maps:* A protocol was devised for preparing aggregate suitability maps from the surficial materials maps. Five categories of aggregate suitability were recognized ranging from unsuitable to good suitability. These special maps make it possible for aggregate exploration to be targeted in the areas where aggregate sources are most likely to be found.
- *Till Geochemistry:* Geochemical analyses were run on several hundred till samples from the Virden area. Digital maps present the results for twenty-six elements or compounds. Activating sample sites 'pops-up' actual values and the map symbol size represents value level, making

it easy to spot anomalous values. In addition to providing information on ice flow direction, as mentioned above, this information can be used to locate areas with high heavy metal contents.

- *Agricultural Soils:* The Virden area report includes a section on agricultural soils. This contains descriptions of soil formation, the effects of climate and parent materials on soil development, descriptions of the soils themselves and maps showing distribution of the soil types. This section provides basic information on agricultural soils useful to anyone concerned about soil contamination.
- *Peatlands:* Enhanced peatland mapping methods developed in the NATMAP project were merged with a LANDSAT scene of the Whitemouth Lake map area resulting in a composite colour polygon/raster map in which complex surface peatland patterns are shown in areas mapped simply as peat. This provides the potential for a better understanding of the nature, development, and exploitation of peatlands in SE Manitoba.

Other:

- *Interactive Digital Report:* Important aspects of the electronic report for the Virden area, such as easy access to databases and illustrations, are described elsewhere. In order to make the information more available to those not familiar with the technical jargon used, an extensive glossary was linked to the report. This makes it possible for the user to immediately jump from an unfamiliar term in the text to the glossary and then back to the

Recognized Impacts

The release of till characterization data for the SE Manitoba segment, through a GSC Open File report (Thorleifson et al., 1994) and presentations at the Manitoba 'Open House' in 1993, that revealed gold, base metal and kimberlite anomalies, led to immediate staking of the entire area - the largest mining claim in Manitoba history - with a corresponding investment of 5-10 million dollars.

Conclusions

In the Southern Prairies NATMAP project, interagency and interdisciplinary organizations compiled surficial geology data for two areas of the Prairie Provinces. This information is of importance to land and community development, the petroleum and other extraction industries, groundwater exploitation and protection, the agricultural industry and pollution concerns. It put together surficial geology maps for areas that had never been studied or had not been considered over the past forty years. It developed new techniques and protocols for manipulating and displaying surficial geology and related information. The success of this work led directly to similar interagency and interdisciplinary work in an adjacent area (the Winnipeg Region NATMAP Project). Unfortunately, major technical difficulties associated with compiling the digital components that, in turn, led to a significant delay in release of the final report, likely meant that the impact of this work has been far below its potential.

Acknowledgements

The Southern Prairies NATMAP project was carried out under the leadership of Robert Fulton, GSC, who also led the field component for the Virden study area. Gaywood Matile led the mapping and research program for the SE Manitoba area for the Manitoba Geological Survey. Although Fulton had retired from GSC when preparation of this summary began, he kindly provided some early documentation from the initiation of the project to help in understanding the reasons for its inception. He also provided important unpublished information on some of the impacts of the geoscience knowledge resulting from the project, and his opinions on the circumstances whereby the project might not have fully realized its potential in this regard. This summary has relied extensively on material from four annual NATMAP progress reports prepared by Fulton, and the GSC Bulletin footnoted in the text. Matile has always obliged my requests for his opinions on the importance of the Southern Prairies and Greater Winnipeg NATMAP projects, and on the value of the NATMAP Program and on how his experience on these projects has helped structure his subsequent studies and that of his Manitoba colleagues. Andrée Blais-Stevens, GSC, replaced Fulton after the field studies had been completed, to oversee the compilation and publication phases of the project. She kindly offered useful comments on an early draft of this chapter, and provided the figures and photographs herein.

VI - OAK RIDGES MORAINE AND ENVIRONS: ENVIRONMENTAL AND QUATERNARY GEOLOGY NATMAP PROJECT

Rationale and Geologic Setting

The Oak Ridges Moraine (ORM) is a prominent, hummocky ridge of sandy hills in southern Ontario lying 20-30 km north of Lake Ontario, roughly 20 km in width and stretching some 160 km from the Trent River westward to the Niagara Escarpment. ORM rests more than 350m above sea level and forms a significant topographic divide between Lake Simcoe and Lake Ontario (~75m asl). Moraines form mounds or ridges of glacial sediment deposited at or near a former ice margin. The ORM formed ~13,000 years ago as a result of enhanced meltwater discharge during retreat of the last (Late Wisconsinan) continental ice sheet. Covering 190,000 hectares, 65% of which lie within the Greater

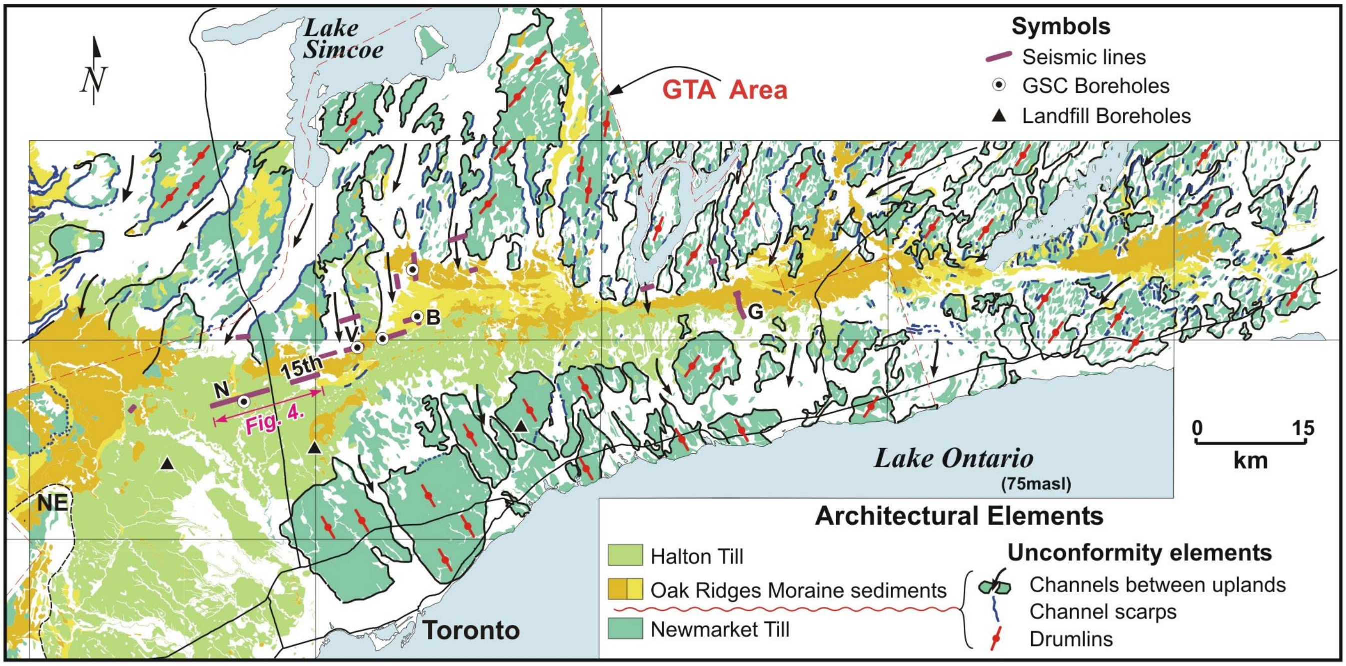

Fig VI-1: Surficial geology features of southern Ontario centred on the Greater Toronto Area (GTA), including the Oak Ridges Moraine, the focus of the ORM NATMAP project. (courtesy of D. Sharpe, GSC)

Toronto Area (GTA), it is one of the main sources of sand and gravel for the aggregate industry serving this ever-growing metropolitan region. As well, the moraine's deposits absorb rain and snow melt that is then stored in the sand and gravel aquifer layers where it is filtered and slowly released as cool, fresh water to the 65 rivers and streams originating in the ORM. Aside from its important economic and hydrologic contributions, the ORM is one of the last remaining, continuous green corridors in southern Ontario. It is still 30 per cent forested; its 130 wetlands, unique kettle lakes and century - old wood lots are home to more than 900 species of plants; it is also one of the last refuges for birds and animals in southern Ontario.

In southern Ontario, thick glacial deposits overlie shallow-dipping Palaeozoic strata, both of which host significant regional aquifers. The most productive glacial aquifer systems are found in the large sand and gravel moraine sequences with a thickness greater than 100 metres. The ORM is among the largest of these Ontario moraine aquifer systems and is certainly one of the most heavily used groundwater sources in Canada. Continued expansion of the use of this resource and decisions relating to land use planning (watershed management, cold-water fishery, e.g.) in the rapidly developing GTA and 33 other municipalities it serves, were being hindered by a poor understanding of the regional hydrogeological system.

This lack of sufficient knowledge of the moraine's function had been recognized since the 1960s, and various plans to remedy the situation had been prepared and discussed in the three decades following. Some modest scientific studies were undertaken but, as they were conceived largely by government planners, rather than geoscientists, the advances in the relevant geoscience were limited. To this point, the role of governments (municipal, provincial, federal, conservation authorities) in managing and protecting the natural resource values of the moraine was modest and mainly restricted to tree planting in the '40s to prevent wind erosion. Geological mapping in Ontario was focussed on the mineral aggregates and the northern part of the province. Although considerable mapping of surficial geology was being undertaken in the south, there was little political will to apply the geoscience to urban problems. However, early initiatives by Ontario Natural Resources, and partly driven by recommendations to Natural Resources Canada by the Minister's National Advisory Committee, the need and the will to bring together adequate resources and the geoscience and environmental expertise of government agencies were realized in the ORM NATMAP. The principal objective of this multi-faceted project was to understand the moraine's geomorphology and its interior structure in sufficient detail to identify the geologic elements controlling groundwater recharge, flow and discharge.

In the geological time scale, the Quaternary system denotes the last approximately two million years of the Earth's history marked by glacial episodes. A variety of complex geological units and landform architectures, mainly unconsolidated glacial sediments, covers the older bedrock formations of this ~10,000 km^2 study area. The project's main goals were: i) to map in 3D, the Quaternary geology of the broad region at 1:50,000 scale; ii) map the central Oak Ridges Moraine study area in more detail, 1:20,000 scale. These tasks would be undertaken using a blend of traditional

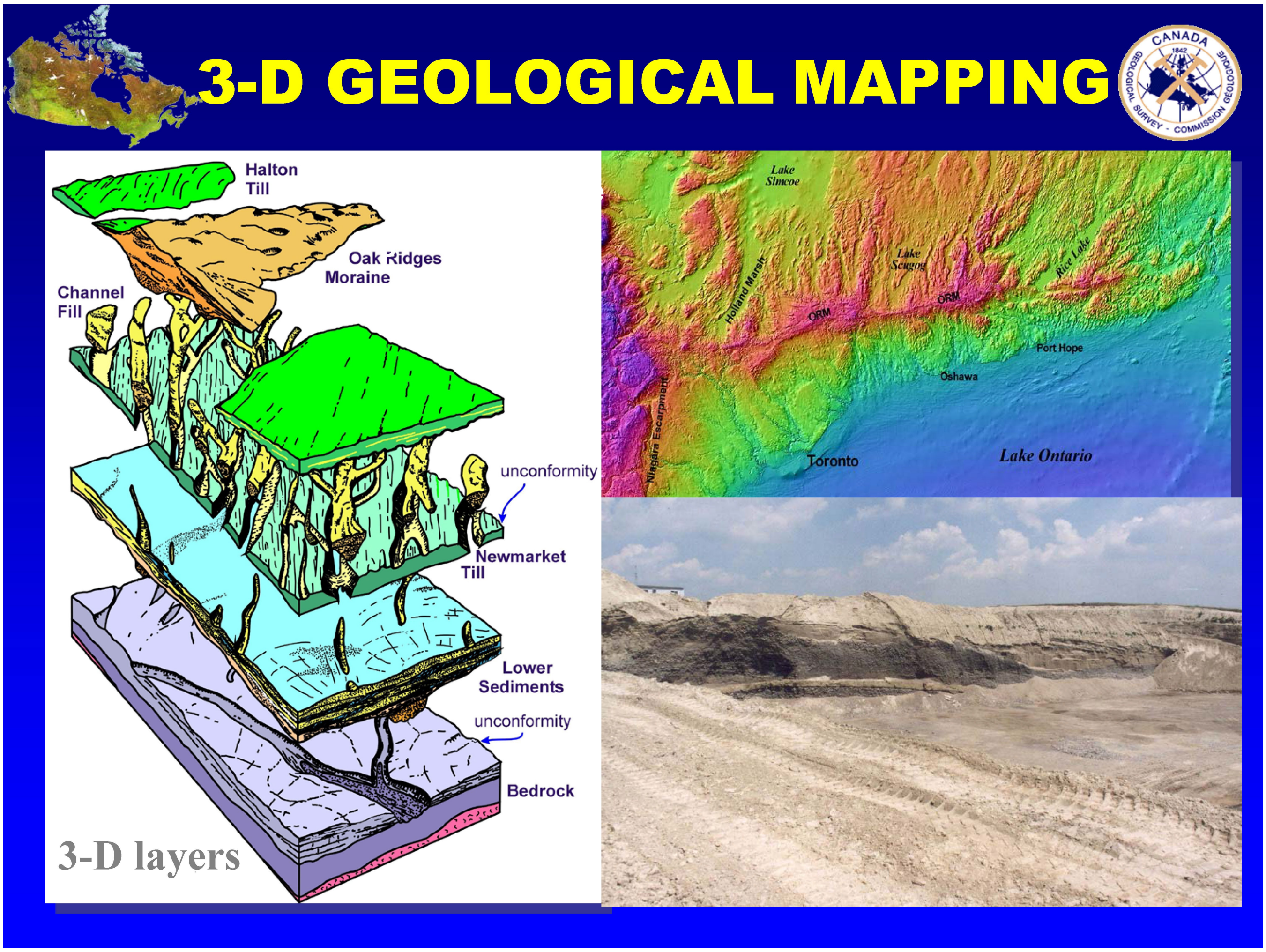

Fig. VI-2: Upper right: Digital elevation model of the ORM region landscape. Left: 3-D conceptual model from bedrock upward through the ORM. This model is the basis for present-day hydrogeological modelling. Lower right: Channel sand and gravel deposits illustrate the nature of water-bearing sediments occurring in channel aquifers that are the conduits of water flow in the ORM. (courtesy of D. Sharpe, GSC)

and state-of-the-art techniques in the ground examination of natural exposures, pits and quarries, assisted by air photo interpretation of the surface, plus geophysical profiles and drilling logs for the subsurface data. Soil and till samples were collected and analysed for geochemical, mineralogical and physical characterization. The use of remote sensing techniques, such as high-resolution reflection seismic profiles, ground-penetrating radar and aerial thermography, would provide tools to better characterize resource targets (buried aggregates, sediment structure, springs) in the ORM. The new, high-quality data would be integrated with a wealth of existing geological records in more comprehensive, standardized digital databases that would form the basis for analysis and modelling studies. This new geoscience knowledge would be applied to environmental issues, including groundwater assessment, waste disposal, geochemical baselines and resource management.

Project Delivery

The ORM NATMAP project commenced in 1993 and was planned for completion in 3 years. However, because of the project's initial successes in its first year, including the strong acceptance by, and impacts on, its intended stakeholders, it was immediately extended by one year to enable additional drilling, geophysics and geochemical studies to be carried out. Coordinated and principally funded by the GSC, the project would draw heavily on collaboration and support from the Ontario Government. Ontario project support was coordinated by the Ontario Geological Survey (Ministry of Northern Development and Mines), with participation also by the Ontario Ministries of Natural Resources, Environment and Energy, Food and Agriculture and the regional Municipalities of Durham, Peel and York. Cooperation from the Credit Valley Conservation Authority and the Metro Toronto Region Conservation Authority, plus added scientific expertise from Queens University and the University of Toronto was important to the success of the project.

A number of related or complementary projects were already underway in the Oak Ridges Moraine area or its surroundings. The ORM NATMAP project was able to cooperatively share resources, expertise and results with these projects providing mutual enhancement to the several aspects of new geoscience knowledge generated for this region of southern Ontario. Principal among these was the Geological Survey of Canada's Oak Ridges Moraine Hydrogeology project. In 1993, the Canadian Geoscience Council had concluded that Canadian efforts in groundwater inventory, protection and research were fragmented and inadequate. In response, the Oak Ridges Moraine Hydrogeology NATMAP project was initiated by the GSC in a conscious effort to reinstate much needed regional hydrogeological research within Canada and within the organization. As the separate NATMAP and hydogeology projects progressed, sharing direction, resources and personnel, it became clear that the goals, activities and results from the two were so inextricably linked that the hydrogeology project should be considered a component of the NATMAP project, and it has been treated as such in this summary of the ORM science.

Also prominent among the concurrent projects benefiting from, or contributing to, the NATMAP ORM research were GSC geophysical investigations in neighbouring areas to facilitate regional stratigraphic correlations, plus GSC studies of the floors of Lake Ontario and Lake Simcoe.

The principal goal of the ORM NATMAP project, as initially conceived, was the production of an extensive suite of digital surficial geology maps, including 9 at 1:50,000 scale covering the project region, plus 10 at 1:10,000 or 1:20,000 over the ORM that incorporated water resource and soils data. The new knowledge and its implications would be synthesized in comprehensive reports and models. The pressing environmental and planning concerns around the GTA/ORM dictated a high demand for rapid communication of upgraded and regional geological data. To partially meet this demand, an integral component of the NATMAP project would be the rapid presentation of new results and knowledge to forums of municipal planners, industry consultants, geologists and the general public. The rationale for extending the project and expanding the drilling and geophysics components was to provide information in the third dimension crucial for verification of the new geological digital database of archival and new surface, subsurface and bedrock information. As well, an expanded geochemical survey would provide critical baseline environmental data for assessments of waste remediation sites, siting of waste disposal facilities and forensic science investigations. As of 2006, the ORM project had published 32 maps and released 33 scientific publications. The new geoscience knowledge was also communicated to professional and general audiences, local, national and international, through >100 talks or poster presentations. An important component of the NATMAP projects was the training of young geoscientists through their participation in the scientific activities, r esulting in 13 theses from students at 7 different universities.

Scientific Results and Implications

The Oak Ridges Moraine NATMAP project made great strides in mapping the surficial geology, resolving the sedimentary origin, and unravelling the complex three-dimensional sequences of sediments in the GTA. The project was designed to provide the geoscience knowledge to enable a sufficient understanding of the moraine's interior structure to identify the geologic elements that control groundwater recharge, flow and discharge. Emphasis was placed on the use of innovative field and digital mapping techniques, on initiating and maintaining broad collaboration with all partners, and, on the timely communication of results to stakeholders at all levels. Not only did the project make many and varied contributions to an improved understanding of the geological and hydrogeological structure of the moraine, it demonstrated the effectiveness of the use or adaptation of new geophysical techniques, of new database management tools, and of new and innovative methods for incorporating various data sets in the depiction and understanding of 3D geological settings and their formative processes.

Many of the initial scientific results highlighted new stratigraphic and process concepts uncovered by integrating surficial and subsurface mapping.

- A new, regional stratigraphic framework was developed and tested using analysis of continuous drill core, geophysics and geological transects.
- The concept of flat-lying "pancake" subsurface stratigraphy, presumed prior to this study, has been replaced with a new, more detailed and more accurate, regional geological model that reveals the region's structural and process complexities.
- While the region's stratigraphic package totals roughly 200m, the ORM itself varies from 5m to all of this thickness, as illustrated in a new digital, 3D model of the region.
- The new, regional geological model, and the improved hydrogeological understanding that results, provides consulting companies with a better conceptual framework on which to base and interpret the results of their site-specific hydrogeological investigations.
- The new model explains, for example, the previously unrecognized large subsurface channels across the region, including at.the site of a proposed landfill in Vaughan. The identification of major buried channels in bedrock and sediment has economic significance regarding new aquifer targets, watershed management and landfill siting.

- Erosional channels, related to surface channels traced from north of the ORM, truncate stratigraphic units, notably the Newmarket Till, and provide connections between shallow ORM and lower aquifers.
- New process models of these channels show formation as large subglacial floods that are providing innovative prospecting concepts for new aquifers
- A thick, regionally extensive, till (Newmarket Till), forms a key marker bed present as surface drumlins at Lake Ontario bluffs, extending north below ORM to Lake Simcoe.
- Halton Till, formerly believed to be the dominant regional till sourced from the Lake Ontario basin, is a thin lake-sediment assemblage linked to ORM formation based on detailed core analysis.
- The new 3D geology shows the ORM to be composed of a series of landforms – fans, sand plains and eskers – that were deposited rapidly as meltwater floods.
- Studies of the ecology and paleohydrogeology of the region's kettle lakes may provide a basis for predictions related to global warming.

The extensive suite of innovative geophysical methods used in surface and borehole research proved their effectiveness in applications to regional hydrogeological studies.

- High-resolution reflection seismic profiles (>50 line-kms)
- New downhole seismic logging in unconsolidated sediments proved very useful in interpreting seismic profiles and in mapping the dense Newmarket Till based on its high seismic velocity.
- Targets identified by seismic surveys are now proved as new, high quality groundwater sources.
- A suite of other downhole geophysical tools map geological detail across the region
- Ground-penetrating radar proved effective in delineating local water tables.
- Gravity surveys are cost-effective for regional mapping of a proxy-bedrock surface.
- Detailed analysis of continuous cores has linked and calibrated sediment properties to geophysical properties for future cost-effective data collection.

Database and methodology development:

- The first systematic watershed map of the ORM was produced using digital elevation model (DEM) techniques.
- A composite (seamless and geo-referenced) LANDSAT/TM/DEM allows for improved regional analysis and hydrogeological investigations.
- A methodology for gauging subwatershed stream baseflow conditions in major drainage basins was successfully developed and tested.
- Identification of the thickness and geometry of sediment packages (isopach maps) - an important component in an integrated strategy for identification of water supply targets - will be greatly facilitated through recommendations presented for the sequence of selected geophysical surveys undertaken in such settings.
- An expert-system, 3D-modeling algorithm was developed for the 10,000 sq km area based on a training framework of high-quality, high-resolution data

Recognized Impacts

The value of scientific knowledge lies not only in the discovery of new facts, concepts and conclusions but in how this knowledge is ultimately used in assisting the socio-economic issues the project is designed to address. Thus, dissemination of the knowledge in accessible and understandable fashion is as critical to a project's success as the scientific endeavours and achievements themselves. To this end, one of the most successful aspects of the Oak Ridges Moraine NATMAP project was the communication plan put in place from its outset to promote awareness of the GSC's environmental geology program in public, scientific, educational and municipal sectors. The plan included: preparation and distribution of information packages designed for the media and public; summary reports mailed to 200 public, private, industry, municipal and provincial clients; workshops, forums and open houses; a web page to increase the public profile and to facilitate public response. At the project's outset, there existed a very poor understanding by the public and, to some extent, the geoscience community, of what the Oak Ridges Moraine was, the extent of this feature and the influence it exerts on the natural environment, even beyond its defined boundaries. However, as a result of the exceptional communications efforts, positive government actions related to management of the ORM and its resources were, in many cases, a direct response to constant, well informed public demand.

- The Oak Ridges Moraine Conservation Act to protect the moraine and its groundwaters was enacted in 2001
- NATMAP members provided two years of science input and testimony to the legal Ontario Municipal Board hearing that led to the ORM Conservation Act.
- A coalition of conservation authorities, largely municipally funded, has built on the GSC/OGS geoscience mapping efforts and has continued the science, outreach and education aspects initiated by the NATMAP project. This group works very closely with local municipalities and conservation authorities and has the ability to influence local planning decisions based on geological and/or hydrogeological conditions.

- Some municipalities have gone beyond the requirements of the Oak Ridges Moraine Planning Act in their planning so that high-quality data is acquired to conduct groundwater studies on a routine basis, e.g., new data collection standards resulted from NATMAP
- The federal government committed significant land holdings in the area towards the broader strategy of preserving the moraine and the natural resources functions it serves.
- The Oak Ridges Moraine project provided much needed operational guidance for implementing the provincial Clean Water Act, introduced in December, 2005, following the Walkerton disaster, that applies across the province
- Methods and protocols developed and employed in the Oak Ridges Moraine for formulating and testing conceptual, stratigraphic and hydrostratigraphic models are actively utilized across Ontario for development of Source Water Protection strategies.
- Local agencies and consultants have developed and are routinely using a 3D, numerical groundwater flow model of the region, derived directly from the NATMAP 3D model, to guide all water resources scenarios in the area.
- City Planners in Aurora have used ORM hydrogeology products in zoning of recharge areas within the municipality
- Consultants across the region now make enquiries of the science agencies about the conceptual geological model and the use of geophysics in hydrogeological site investigations and in searches for groundwater supplies for bottled water.
- GSC is consulted on groundwater issues within government (International Joint Commission, Federal Water Policy)
- Stream baseflow methodologies were adopted by the Ontario Ministries of Natural Resources and Energy and Environment and by the Credit Valley Conservation Authority; they are now adopted for use in all Source water production studies.

The Oak Ridges Moraine NATMAP project invested time and effort to attract and train a range of students who, in return, made significant contributions to the project. ORM project data used as the basis for undergraduate and graduate theses have filled key gaps in the region's geoscience knowledge and have been an influential stepping stone to these students pursuing higher academic degrees or advancing to academic positions. Younger students are also being educated in the geoscience and issues related to the Oak Ridges Moraine through the Toronto GEOSCAPE project and associated school curriculum materials which rely heavily on the NATMAP products. The Geoscape Toronto work won a National Planning award.

Recently (2010), an international research group (18, mainly oil company reps.) requested a 1-week fieldtrip / training session to the ORM area by the NATMAP team. The research group was interested in buried valleys (BVs) in glaciated terrain, as a analogue for similar settings in Ordovician glacial sequences that host economic oil and gas reservoirs in North Africa and adjacent areas. This formal research group considers the ORM BV dataset as a world-class analogue for ancient valleys with oil and gas reservoir potential. The wealth of data collected within the ORM NATMAP framework was most attractive to this research group as were skill-sets and knowledge of the NATMAP team-this is an international legacy item.

Conclusions

The principal impact of the ORM NATMAP project lies in how it has profoundly changed the regional geological concept of how hydrogeological investigations should be carried out in southern Ontario's urban and near-urban areas, in fact in glaciated terrain across Canada. It highlighted the importance of regional groundwater issues, new innovative methods and demonstrated the value of using a regional approach to hydrogeology. The benefits of scientific research should, and commonly do, extend beyond the scientific knowledge and results gathered during the research. The Oak Ridges Moraine NATMAP project demonstrated that scientific research within the public sector can effectively raise awareness of environmental issues, both within governments and the concerned public, to impact policy and legislation. This project, like many of the other NATMAP projects, demonstrated that scientists are able to communicate the wider significance of their research to their client groups, including the general public and policy makers. The ORM NATMAP has especially demonstrated the value of productive working agreements among different levels of government and other agencies and organizations.

Acknowledgements

The assistance of David Sharpe, Geological Survey of Canada and GSC project leader of the ORM NATMAP project, in preparing and revising this chapter and providing the figures used, is greatly appreciated. Sharpe was assisted by Peter Burnett as co-leader for the Ontario Geological Survey (OGS). Much of the information in each section has been gleaned from a number of reports, many of them internal GSC documents, on the rationale, results and impacts of this important project, prepared by Sharpe and his colleagues. In particular, parts of the Oak Ridges Moraine Hydrogeology Project: Impact Statement, October 1997, have been quoted or paraphrased to furnish examples of the importance of the science and the immediate and continuing influence of the project. As well, Frank Kenny, of the Ontario Ministry of Natural Resources' Water Resources Information Program and former participant in the ORM NATMAP project, provided important insights into the contributions of this project.

Others who kindly provided information are Cam Baker (OGS), Richard Berg (Illinois State Geological Survey), Gayle Soo Chan (Groundwater Resources Control, Lake Ontario Conservation Authority) and John Gartner (Gartner Lee).

VII - ORIGIN AND EVOLUTION OF THE DEVONIAN TO CARBONIFEROUS MAGDALEN BASIN, EASTERN CANADA NATMAP PROJECT

Rationale and Geologic Setting

The Magdalen Basin NATMAP project was introduced in 1993 to bring together the scientific elements and expertise required for a thorough understanding of this largely submarine area, some 600km by 300km in extent, centred roughly on the Magdalen Islands of the Gulf of St. Lawrence. The Magdalen Basin's 12km-thick sedimentary sequence of continental and shallow marine strata was known to host important deposits of salt, potash, gypsum and coal. As well, the basin had also shown a high potential for base metals and there was a strong perception that reserves of hydrocarbons, most notably coal-bed methane, also existed. There was an expectation that this potential could equal the proven resources of rocks of a similar age and history in western Europe. But a true measure of the economic potential required an understanding of the entire basin, its origins and tectonic history.

The Magdalen Basin is regarded as an example of a typical 'successor basin' - a basin or depression created following uplift, erosion, tectonism and renewed subsidence and compression of a pre-existing basin sedimentary sequence, in which sedimentation begins again. The Magdalen Basin exemplifies successor basins of Devonian to Carboniferous age, and serves as a potential model for this class of sedimentary basin on a global basis. Despite a long history of research, these Late Paleozoic basins have continued to challenge researchers interested in their origin and development through time. Formation of the basin dates from the Acadian Orogeny, 430-390 million years ago, the middle of the three successive orogenic phases that created the Appalachian mountain chain of eastern North America. While rocks of the sedimentary sequence deposited in this ancient depression lie predominantly under the waters of the Gulf of St. Lawrence, outcroppings of sedimentary strata deposited near the basin's margin are well exposed on land in all four Atlantic Region provinces. These rocks, lying in the earliest settled regions of Canada, initially attracted the attention of geologists in the middle of the nineteenth century, and have continued to be of interest ever since. Despite this long history of investigation, large areas of the basin rocks have remained unmapped in detail and geological maps of other parts of the region, some dating from the early 1930s, were recognized as inadequate. In more recent times - primarily the 1980s - studies of sedimentological and structural aspects of the rocks of particular but disparate parts of the basin were undertaken on a bilateral basis by the Geological Survey of Canada (GSC) and the respective provincial agencies under various Mineral Development Agreements (MDAs). However, a systematic, basin-wide effort that would cross geological and jurisdictional boundaries to collect, compile and understand the nature of the basin's stratigraphy and evolution was sorely needed. The Magdalen Basin NATMAP project provided the coordinating links to rectify this weakness.

Several scientific advances of the early 1990s in this region made an integrated investigation of the southern margin of the Magdalen Basin a timely endeavour. Reflection and refraction seismic studies across the basin had revealed its deep structure. Existing tectonic models were being challenged by newly developed concepts. Detailed studies and knowledge synthesis of specific sedimentary sections had led to a better understanding of the possible importance of the basin as a resource repository. Renewed interest had been shown by Canada's exploration resource sector in both the sedimentary and igneous rocks of the basin for their hydrocarbon and metallogenic potential.

Project Delivery

The Magdalen Basin NATMAP project was undertaken between 1993 and 1998, with principal leadership and financing by the Geological Survey of Canada. The provincial surveys of New Brunswick and Nova Scotia provided additional funds and expertise, plus leadership of geological mapping components in their respective jurisdictions. GSC was assisted by geoscientists of three Atlantic Region universities in several mapping components.

The new geoscience knowledge was released as geological and geophysical maps and reports by the Geological Survey of Canada, the New Brunswick Geological Surveys Branch and the Nova Scotia Mines and Minerals Branch. Some of the maps completed at 1:50,000 scale and more detailed had already been planned by the GSC and Nova Scotia under the Canada-Nova Scotia Mineral Development Agreement and provided the basis for the 1;250,000 scale bedrock geology map compilations prepared under the NATMAP project. Bedrock mapping at the surface was supplemented by diamond drilling in certain areas to help characterize the subsurface lithologies.

From the information provided in the NATMAP annual Review of Activities from 1993-94 to 1997-98, the new Magdalen Basin geoscience was released as a) GSC: 10 maps at 1:250,000 and 10 at 1:50,000 scales plus 20 scientific papers, b) NB Geological Surveys Branch: 6 maps at 1:50,000 and 7 at 1:20,000 scales, plus 6 scientific papers, 2 Field Guidebooks and a palynology database), c) NS Mines and Minerals Branch: 4 maps at 1:10,000 scale.

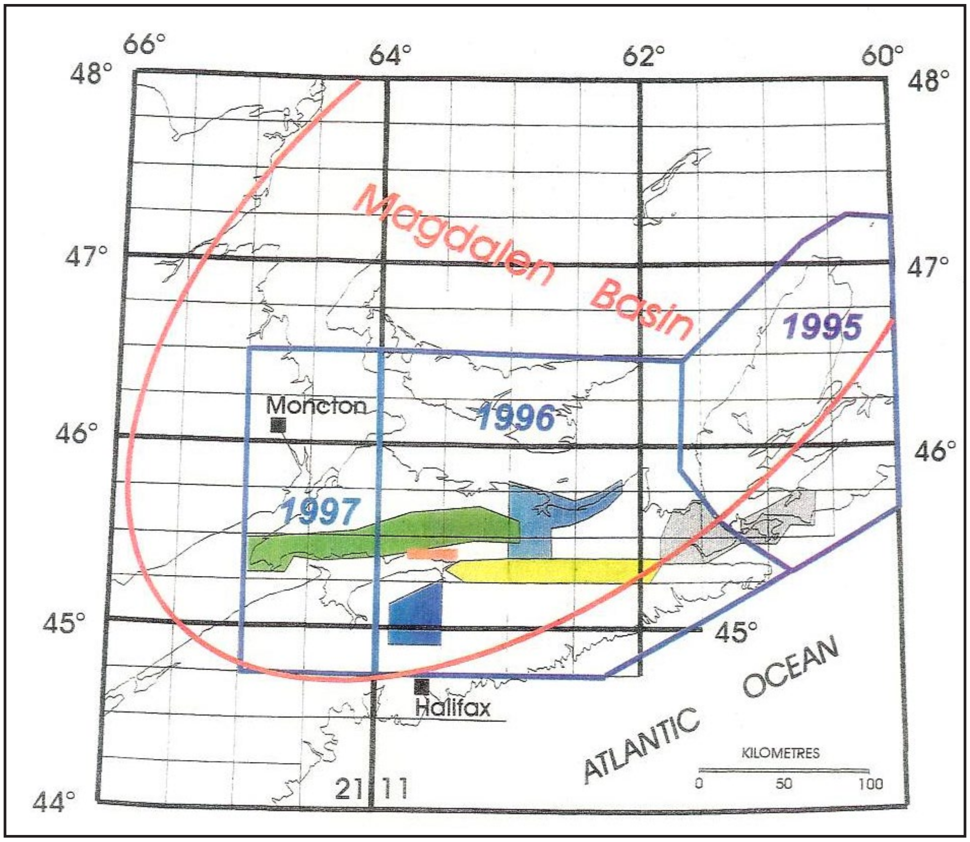

Fig. VII-1: Location of eastern Canada's Magdalen basin showing principal mapping areas undertaken in the Magdalen basin NATMAP project.

Scientific Results and Implications

Prior to undertaking the NATMAP project, several apparently conflicting basin-forming mechanisms had been invoked to explain the evolution of the Magdalen Basin, each model implying a range of tectonic and sedimentary processes which should be reflected in all aspects of basin development. Testing of these alternative models demanded a re-assessment of these processes, including those critical to resource potential, such as fluid flow and character and thermal history of the basin-filling sediments. Some specific goals of the project were to:

- Substantially enhance the quality and availability of geological map coverage, at 1:50,000 or more detailed scales, using a consistent approach for stratigraphic and structural interpretation by the participating groups across provincial boundaries;
- Synthesize the geology of the Magdalen Basin combining new mapping with existing geological maps at 1:250,000 scale, and produce a unified, digital database of the geology, augmented by gravity, magnetic and seismic data;
- Integrate for the first time the offshore seismic data with the onshore geological mapping to characterize the nature and geometry of the basin fill at depth;
- Compare the Late Paleozoic tectonics of eastern Canada and Hercynian Europe to test for new mineral potential in Atlantic Canada's successor basins.

The Magdalen Basin provides a record, not only of local tectonic and depositional processes, but of much larger processes operating at crustal scales and reflecting the influence of events far-removed from the present basin. A complete cycle of orogenic buildup, extensional collapse and successor basin formation is recorded. A major challenge of the NATMAP project was deciphering the relative importance of local versus extra-basinal factors to the origin and evolution of the basin.

- The new digital map compilation at 1:250,000 scale effectively outlines broad stratigraphic correlations through which the large scale nature of important structures becomes evident while many of the details established at 1:50,000 are still preserved
- Availability of the 1:250,000 scale compilations in digital format allows advanced spatial analysis of geological trends with geophysical overlays, which will greatly assist resource exploration
- Refined stratigraphic correlations; for example, the change upward from largely carbonates of the Windsor group to red-beds of the Mabou Group marks a change from marine to continental sedimentation

- In New Brunswick, several key stratigraphic findings and/or re-interpretations of Carboniferous stratigraphy were made: stratigraphic nomenclature was revised to be consistent across the Magdalen Basin; geological units were recognized to correlate with others in Nova Scotia
- New interpretation of Devonian and Carboniferous stratigraphy in northern Nova Scotia (Lynch, 2001) shows the regional significance of this previously poorly understood area and its tectonic development can now be incorporated into models for the origin and evolution of the Magdalen Basin.
- Enhanced regional biostratigraphy;
- Recognition of large scale shear zones and detachment faults within the basin and underlying basement, such as the Ainslie Detachment at the base of the Windsor group evaporites
- Recognition of mid- to late-Devonian extension and exhumation of basement rocks along the low angle Margaree Shear Zone in southwest cape Breton Island.
- Nature of the typical sandstone successions indicates they are derived from continental sources far-removed from the present basin to the north, west and southwest
- Regional correlations of lithostratigraphic units across the basin reveal systematic vertical and lateral variations indicative of the temporal changes in depositional environment and an evolutionary migration of the regional source area for the clastic sediments from north to southwest; the source region for material deposited as the Lismore Formation of mainland Nova Scotia was identified as in the northwest, from the interior of the Appalachian Orogen
- A new understanding of the origin of three distinct types of breccias (angularly fragmented rocks) reveals that those breccias formed during the sedimentation stage within the basin, or during its subsequent tectonic deformation have been key to localizing base metal mineral deposits because of the increased permeability of the breccias, whereas later breccias, formed after the ore emplacement, are barren of such deposits.
- Studies of sandstone-hosted base metal deposits (redbed copper) and the paleoclimate record reveals that such deposits can form in a 'monsoonal' climate, and that an arid climate is not required.
- Interpretation of Pb and Nd isotopic compositions of selected igneous rocks emplaced in the basin provide new information to help discriminate between tectonic hypotheses for the origin of the Magdalen Basin.
- Volcanic activity occurred in four main phases in the period 390-350 million years ago.
-
- A combination of thermal maturity indicators suggests that organic matter in the Colindale Member is in the early stages of the "oil window". Although the thermal maturity results indicate that these rocks are immature in onshore areas, potential exists for more mature (within the oil window) sediments at depth. Rocks of equivalent age can be traced beneath the southern Gulf of St. Lawrence, implying a viable regional hydrocarbon source within the Gulf, if proper seal and reservoir parameters are met.

Recognized Impacts

While the geological mapping and interchange of ideas among the NATMAP project participants and stakeholders provided a much better understanding of the stratigraphy and structure of Carboniferous basins in Atlantic Canada, socio-economic impacts resulting directly from the use of the new knowledge by stakeholders are difficult to quantify. However, the information has without a doubt benefited, and will benefit in the future, those involved with groundwater studies and municipal water supplies, oil and gas exploration and metallic mineral exploration.

Completion of the NATMAP project in 1997 and publication of the geological maps and reports was timely in that it coincided with a sudden renewed interest in oil and gas exploration in eastern Canada due to the announcement of the construction of the Maritimes and Northeastern Pipeline that would bring Sable Island gas through New Brunswick to New England. This renewed interest resulted in a flood of requests for up-to-date geological information on the stratigraphy and structure of Carboniferous basins.

The McCully natural gas field in the western part of the Magdalen Basin northeast of Sussex, NB was discovered in 2000. Although the discovery was not a direct result of the NATMAP project, as it lies approximately 50 km west of the area mapped during the project, the knowledge gained during the project no doubt provided a better understanding of the basin's stratigraphy and, therefore, indirectly contributed to the discovery.

The information gained from the Magdalen Basin project has also allowed the New Brunswick survey to promote and assist exploration companies in their search for sediment-hosted base-metal sulphides, gold and uranium within the Carboniferous rocks of the province.

Also in New Brunswick, the new bedrock geology maps are utilized by land use planners and companies conducting environmental assessments, in particular related to the new bridge in Moncton over the Petitcodiac River, and in route planning for the now-completed Maritimes and Northeast gas pipeline.

Conclusions

The Magdalen Basin project amply demonstrated one of the fundamental precepts of the NATMAP Program: addressing a geological problem whose solution requires coordinated and standardized input across provincial and federal terrain boundaries, provided through the expertise of the GSC and the provincial geological surveys of the region. The new knowledge gained from geophysical studies and interpretations of the marine component of the basin, combined with the direct observations and correlations afforded by mapping of the onshore margin of the basin, yielded, on the one hand, the improved understanding of its character and history on which to base future higher-level hydrocarbon resource exploration strategies and, on the other, localized, more detailed information to aid in more site-specific mineral exploration ventures in New Brunswick and Nova Scotia..

Acknowledgements

The Magdalen Basin NATMAP project was planned and led by Peter Giles, GSC Atlantic, assisted by Greg Lynch, formerly GSC Quebec. Some of the material that forms this chapter was taken from the annual reports to the NATMAP Steering Committee, prepared by Giles. In addition, I am particularly grateful for the important contributions of Susan Johnson, New Brunswick Geological Surveys Branch, who prepared a summary report especially for my use on the background, significant findings, products and societal impacts of the New Brunswick portion of the NATMAP project, elaborated on a number of points from her summary and added information gleaned from her colleague, Clint St. Peter.

VIII - NECHAKO NATMAP PROJECT OF THE CENTRAL CANADIAN CORDILLERA

Rationale and Geologic Setting

The Nechako NATMAP project was designed to enhance the knowledge of bedrock and surficial geology in central British Columbia in order to stimulate mineral exploration and support sustainable development. The project focussed on improving understanding of the rock assemblages and the various geological tectonic events that created them over the past 400 million years. It concentrated on understanding the role of the Eocene age (56-35 million years) plate tectonic event on the emplacement and localization of known and potential mineral deposits. In the Nechako project, the enhanced knowledge would be achieved by applying modern techniques of isotopic and paleontological geochronology; lake-sediment, till, and plant geochemistry; isotopic and trace element geochemistry; and detailed gravity, magnetic, radiometric, paleomagnetic and electromagnetic surveys, all in support of extensive bedrock and surficial mapping. In addition to contributing to mineral exploration and enhanced economic development, the new geoscience knowledge would be valuable for land-use decisions such as those related to reservoir siting, the impact of logging and mining on the terrain and for aboriginal land-claim negotiations.

The Nechako NATMAP project area lies in the Intermontane Belt of central British Columbia, the geological designation for the relatively flat terrain, transected by the Nechako River, between the Rocky Mountains to the east and the Coast Mountains to the west. The bedrock consists of several assemblages of volcanic and sedimentary rocks laid down during at least eight different tectonic events over the last 350 million years. These assemblages formed as: oceanic crust during early ocean spreading (Cache Creek and Sitlika complexes); magmatic and volcanic island and continental arcs over various subduction zones (Stikine, Quesnel, Francois, and Bulkley arcs); volcanic and sedimentary basins during continent scale translation and extension (Ootsa and Endako formations); and volcanic sheets extruded from mantle plumes (Chilcotin and Nechako Plateau groups). Several of the older assemblages are recognizable as discrete and distinct fragments of former lithospheric plates, known as terranes. The Nechako region is dominated by three terranes: oceanic Cache Creek (320 - 180 million years), and island arc Stikine and Quesnel (270 - 165 million years), which were amalgamated by subduction that terminated with their collision around 180 million years ago.

The assemblages older than 50 million years were highly deformed through intense folding and faulting concentrated during approximately 10 million year intervals around 220, 175, 150, 100, and 75 million years ago. They were intruded by granitic plutons during those same times, and subsequently torn apart and transported hundreds of kilometres during extensive igneous activity 55-43 million years ago. Vast, thin, volcanic flows of the Nechako Plateau Group were laid down over these deformed and transported assemblages from 15 - 9 million years ago. These rocks are generally covered by thick deposits of commonly unconsolidated sediments (drift) eroded from the adjacent mountains in the last 2 million years during and after the last great ice age.

Prior to the NATMAP project, the extant geological maps dating from 1949 and 1962 had been produced by reconnaissance mapping at a time when access to the region was poor and without the benefit of modern geological techniques and knowledge. Nonetheless, mineral exploration based on these maps had led to the discovery of numerous mineral deposits, and copper, gold, molybdenum, mercury and silver had been mined. More recent information from mapping by the British Columbia Geological Survey and from industry exploration pointed up problems with the earlier maps and reports, primarily the recognition of many still unmapped rock suites and more tectonic and plutonic events,

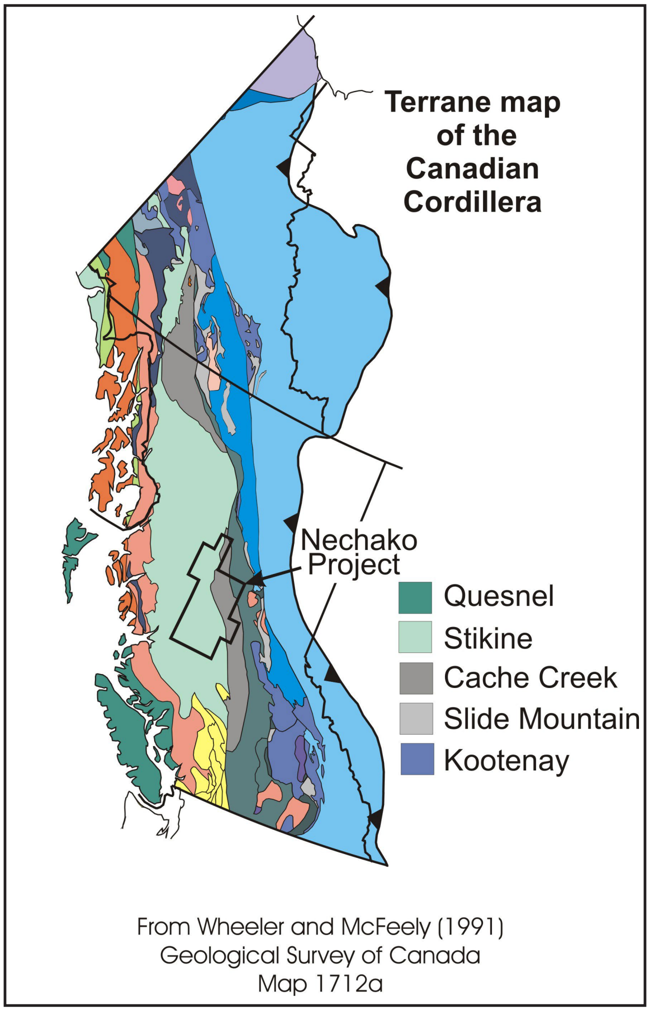

Fig. VIII-1: Simplified terrane map of the Canadian Cordillera physiographic region from southern Alberta northward through B.C., NWT and Yukon, indicatring the five main geomorphological belts and the Nechako NATMAP project area. (courtesy of L. Struik, GSC)

Fig. VIII-2: Looking north across the western end of Burns Lake, B.C. in the western Fort Fraser map area, and the west side of the Nechako project area. (courtesy of L. Struik, GSC)

Fig. VIII-3: Looking northwest across Euchiniko Creek in the southeastern corner of the Nechako project area. (courtesy of L. Struik, GSC)

the existence of large areas of bedrock covered by extensive drift and the resultant poorly tested mineral and hydrocarbon potential of the area.

Project Delivery

The Nechako NATMAP was jointly coordinated and principally funded by the Geological Survey of Canada (GSC) and the British Columbia Geological Survey (BCGS) (Tables 1-3). During the period from 1995 to 2000, geoscientists from these agencies were joined in the effort, formally and informally, by earth scientists from other federal and BC provincial government agencies, eleven universities and four companies, bringing together the necessary spectrum of expertise and experience. A total of 37 new regional and detailed geological and geophysical maps and compilations were published for an area of roughly 33,000km2 (Figure 1). In addition to the hardcopy maps and reports, the data were made available in computer-accessible, GIS-compatible format on CD-ROM and through the BCGS MapPlace and GSC CORDLink websites, and a compilation of the scientific achievements was published in a special issue of the Canadian Journal of Earth Sciences (Jones, 2001).

Aside from the actual new knowledge derived from the geoscience studies in the Nechako area, the multidisciplinary approach demonstrated the value of applying modern isotopic and paleontologic geochronology and detailed aeromagnetic surveys to 'look through' the surficial deposits to the bedrock obscured beneath, and that such techniques will be absolutely essential for future studies to understand the geology of the entire Canadian Cordillera of British Columbia.

The Nechako NATMAP project set out to test four scientific hypotheses related to the nature, age and deformational history of four enigmatic geological terranes in particular, and a fifth hypothesis related to the direction of ice flow during regional glaciation. They addressed the conditions that would influence the potential in the Nechako region for several types of mineral deposits known from other parts of B.C.. Those hypotheses were:

- The Eocene volcanic complex in central British Columbia represents the tectonic/magmatic expression of an Eocene regional extensional event and has the potential to host precious metal epithermal and intrusion-related copper-gold and molybdenum deposits.
- The boundaries between Stikine, Cache Creek and Quesnel terranes are regional thrust faults.
- Understanding the stratigraphy, tectonic history and rock distribution of the Triassic-Jurassic volcanic arc of the Skeena Arch will permit the discovery of new Cu-Au associations.
- Volcanogenic massive sulphide deposits of the Kutcho type exist in Triassic and older rocks.
- Regional Pleistocene ice flow directions varied through time in central British Columbia and understanding the flow patterns can help locate buried mineral resources.

Scientific Results and Implications

The project successfully added new knowledge to each of the hypotheses and, as the participants expected, made several additional surprising discoveries.

- The Eocene volcanic and magmatic complex has been extensively dated, with ages ranging from 58 million to 45 million years ago. The rocks were formed during regional, northwesterly directed strike-slip faulting that detached and slid upper crustal rocks from the underlying highly metamorphosed rocks of the middle crust, as represented by the Wolverine and Vanderhoof metamorphic complexes.
- Eocene magmatism and tectonics formed the Babine porphyry copper district, and it was superimposed on an earlier copper-gold porphyry environment with potential for volcanogenic massive sulphide mineralization. Such Eocene magmatism and extensional tectonics permeate much of the Nechako River map area, making it prospective for epithermal gold deposits.
- Prior to 173 million years ago, the oceanic Cache Creek terrane (180-315 million years) was thrust westerly over the volcanic arc terrane of Stikinia (175-270 million years) , just as it was in northern British Columbia. The original 223 million year-old subduction zone contact of Quesnel over Cache Creek terrane was deformed into a steep suture between the edges of the Jurassic North American craton and Cache Creek ocean lithosphere that lay to the west.
- The Triassic-Jurassic volcanic arc of the Skeena Arch has been subdivided into 15 magmatic suites with distinct ages and compositions, four of which host Cu-Au mineral occurrences.
- Age determinations confirm the hypothesis that rocks exposed along the Skeena Arch uplift are prospective for volcanogenic massive sulphide deposits like those of the Eskay Creek deposit outside the region to the northwest.
- The Sitlika assemblage of Cache Creek terrane is equivalent to the Kutcho assemblage of northern B.C., extending the area prospective for Kutcho Creek type Cu-Zn-Ag-Au-Pb deposits.
- Distribution of the Sitlika Assemblage has been extended and, therefore, also the area prospective for Kutcho Creek type volcanogenic massive sulphide deposits south of Takla Lake.
- A northerly oriented, late Pleistocene ice divide was discovered in west central B.C., from which ice flowed west and east. In addition, maps of the chronology and geography of the ice flow patterns and glacial sediments can be used to explore for the sources of mineralized debris.
- Four plate-tectonic regimes since 350 million years ago include: 1) ocean spreading and concurrent subduction at the North American margin from 350 to 180 million years ago, stopped by volcanic arc - continent collision, 2) the subsequent subduction magmatism from 180-55 million years ago was interrupted by 3) 10-15 million years of crustal extension around 100 million years ago when the subduction appeared to relax, and 4) northerly directed strike-slip motion and concurrent crustal extension for 10 million years around 50 million years ago.
- Newly discovered Late Cretaceous magmatism in the Babine Lake district has many of the characteristics of the Eskay mining district's rift-controlled mineralization. Detailed till, lake sediment and water geochemical surveys in this district have identified numerous precious metal and base metal geochemical anomalies, some in under-explored parts of the area.
- Upper Cretaceous magmatic suites associated with copper-gold porphyry deposits to the west have been discovered in the Nechako River map area, increasing the potential for these types of deposits.
- The Nechako project clearly defined the Eocene age range for mineralized host rocks of the Babine mining district, and determined that the most prospective areas for new exploration lie in the large geological blocks that were faulted downward during the major deformational events of this defined time period, and not in the better exposed, uplifted blocks that expose less fertile lithologies.

- Biogeochemical surveys over the Endako batholith have recognized the world's largest known biogeochemical anomaly for molybdenum, and strengthen the potential for a new and expanded economic ore deposit.
- The sources of mercury minerals were determined around Canada's only two formerly operating mercury mines, at Pinchi Lake and Bralorne-Takla along the Pinchi Fault in the northern part of the Nechako project area. The research clearly showed that mercury in the deeper horizons of the soils is natural and is derived from erosion by glaciers. In contrast, in the organic humus layer of the soils, mercury is, in part, derived from the anthropogenic mining activities. Mercury in all soil layers is dominantly in a form not considered toxic.
- The rock-dating method using isotopes 40 and 39 of Argon proved accurate throughout the region for dating the emplacement and metamorphic age of the magmatic and metamorphic rocks. It provided broader, spectrum event information than conventional, and more expensive, zircon mineral dating using isotopes of uranium.
- Studies on the distribution of mercury and molybdenum in soils should be extended to plant materials to better determine the toxic hazard potential;
- Water well data and Quaternary stratigraphy demonstrated the capability to reveal several unique aquifers and the potential for groundwater resources.

Recognized Impacts

The Nechako NATMAP studies were conducted during a downturn of mineral exploration and mining in BC and, as commodity prices and investor confidence outweigh the stimulus of new geoscience knowledge, the economic impact of the project has yet to be realized. However, a recent rise in commodity prices, a return of investor confidence due to improved government support for the BC mining industry, and a stability of the BC social fabric compared with other parts of the world are expected to reinvigorate exploration in the Nechako area, especially for the metal molybdenum. Nonetheless, some projects have utilized and benefited from the new Nechako geoscience knowledge over known mineral properties, although most of these efforts were set aside in conjunction with the economic downturn.

- The expansion of known reserves at the Endako molybdenum mine used Nechako project data as it was released to target new prospects and evaluate the mineral camp; Endako Mines staked claims over a molybdenum geochemical anomaly found by a regional geochemical survey;
- Nechako geochemical survey data (till, lakes, bark and rock), plus geophysical survey results (multiparameter gamma, electromagnetics and magnetics) were used by other exploration companies as soon as the new data were released to focus in on potential targets.
- The Morrison/Hearne Hill prospects were evaluated further based on the geological and geochemical data and information supplied by the Nechako project. The geological context for the prospects were developed using the isotopic age dates for the host rocks, as well as the structural interpretation of the prospective area;
- Nechako project maps and reports that identified favourable geology and mineral chemistry were the stimulus to initiate mineral exploration in central BC. One exploratory drill hole intersected a mineralized zone, resulting in some staking around the property;
- The Nechako geoscience has fostered new confidence in the area's mineral potential, a confidence that translates into new investor capital to further advance private sector mineral exploration across the region;
- Nechako project geoscience is now being recognized for its potential to aid in evaluation of the hydrocarbon potential of the Nechako Basin.
- Scientifically, the project has made extensive re-interpretations of how we understand 350 million years of geological history and its implications for the geochemistry, geophysical properties, geography and mineral deposits in central British Columbia, and how we use geological techniques to study such environments.

Conclusions

The Nechako NATMAP project has significantly added to and upgraded the geoscience of a mineralogically important region of central British Columbia. In addition to the new knowledge released in geoscience maps, reports and databases, the project demonstrated the necessity of conducting airborne geophysical surveys and applying various geochemical techniques to solve geological problems in terrains extensively covered by glacial deposits and soils that obscure the bedrock. While no major mineral discoveries can yet be linked to the Nechako geoscience due to a period of slowed exploration in BC, it is fully expected that higher mineral and hydrocarbon commodity prices and government support for the mineral and hydrocarbon industry in this province will stimulate exploration over this region, exploration that will be highly influenced by the new geoscience resulting from this NATMAP project.

Acknowledgements

The Nechako NATMAP project was planned by Lambertus (Bert) Struik, GSC Pacific (Vancouver) and carried out under his leadership. He was assisted in the

leadership role by Don MacIntyre, B.C. Geological Surveys Branch. The author is indebted to Struik for his continual assistance with many aspects of this summary. He prepared the main draft of this chapter and provided the accompanying figures. Additional important material was taken from the annual NATMAP Review of Activities reports written by Struik and from his publication footnoted in the text. Struik also contacted several companies working in the Nechako project area and provided summaries of their impressions of the value of the new NATMAP geoscience to their endeavours. Thus, thanks are due to Erik Tornquist, Pacific Booker, Bob Weicker, SilverQuest Resources and Jim Davis, Leeward Capital. Alain Plouffe, GSC, who carried out studies of the surficial geology and till geochemistry as part of the Nechako project, kindly summarized the main results of his research.

IX - WESTERN CHURCHILL NATMAP PROJECT OF SOUTH - CENTRAL NUNAVUT

Rationale and Geologic Setting

The Canadian Shield, composed of stable, Precambrian age (>540 million years) rocks, occupies almost half of Canada's landmass. The Shield comprises seven geological provinces, each distinguished by its unique internal structural trends and style of deformation. The Churchill Province is centred on Hudson Bay and spans considerable areas to the west, north and south. That part of the Churchill Province exposed on the western side of Hudson Bay is known as the Western Churchill Province (WCP) and covers extensive, contiguous areas of northern Manitoba and Saskatchewan, eastern NWT and the Kivaliq region of Nunavut. Prior to the Western Churchill NATMAP Project (1997-2002), the WCP was one of the largest, yet most poorly known, fragments of Archean (>2.5 billion years) crust in the world. Divided into the Rae (northwest) and Hearne (southeast) domains, it contains an extraordinary diversity of gold, base metal and uranium resources, as well as diamond prospects. However, the lack of a comprehensive geoscience knowledge infrastructure, including modern geological maps in key areas, continued to hamper mineral exploration and effective land use management. The absence of modern integrated maps was exacerbated by the sheer aggregate size of the WCP (roughly 1 million km^2), its internal complexity, and the long span of geological time during which it was subjected to major geological events (~ 1 billion years). For example, the tectonostratigraphy of the ancient Archean supracrustal belts was essentially unknown, and we had little understanding of the Paleoproterozoic deformation and metamorphism which affected them. Compounding the gaps in our knowledge of the bedrock geology, the apparently complex glacial history of the overlying Quaternary sediments deposited by the largest sector of the Laurentide Ice Sheet (90,000 years ago) was poorly known, despite their importance for mineral exploration, and for the formulation of environmental baselines.

The WCP has many features in common with other Archean terranes. What sets the WCP apart from its Canadian equivalents, and many other Archean cratons elsewhere in the world, is the extent and intensity of Paleoproterozoic tectonothermal events which overprinted and significantly affected the Archean supracrustal belts and the intervening crust. Understanding the effects of Paleoproterozoic tectonometamorphic events was of critical importance, both for deciphering the geology of late Archean supracrustal belts (including the potential for overprinting and further concentrating existing Archean mineral occurrences), and to understand the potential for primary mineral deposits of Paleoproterozoic age.

The Western Churchill NATMAP project was designed to provide modern geological maps of late Archean and Paleoproterozoic supracrustal belts in five separate areas straddling the Rae-Hearne boundary in a part of the WCP with significant mineral potential, but where an adequate understanding of the geoscientific infrastructure that influences this potential was lacking. The maps would be the new foundation for an enhanced, multidisciplinary geoscience knowledge base of the scale and scope required to provide the basis for understanding the crustal growth, tectonic evolution and mineral potential of a significant sector of the WCP. To that end, the following objectives were envisaged:

- To establish the tectonostratigraphy and tectonic settings of the late Archean supracrustal belts.
- To determine the extent, nature and significance of Paleoproterozoic tectonothermal events.
- To track the Quaternary history of the Keewatin Ice Divide.
- To develop an accessible digital geoscience knowledge base and GIS (Geographical Information System).

Project Delivery

At the outset of the Western Churchill NATMAP Project, the Northwest Territories included what is today Nunavut. Accordingly, the Project was a collaboration between the Geological Survey of Canada (GSC), the Government of the Northwest Territories (GNWT) and the Department of Indian and Northern Affairs (DIAND), wherein the latter two were represented by the C.S. Lord Geoscience Centre. As well, some mapping was undertaken sharing costs, camps and logistics with exploration companies active in the area. Reflecting the lateral discontinuity of the five targeted supracrustal belts, the GSC was responsible for the Kaminak, MacQuoid and Woodburn belts, GNWT took the lead on the Yathkyed belt, and DIAND (through a contractor) worked

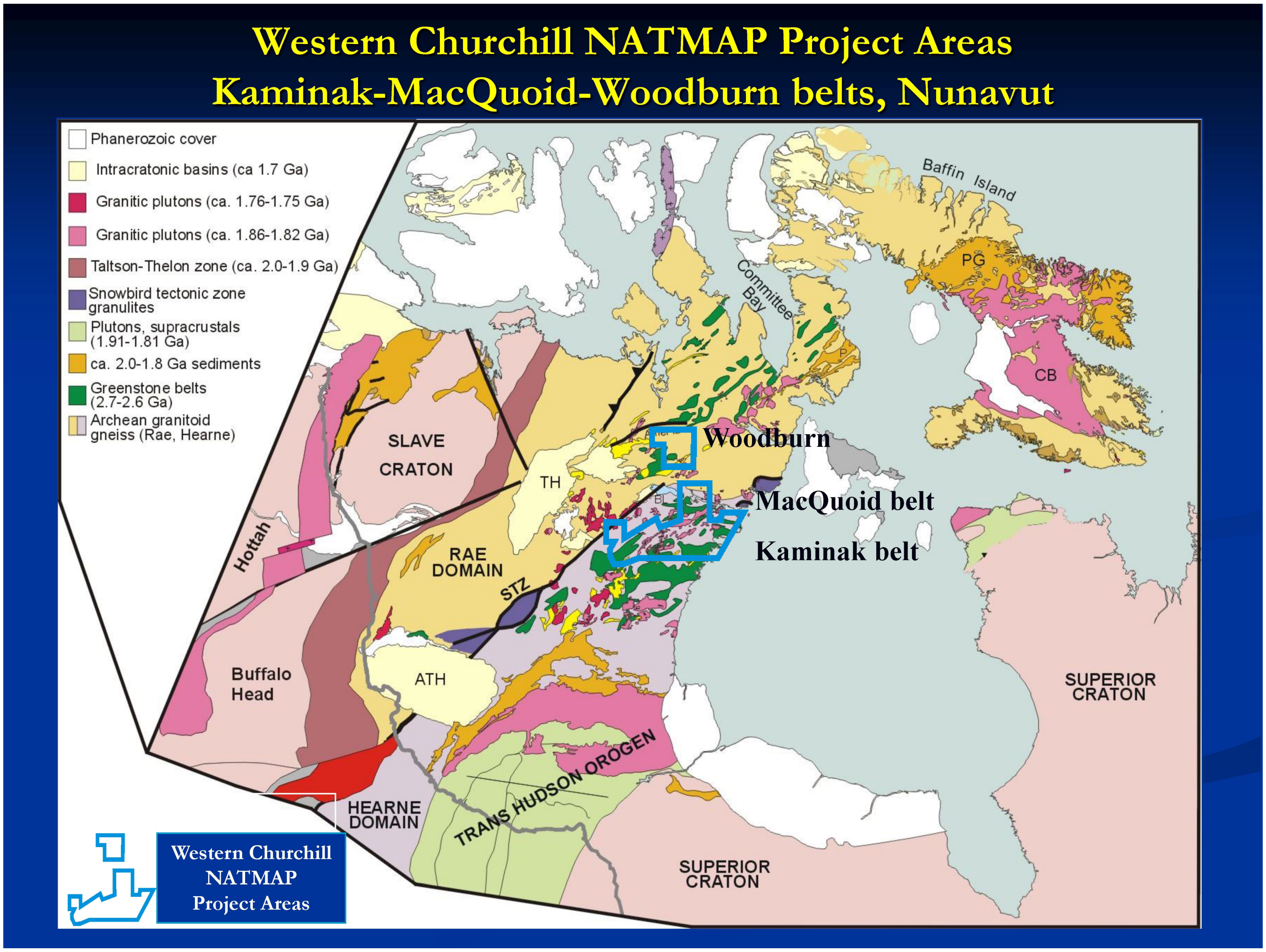

Fig. IX-1: Location and geologic setting of the component areas of the Western Churchill NATMAP project. (courtesy of S. Tella, GSC)

in the Angikuni belt. Students, from undergraduate to PhD, and their academic supervisors from universities across the country, participated at all levels in all project components.

Despite logistical difficulties inherent to working in the remote Barrens, the project set two important precedents. First, a geophysical transect was successfully undertaken across the entire project area using seismic and electromagnetic techniques to image major buried structures hundreds of kilometres in extent. Second, helicopter-supported field workshops, directed at the exploration industry, were undertaken at the end of each of the three principal field seasons in the Kaminak (1997), Yathkyed-Angikuni (1998) and Woodburn areas (1999).

The project mapped the equivalent of 75 1:50K NTS sheets, published as 19 bedrock maps, 30 Current Research papers and 4 CD-ROM releases. The new information was also disseminated in 83 conference abstracts, including 33 presentations and posters in a 2-day Special Session at the GeoCanada 2000 meeting in Calgary organised by the NATMAP Working Group. Two formal collections of papers focused on the Kaminak and MacQuoid supracrustal belts in *Precambrian Research* in 2004 and 2006, in addition to numerous individual papers in the international literature.

Scientific Results and Implications

The Project was successful in contributing significantly to each of the principal scientific issues it set out to address:

- Distinct deformational histories of the Central and Northwestern Hearne subdomains, and the Woodburn group in the Rae domain, were identified and characterized.
- A working model was formulated for the tectonic settings of the 2740-2660 Ma Neoarchean supracrustal belts of the Hearne domain.
- The history and extent of complex, multiphase, Paleoproterozoic reworking of the central WCP was characterized: in particular (i) a period of thrusting at ~2660-2600 Ma attributed to the initial juxtaposition of

Fig. IX-2: Typical terrain in the Western Churchill NATMAP project region. (courtesy of S. Tella, GSC)

Fig. IX-3: Multiple deformation events are recorded in layered anorthosite, mafic granultic Uvauk Complex, Western Churchill NATMAP project. (courtesy of S. Tella, GSC)

the continental Rae and the oceanic Hearne domains, (ii) the major reworking of the NW Hearne by thick-skinned thrusting at 2550-2500 Ma , (iii) a disconformity recognized within the Paleoproterozoic Hurwitz Group that indicates a major change in sedimentation history at 2100-1910 Ma , (iv) the penetrative thrusting in a north-westerly direction of the southern Rae domain and the localised reworking within the Hearne domain are now interpreted to be Paleoproterozoic in age, (v) late oblique extension and localized uplift was recognized along the NWT Hearne at ca. 1.8 Ga.

- The ice flow history of the Keewatin Ice Divide of the Laurentian Ice Sheet was revised significantly. Ice flow patterns within the Hearne domain show strong variations with time, swinging progessively from a southwesterly direction to east-southeast and finally to the southeast. A later northward flow has also been identified.
- A wide variety of mineral deposit types in a diverse suite of host rocks were known from the Western Churchill Province at the outset of the NATMAP project; deposits of gold and sulphides were recognized to have formed under a range of geologic situations and processes. The apparent contrasts, however, in the style of gold mineralization in the Meliadine and Meadowbank deposits, as an example, emphasized the importance of understanding the timing of gold mineralization with respect to regional deformation in the search for new mineral occurrences.
- Metallogenic investigations have identified new targets for gold exploration in several greenstone belts of the Western Churchill Province, including those types of deposits that formed within sediments at the time of their compaction (diagenetic) and others formed in conjunction with volcanic activity (synvolcanic). This evidence greatly enhances the chance of discovering world-class gold deposits in this region.
- Mapping of the surficial, glacial ice-sheet deposits (till) in two of the five areas investigated has demonstrated the usefulness, but complexity, of using the geochemistry of the till deposits as a guide to mineral exploration.
- The new geoscience has placed the principal metal deposits and mineral showings in a tectonic context, revealing the strong potential links between metal reworking and remobilisation in late Neoarchean and Paleoproterozoic time that could have led to the creation of economic deposits.
- The new geoscience has signaled the potential extension of the mineralogically prospective Hearne domain into the Rae domain, thereby broadening the region of mineral potential.

Recognized Impacts

- The new geoscience knowledge stimulated new, detailed exploration efforts by Cumberland Resources that resulted in the extension of its Meadowbank gold deposit in the Rae domain.
- The new geoscience prompted work on a gold-bearing granite at Nowyak Lake that led directly to renewed staking in the area.
- The NATMAP project was followed by renewed exploration activity on lapsed base and precious metal showings in the Kaminak and MacQuoid areas; for example, Newmont Mining is currently evaluating Witwatersrand-style gold mineralisation at the base of the Hurwitz Group.
- The new geoscience has influenced geological thinking and, therefore, the direction of future work in the Comaplex Minerals Meliadine gold deposit.

- Discovery of minerals generally associated with kimberlites (kimberlite indicator minerals - KIM) plus discrete fragments of kimberlite in glacial deposits in the Rankin Inlet area, when merged with the new knowledge of the regional glacial history and ice movements, provided the impetus and critical knowledge used by industry to undertake and direct a major exploration program for diamonds in the WCP.

The success of the Western Churchill NATMAP Project in unravelling the complexity of the regional geological framework and evolutionary history, combined with an expanded recognition of the regional mineral potential, laid the groundwork for two further major projects in the WCP undertaken by the Geological Survey of Canada and its partners. First, the Committee Bay Project northward along the trend of the Woodburn group in the northern part of the Rae domain. Second, the Western Churchill Metallogeny Project that spans most of the WCP and extends into NWT, Manitoba and Saskatchewan. Building on the success of the NATMAP project, both in terms of the new knowledge gained and the productive and important collaborative research among the federal and territorial geoscience agencies, both these later projects have already added new insights that go beyond those attributable to the Western Churchill NATMAP Project.

Conclusions

The Western Churchill NATMAP Project significantly impacted our understanding of the geological origins and evolution of the central part of the WCP. It laid out a working hypothesis for the Archean development of the main supracrustal belts, and highlighted the extent and complexity of Paleoproterozoic reworking with potential significance for mineral exploration. It laid the groundwork and stimulated new public geoscience that currently accompanies a strong revival of exploration activity throughout much of the WCP.

Acknowledgements

The Western Churchill NATMAP project was initially developed and proposed by Subhas Tella and Tony Peterson, GSC. With additional development, overall project leadership was undertaken by GSC's Simon Hanmer, Continental Geoscience Division, while leadership for the Geological Mapping Division of DIAND was by Carolyn Relf. Hanmer very kindly offered to write much of the summary chapter and I greatly appreciate his contribution. Additional material was taken from the NATMAP Annual Review of Activities summaries prepared by Hanmer and Relf. The latter also provided important information on the economic impacts that could be attributed to the new geoscience knowledge derived from the NATMAP project, plus useful suggestions to complete other sections of the text. I thank Subhas Tella for providing the figures.

X - WESTERN SUPERIOR NATMAP PROJECT: TECTONIC EVOLUTION AND MINERAL POTENTIAL OF ARCHEAN CONTINENTAL AND OCEANIC BLOCKS, NORTHWESTERN ONTARIO AND SOUTHEASTERN MANITOBA

Rationale and Geologic Setting

The Western Superior NATMAP project was conceived to provide an up-to-date picture and understanding of the geological units and their structural development - the tectonic framework - for a region of approximately 500,000 km^2 straddling the boundary of northwestern Ontario and southeastern Manitoba. The targeted geoscience studies at the surface were carried out by the Geological Survey of Canada (GSC) in partnership with the geological surveys of Manitoba (MGS) and Ontario (OGS), in coordination with the concurrent Western Superior Lithoprobe transect employing geophysics to understand the deeper-seated geology.

The region is characterized by a series of east-west trending greenstone belts - elongate areas of metamorphosed and deformed volcanic and sedimentary rocks that commonly host gold and base-metal deposits. Regional reconnaissance- and detailed-scale maps of the greenstone belts were available for most of the region, but the context for their interpretation varied vastly from belt to belt, limiting the overall effectiveness of exploration models for base metals (copper, lead, zinc) and precious metals mineral deposits. The project aimed to improve understanding of the depositional setting and structural history of large crustal blocks within the western Superior Province, to determine their age, affinity (continental *vs* oceanic), and to re-assess their mineral potential in order to guide exploration strategies. Some of the research involved detailed mapping and tectonostratigraphic correlation of the various greenstone belts, aided by structural, geochemical, tracer isotopic and U-Pb geochronological studies. Insight on the regional scale and continuity across belts was established by conducting mapping and associated studies within a broad north-south transect that extended from the overlying Phanerozoic rocks in the north to the U.S. border in the south. In addition to the support that the results of this project would offer to mineral exploration clients and local economic development, the new geoscience knowledge would contribute to the land-use decision process through provision of current and accessible information.

The western Superior Province forms the western edge of the Canadian Shield, and is made up of rocks formed between 3600 and 2650 million years ago. These rocks host producing gold mines at Red Lake (Red Lake & Campbell mines) and Opapamiskan Lake (Musselwhite), a palladium producer (Lac des Iles) near Thunder Bay, and several

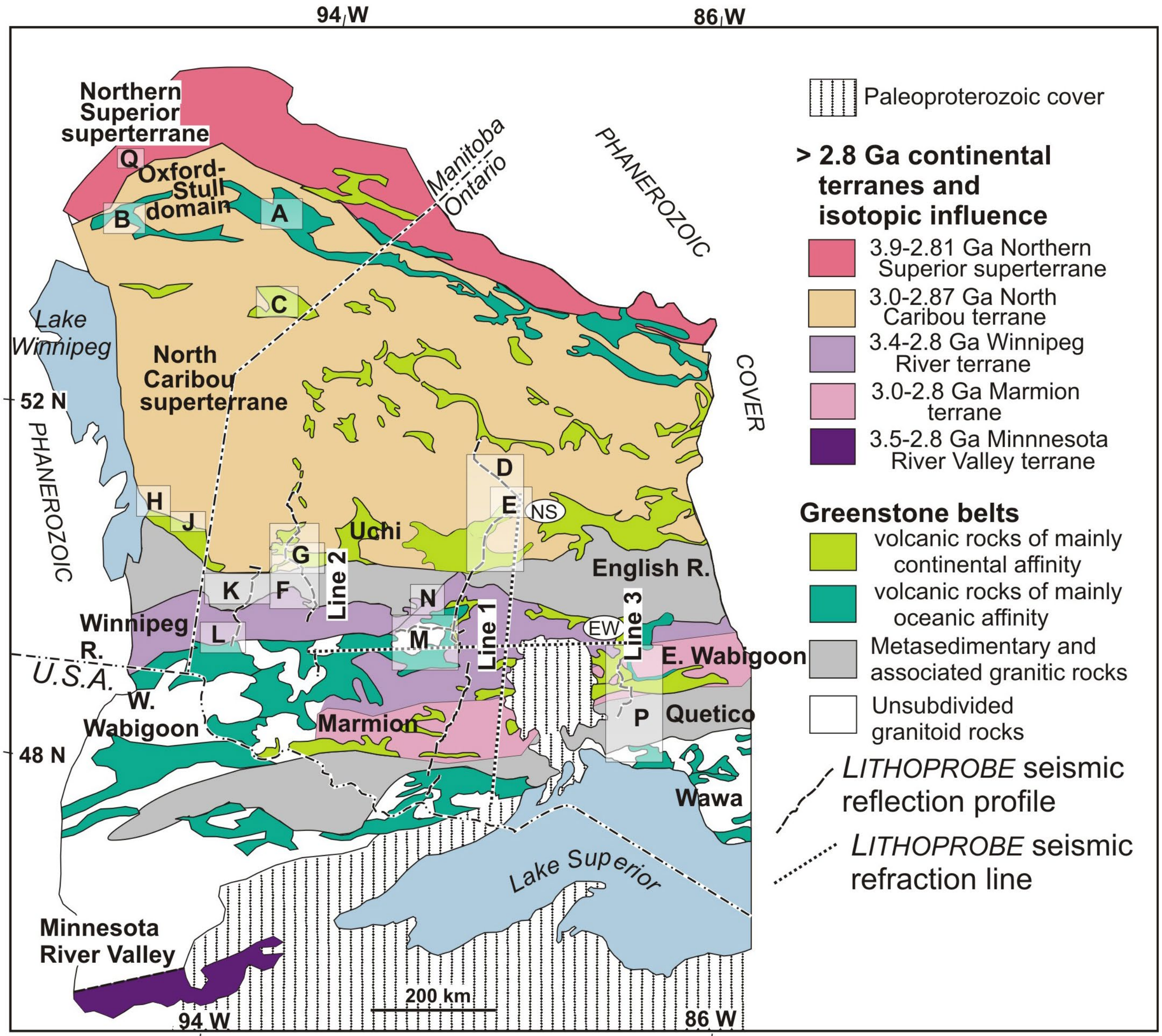

Fig. X-1:general geology of the Western Superior NATMAP project area, straddling the Ontario-Manitoba boundary. Rectangles labelled A to Q (omitting I and O) indicate areas of specific studies over the duration of the project. (courtesy J. Percival, GSC)

past-producing gold (Pickle Lake, Bissett) and base metal (Sturgeon Lake, South Bay) mines, in addition to a large number of sub-economic deposits. Despite the existence of detailed maps of greenstone belts that host the known mineral deposits, the age, stratigraphic sequence, geodynamic setting and regional context of these belts were commonly incompletely known and, hence, the controls on mineralization - the knowledge essential to the discovery of additional deposits - were not fully understood. In particular, whether the greenstone belts had developed from volcanic rocks in ocean basins or island arcs, as opposed to sediments deposited on a continental margin, was considered to be a major factor in determining the potential for base metal mineralization based on analogues in younger terranes. Similarly, the distribution of lode gold deposits in the western Superior Province suggested that proximity to ancient continent-ocean boundaries was a controlling factor in gold localization. However, the distribution of former continental and oceanic domains and whether their deformation was due to splitting apart (rifting) or collisional events were outstanding questions prior to commencement of the NATMAP project.

An additional mandate of the western Superior NATMAP project was to provide information on the rocks at the surface as ground control for the western Superior Lithoprobe project geophysical investigations of the deeper-seated rocks and structures. The concurrent Lithoprobe research - seismic and electromagnetic imaging of the crust and upper

Fig. X-2: Sampling for geochronological analysis in the Western Superior NATMAP project. (courtesy of J. Percival, GSC)

mantle - was designed to test the hypothesis that assembly of the western Superior Province occurred through the accretion on its oceanic margin of a succession of volcanic and sedimentary terranes that are now largely represented by the greenstone belts complexly mixed with the continental material. The NATMAP corridor, highlighted through new geological maps and geoscience compilation products, corresponded to the transect imaged by Lithoprobe. New map information was critical in establishing linkages between rock types, structures and shallow seismic reflection patterns, collectively increasing the robustness of lithosphere-scale interpretations.

Project Delivery

The Western Superior NATMAP project was jointly coordinated and funded by the Geological Surveys of Canada, Ontario and Manitoba during the period 1997-2002. Interchange with university- and government-based Lithoprobe scientists was accomplished through joint field trips, workshops and student supervision. A total of 41 new geological, multimedia geochemical and integrated compilation maps were published, and several comprehensive geoscience data sets were jointly released in GIS-compatible format on CD-ROM through sales offices of the GSC, OGS and MGS. Collections of peer-reviewed scientific articles were published in special issues of *Precambrian Research* (Percival, 2004) and the *Canadian Journal of Earth Sciences* (Percival and Helmstaedt, 2006).

In addition to providing new map information, the coordination with Lithoprobe activities allowed the project to address fundamental questions surrounding the tectonic assembly of the Superior Province. Although the accretionary model for the Superior Province has steadily gained acceptance over the past two decades, improved understanding resulting from the NATMAP project of the nature of continental and oceanic blocks, their timing and style of assembly, has significantly refined the tectonic framework for the western Superior Province.

Scientific Results and Implications

The project provided important new geoscience maps and increased understanding in three economically prospective regions of the western Superior Province: the Wabigoon, western Uchi and Sachigo corridors. The work in the corridors was augmented by broad-scale regional compilations and interpretations.

- Through work in widely-spaced locations, evidence that these three broad geological domains represent independent terranes separated by suture zones was strengthened. As evidence, volcanic strata could be correlated within these terranes, but not across sutures. For example, the 2741 million year-old volcanic rocks that can be correlated from Red Lake to Confederation Lake host volcanogenic massive sulphide (VMS) mineralization in the Uchi subprovince. Across a structural boundary to the south, however, similar-age rocks of the Wabigoon subprovince contain no economic deposits to date. Rather, there it is the 2735 million year-old volcanic rocks that host the past-producing Sturgeon Lake VMS deposits.
- The western Superior Province was assembled from diverse continental and oceanic terranes through 5 accretionary events between 2720 and 2680 million years ago. These events were each marked by sequences of magmatism, sedimentation, deformation, metamorphism and gold mineralization.
- A break in the geologic record (unconformity) on the North Caribou terrane (north of Pickle Lake) margin marks the beginning of a roughly 300 million-year period of transition from continental margin to oceanic magmatism and sedimentation, prior to collision of the oceanic terrane with the Winnipeg River continental terrane to the south about 2700 million years ago.

- Very old rocks (>3.6 billion years) occur within a distinct terrane (Northern Superior superterrane) at the northern edge of the Superior Province, which is separated from the younger (<3 billion years) North Caribou terrane by dominantly oceanic crust, bordered by continental margin deposits and major shear zones.
- A previously unrecognized unconformity between Mesoarchean (>2800 million years) and Neoarchean (2750-2700 million years) strata in the Red Lake belt appears to have been an important fluid conduit leading to enhanced gold localization. Conversely, shear zones previously considered to have controlled gold mineralization in the Red Lake belt appear to be minor and to have secondary relevance.
- The NATMAP scientific results have been integrated with Lithoprobe observations to present a comprehensive, four-dimensional view of crustal evolution of the western Superior Province lithosphere.

The new results provide a modified regional framework for the western Superior Province, emphasizing the tectonic setting of volcanic, sedimentary and plutonic rocks and their mineral potential. Insights into the structural and stratigraphic controls on gold localization have influenced exploration strategies. Comprehensive geoscience data sets packaged in GIS format provide the basis for additional analysis and sound land-use planning decisions.

- The most favourable environment for formation of VMS deposits appears to have been areas of the continental margin related to subduction of the oceanic plate known as >back-arc and >rifted arc= settings. Hot magmas of a rhyolitic composition ascended rapidly through either thinned continental, arc or oceanic crust, interacted with sea water and formed hydrothermal cells, leading to seafloor sulphide deposition. A new interpretation of a back-arc setting in the Rice Lake - Lake Winnipeg area should attract VMS exploration.
- The deformed Mesoarchean-Neoarchean unconformity in the Red Lake belt appears, along with deformation structures, to have had an important role in gold localization, considering that the majority of past- and currently producing mines are located in proximity. This tectonostratigraphic feature provides a first-order guide for gold exploration within the Red Lake belt, in rocks of similar age elsewhere in the Uchi subprovince, and elsewhere in the Canadian Shield where host rock composition, alteration systems and major breaks facilitate fluid flow and gold concentration.
- The ancient Northern Superior superterrane may be associated with very old, cold, thick lithosphere, which in other cratons such as the Slave (NWT) and Kaapvaal (South Africa), hosts diamonds. Kimberlite indicator mineral suites in northern Ontario and Manitoba support the presence of undiscovered diamondiferous kimberlites in the region.
- Multimedia geochemical data for northern Manitoba have identified new targets for gold, VMS and diamond exploration.
- Gold deposits of the North Caribou terrane, although not of economic importance, occur along late transcurrent faults that overprint the geological domain boundaries, thus providing additional exploration targets for this precious metal.
- The sanukitoid suite of rocks of similar age to the productive Lac des Iles complex near Thunder Bay have been shown to have elevated levels of platinum-group elements. These widespread bodies require assessment for this style of mineralization not detectable in the outcrops and previously unrecognized in this district.

Recognized Impacts

Western Superior NATMAP results were made available rapidly through open workshops, current research reports and open file map releases. Because the region maintains a high, but variable level of exploration activity dependent upon commodity prices, it is difficult to demonstrate the incremental impact of the NATMAP project. However, anecdotal evidence indicates rapid uptake of NATMAP findings and impact on exploration strategies.

- Companies have now focussed VMS exploration efforts on certain rhyolites in the Uchi subprovince, including the Rice Lake belt.
- Major and junior companies have adapted their gold exploration strategies to target ultramafic rocks of the Balmer assemblage that specifically are in proximity to the Mesoarchean-Neoarchean unconformity within the Red Lake belt (e.g. Wolfden Resources' Sabina-Follinsbee property and several joint venture projects in the north end of the belt).
- Westward correlation of geologic units of the Red Lake belt has led to redoubled gold exploration investment on the part of companies in the Rice Lake-Lake Winnipeg corridor, while southeastward correlation has led to new staking (24,000 acres), drilling and follow-up surveys (i.e., TriOrigin Exploration).
- Diamond explorers have focused their efforts on the ground corresponding to the Northern Superior superterrane on the basis that it may be underlain by ancient, thick cold lithosphere, prospective for diamonds.
- New exploration permits were acquired to test anomalies identified in multimedia geochemical studies.
- Attention has been focused on shear-zone hosted gold deposits in the Little Stull Lake area, with ensuing development of the Monument Bay discovery.

Conclusions

Through pooling of intellectual and fiscal resources of the GSC, MGS, OGS and Canadian universities, the Western Superior NATMAP project has made significant advances in the understanding of a scientifically and economically important part of Earth's largest Archean craton. The broad perspective thus enabled for the regional scope of the project has led to an integrated model of accretionary assembly of disparate continental and oceanic terranes through processes akin to modern-style plate tectonics. Built through meticulous mapping, geochronology and correlation on the belt scale, this new tectonic framework provides insight into the setting of the major mineral deposit types of the region, provides a state-of-the-art guide to exploration for new base, precious metal and diamond resources, and a guide to unanswered questions for further field-based research on the tectonic evolution of the western Superior Province.

Acknowledgements

The Western Superior NATMAP project was developed and carried out under the leadership of John Percival, Continental Geoscience Division, GSC. Leadership for components undertaken by the partnering provincial geological surveys was by Phil Thurston Ontario Geological Survey and Tim Corkery, Manitoba Geological Survey. I am indebted to the considerable assistance of Percival in compiling this chapter, through his notes and the NATMAP Annual Review of Activities summaries prepared by him and his provincial counterparts. As well, Jack Parker, OGS, furnished contact information for several exploration companies active in the Red Lake area, as a source for potential impacts from the new NATMAP geoscience.

XI - GEOLOGY OF THE WINNIPEG REGION NATMAP PROJECT

Rationale and Geologic Setting

The Winnipeg region is one of Canada's major urban centres and there is increasing demand for geological mapping in the area as activities such as land use planning and groundwater management intensify. The City of Winnipeg is situated in the southeast corner of the physiographic region of Canada known as the Interior Plains, whose low-relief topography is a reflection of the underlying, gently-dipping sedimentary rocks that lie between the western mountains of the Cordillera and the Canadian Shield to the east. The Geology of the Winnipeg Region NATMAP project encompassed the city of Winnipeg and contiguous tracts to the south extending to the US-Canada border, west to Lake Manitoba, north to the Lake Winnipeg Narrows and east to the Ontario border and the edge of the Canadian Shield. The earlier Southern Prairies NATMAP project, in the five years previous, had permitted the first phase of work in this area. Together, these two NATMAP projects would provide new geoscience knowledge for an area of southeast Manitoba centred on Winnipeg of roughly 30,000km2 .

The bedrock of the eastern third of the map area comprises the ancient, crystalline rocks of the Superior Province of the Precambrian Shield. This Precambrian 'basement', sloping gradually southwestward, is overlain by a succession of Paleozoic (460-360 million years) and Mesozoic (190-70 million years) sedimentary units that increase in thickness westward. Exposures of these sedimentary rocks are sparse, however, because the lowlands of southern Manitoba are covered by thick deposits of unconsolidated sediments laid down in the several episodes of glaciation. The Paleozoic rocks are a source of Manitoba's industrial minerals, such as building stone, crushed stone and high calcium lime. Petroleum is also extracted from equivalent Paleozoic units to the west. Gypsum is also an important commodity, extracted from Mesozoic rocks in the area. The glacial deposits furnish building aggregates and play a critical role in recharging the bedrock aquifers, the main source of the region's potable groundwater supply.

In the mid 1990s, it was recognized that updated, 3-dimensional geoscience knowledge of the region was essential to understanding and addressing several economic and environmental concerns. For example, at the inception of the Geology of the Winnipeg Region project in 1997, a major element of the Province of Manitoba Sustainable Development strategy for the area was the mapping of industrial mineral resources to ensure that such commodities would be protected and available for future use. In addition, increasingly intensive management of groundwater quantity and quality was calling for much better geological mapping and understanding of aquifer geology. Also, in the Lake Winnipeg Basin north of the city, perceived conflicts between hydroelectric power generation and shoreline erosion, and between waste disposal and water quality, drew attention to the urgent need for an enhanced knowledge of the natural history of this basin. Furthermore, close to, and beneath, the well-developed urban infrastructure are areas of high mineral potential whose exploitation and stewardship rely on a well-maintained geoscience knowledge base.

The existing geoscience knowledge base for the area in question was incomplete, both in the area covered and the range and currency of information available. The most detailed surficial map was a Province of Manitoba compilation at 1:1,000,000 scale, largely based on interpretation of soils mapping. Aggregate maps existed for scattered areas west and east of Winnipeg. Reconnaissance mapping of the Precambrian terrain and its margins to the northwest of the city had been largely based on air photo interpretation with limited field work and no analyses of sediment composition. Thus, the primary objectives of the Geology of the Winnipeg Region project, in the broad sense, were to obtain an enhanced understanding of the geological history and

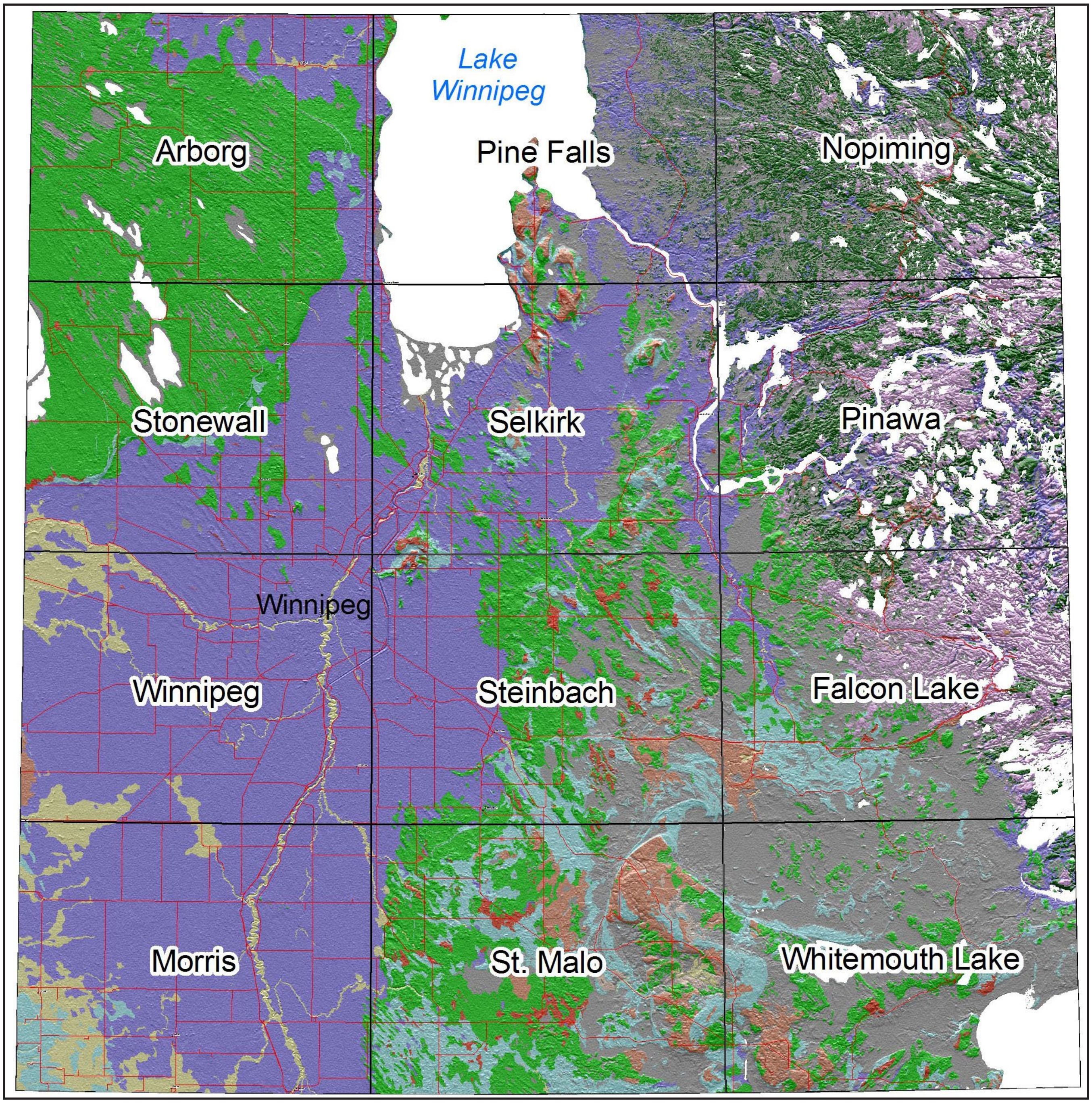

Fig. XI-1: Surficial geology of the portion of southeastern Manitoba – the focus of the Greater Winnipeg NATMAP project. (courtesy of G. Matile, Manitoba Geological Survey)

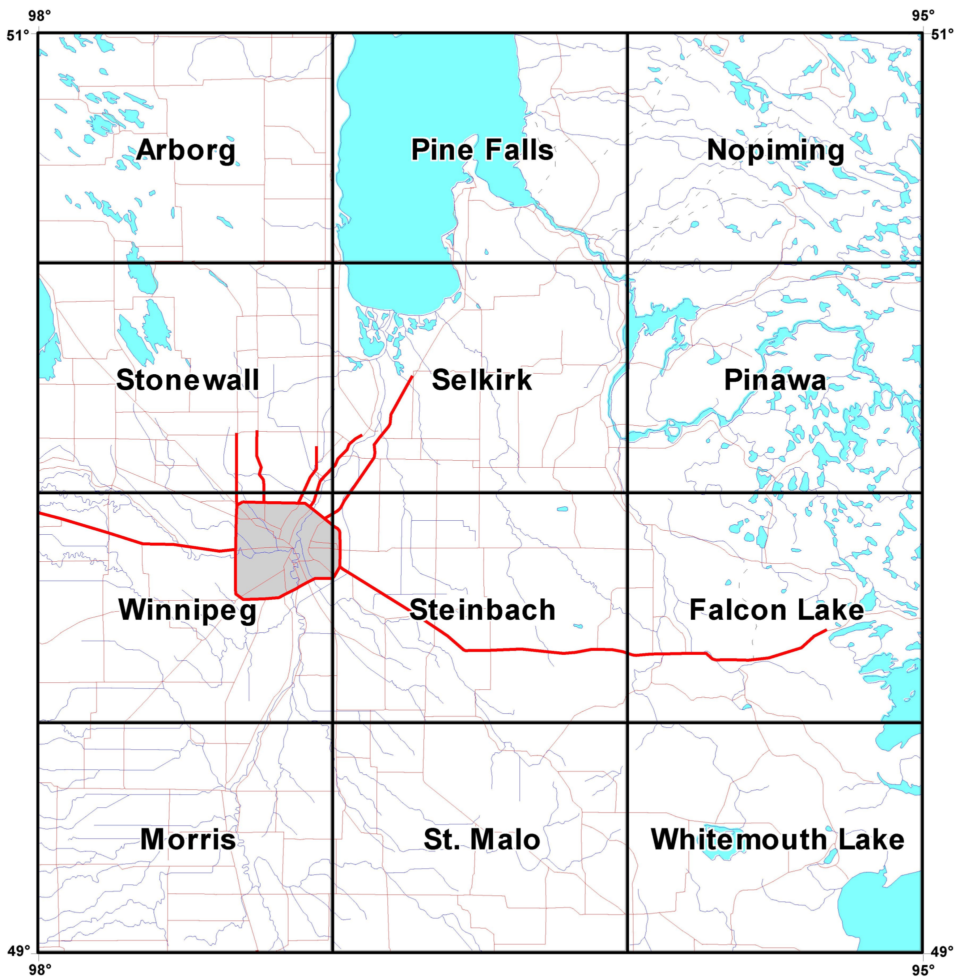

Fig. XI-2: Location of the 12 surficial geology map areas covered by the Greater Winnipeg NATMAP project. (courtesy of G. Matile, Manitoba Geological Survey)

environmental framework of the region through the collection of new field data, and to communicate this knowledge primarily in the form of new, computer-based geological maps. These maps would also be linked to soil maps produced by Agriculture and Agri-Food Canada, enhancing their benefit to agricultural scientists and land use planners. Mineral exploration would be aided both by the surficial geology maps and by geochemistry of till deposits sampled from deposits and from drilling. Thus, the project would generate a range of geoscience maps and databases - outputs that would be of immediate use by both private and public sector groups involved in resource extraction, land use planning and environmental management. Among the primary concerns that would benefit from this new geoscience knowledge:

- The 750,000 people of the eastern Red River Valley and southern Interlake regions of Manitoba rely heavily on groundwater to supply municipal, industrial, agricultural, and rural residential use. This water is drawn from thousands of wells, most of which utilize two aquifers formed in Ordovician sedimentary rocks. In order to facilitate sustainable groundwater-reliant economic development in the region, to protect existing utilization, and to coordinate management across the international boundary, enhanced knowledge was required of the dynamics - sources and means of recharge and discharge - of this groundwater system.
- Lake Winnipeg is the eleventh largest lake in the world and is 25% larger than Lake Ontario. Not only is the lake used for fisheries and recreation, it is vital to the Manitoba economy for its role in hydroelectric generation. Despite its significance, Lake Winnipeg had previously been the subject of little study and knowledge of its geology and, hence, the structure and evolution of the basin had been limited to tenuous predictions based on shoreline studies. An enhanced fundamental understanding of the lake to support management of issues, such as shoreline erosion, water quality and groundwater discharge, required an offshore survey to determine the nature, thickness and structure of the lake bottom sediments and underlying bedrock and to draw inferences on the long-term history of the lake on which recent perturbations had been imposed. These goals would be accomplished through ship-borne, low frequency air gun

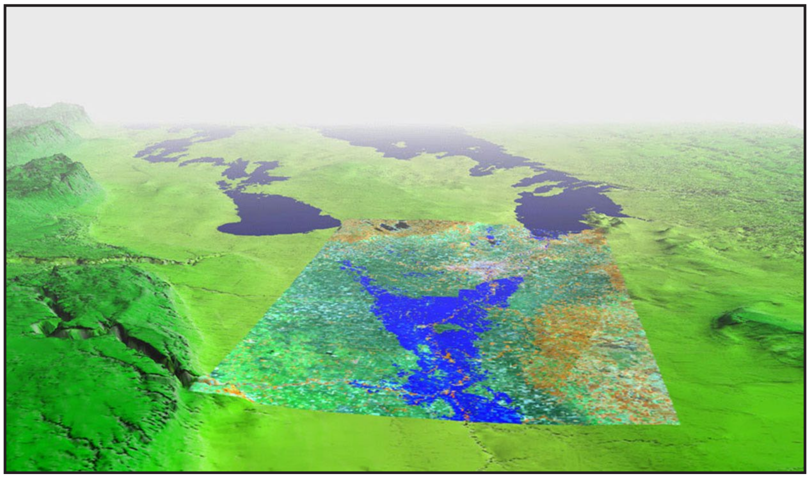

Fig. XI-3: Digital topography of a portion of the Red River region, southeastern Manitoba. The bright blue area coincides with the extent of 1997 flooding. (courtesy of G. Matile, Manitoba Geological Survey)

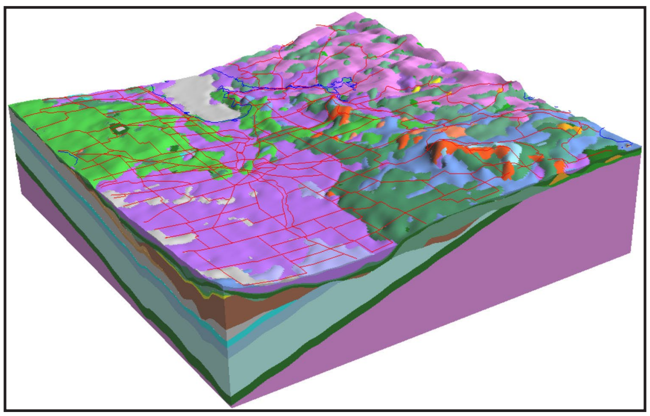

Fig. XI-4: Three-dimensional block diagram of regional geology and topography of the Greater Winnipeg region (cf. Fig. XI-2). (courtesy of H. Thorleifsson, Illinois Geological Survey)

seismic, high frequency seismic, side-scan sonar, and coring operations, guided by real-time differential GPS navigation, and supplemented by limnological and biological sampling.

- The Red River flood of 1997 was a major natural disaster that caused immense damage and disruption. Proposals were subsequently advanced for the construction of additional dikes and diversions, as well as revised land use and water management practices, to spare residents of the valley a repeat of this damage and disruption. The design of major works on both sides of the international boundary, however, required a better understanding of the flood risk; research on the history, evolution, geomorphology and stratigraphy of the Red River and of the major floods documented over two centuries was urgently required.

Project Delivery

One of the governing principles of NATMAP was that it would be a coordinating and supporting mechanism to assist in planning and assembling the resources necessary to complete multidisciplinary projects. It would not provide the total funding required for a project, but would provide supplementary funding to expand and enhance mapping programs that were largely funded from other sources. Another NATMAP principle was that projects should involve more than one agency and, where possible, result in integrated products that combine the results of the different agencies and different geoscience disciplines. In the case of the Geology of the Winnipeg Region project, NATMAP support greatly enhanced two existing initiatives being carried out in the area while also following Mineral Development Agreement work in the area in the early 1990s that had addressed mineral exploration. First, a hydrogeological investigation being undertaken by the Geological Survey of Canada (GSC), the Manitoba Geological Survey (MGS) and the Manitoba Water Resources Branch (MWRB) was examining heavily-used bedrock aquifers and the Quaternary sediments that control their recharge, but the activity needed to address regional geological controls. Second, offshore mapping results from ongoing GSC/MGS Lake Winnipeg Project studies that provided new understandings of coastal processes and crustal motion (postglacial rebound), required incorporation with a synthesis of regional geology. Mapping outputs from the various activities associated with these projects - geophysical, geochemical, geomorphic, paleoecological and stratigraphic studies - would be fragmented and not necessarily presented as formal geoscience maps. The NATMAP support would permit an essential, fully-developed mapping component to be added to the existing, well-funded efforts to define the hydrogeology of the Winnipeg region, the offshore and shoreline geology of the Lake Winnipeg basin and subsequent work on Red River flooding.

The Geology of the Winnipeg Region NATMAP project, undertaken between 1997 and 2001, was jointly coordinated, funded and led by GSC and MGS, with additional participation and resources from Agriculture Canada, Manitoba Hydro and the Manitoba Water Resources Branch.. GSC scientists from five different divisions would concentrate their efforts on the onshore and offshore (Lake Winnipeg) surficial geology, aquifer and groundwater studies, shoreline processes and crustal uplift analyses. Bedrock geology of the Precambrian and Paleozoic rocks and compilation of industrial minerals knowledge were the focus of the MGS researchers. Specialized contributions in aid of these activities were provided by the Department of Fisheries and Oceans and several universities in Canada and the United States.

Principal outputs of the project were to be new surficial geology maps at 1:100,000 scale. These maps would clarify the glacial history of the area, would define aggregate resources, would better outline the geological factors which govern groundwater and Lake Winnipeg shoreline erosion and provide a better definition of flood risk from the Red River. The project involved more than straightforward geological mapping, however. As the region's bedrock geology is almost entirely obscured by a thick layer of overburden, critical information for a number of geological elements available only from the subsurface would be compiled and comprehensive databases released to support construction of a new, 3D model of the Precambrian surface and Phanerozoic geology. Prime examples are a re-processed version of the City of Winnipeg Engineering Drillhole Database, which would influence post-flood, billion-dollar engineering and construction activities, and a new compilation of the region's drill hole data to include several thousand water wells not previously used in geological syntheses.

In addition to these mapping activities, The Geology of the Winnipeg Region project would take major strides towards understanding fundamental geological and geomorphic features in the project area, including the Belair/Sandilands glaciofluvial complex, a crucial groundwater recharge area and a likely future water source for Winnipeg, and the eastern margin of the Williston Basin centred in North Dakota that was a major basin influencing sedimentation in southern Manitoba.

As these plans were carried out, they resulted in a broad range of outputs that fundamentally changed thinking on engineering and environmental geology in the region. These results included release of twelve 1:100,000 surficial geology maps, several widely-used databases, and contributions to influential research now published in the peer-reviewed literature, including papers on groundwater resources, the evolution of Lake Winnipeg and Red River flooding.

Scientific Results and Implications

Key questions addressed by the NATMAP project during the life of the project and immediately afterward included groundwater sustainability, human and natural influences on Lake Winnipeg evolution and a better understanding of Red River flooding from a long-term perspective, along with additional applications to engineering geology, mineral potential and industrial mineral sustainable development. But the NATMAP activities and products that resulted in an improved understanding of the surficial and bedrock geology of the region will also provide a knowledge legacy to be consulted over coming decades in support of a variety of new land use, environmental and economic applications and issues that will require a geoscience input.

Groundwater:

An enhanced knowledge of the region's groundwater system was acquired through field and laboratory investigations to facilitate sustainable groundwater-reliant economic development in the greater Winnipeg region, to protect its utilization and to co-ordinate management across the international boundary. These studies dealt with the physical hydrogeology and hydrogeochemistry of the freshwater-bearing portions of the Paleozoic rock aquifers in southeastern Manitoba and the southern Interlake district. Research addressed the recharge of freshwater to the system as well as the encroachment of saline waters from the sedimentary basin to the west. Combined with the new 3D geology compilations from the Winnipeg NATMAP investigations, a three-dimensional density dependent flow and transport model was constructed for the important carbonate and sandstone aquifers and the resulting model was used to evaluate several water resource scenarios within the province. Specifically, examination of the sustainability over twenty years with constant pumping rates predicted a decline in hydraulic heads in both aquifers in climate change and pumping scenarios.

In another modelling exercise, a pseudo-flood was assumed to last for a period of one month, and the model was run forward for a period of fifty years to observe the long-term effects on groundwater quality. The solute transport results showed a concentration increase in the region south of Winnipeg after one month, indicative of a decline in water quality. Incorporating reduced recharge rates to the aquifers within the model to simulate drought conditions produced a concomitant decline in the hydraulic heads within the carbonate aquifer across the area, but most significantly in the Sandilands region southeast of the city. None of these research approaches could have been contemplated were it not for the concurrent NATMAP-supported production of geological maps and 3D models.

Lake Winnipeg:

Two major questions were addressed by the Lake Winnipeg Basin studies: 1) What is the structure of the Lake Winnipeg basin? 2) Are present-day environmental changes superimposed on long-term evolutionary trends?

Structure of Lake Winnipeg Basin: Results have demonstrated that the structure of sediment and rock below Lake Winnipeg differs dramatically from expectations. Prior to the 1994 cruise, it was thought that sedimentary rocks extended close to the eastern shore, and that these rocks were buried by at most 15 m of sediment. In fact, sedimentary rocks only extend 10 km east from the end of Long Point, and terminate at a buried escarpment south of Hecla Island. Beyond these Paleozoic rocks, sediments consisting almost entirely of Lake Agassiz clay reach unanticipated thicknesses of over 50 m in the South Basin and over 100 m in the North Basin. Till and other gravel-bearing glacial sediments were found not to be extensive, but are present as formerly unrecognized major moraines at George Island and Pearson Reef. Sediments deposited by postglacial Lake Winnipeg, which rarely exceed 10 m in thickness, rest on a regionally pervasive, low-relief angular unconformity, and are ornamented by a complex array of furrows formed by the action of lake ice. Vigorous currents have stripped sediments from The Narrows and east of Black Island, producing the greatest water depths in the lake, over 60 m. Several of these startling results were unanticipated.

Environmental changes: Without knowledge of the history of a lake, as recorded in its sediments, it is difficult to determine whether a basin was in a state of equilibrium prior to human intervention, or whether recent perturbation is only an addendum to more profound natural changes. The surveys have shown that Lake Winnipeg has, for centuries and millenia, been undergoing a steady expansion. Sediment cores from the centre of the South Basin have revealed that Lake Winnipeg offshore sediments have buried fossiliferous material that could only have been deposited at a pre-existing shoreline. Radiocarbon and paleomagnetic analysis of this material indicate that most of the South Basin was dry land at 4,000 years BP (4000 radiocarbon years ago). The dominant control that has caused southward transgression is tilting, as a result of the uplift of the Hudson Bay region that resulted from melting and breakup of the continental ice sheet around 10,000 years BP. The rise of the lake has been punctuated by climate change, especially the shift to cooler, moister conditions around 4,000 years BP, natural diversion due to tilting of the Saskatchewan River into the North Basin at 4,700 years BP, switching of the Assiniboine River due to channel aggradation from a path through Lake Manitoba to the North Basin over to the Red River and the South Basin around 4 ka BP, as well as progressive merging of several sub-basins from Playgreen Lake to the South Basin into one Lake Winnipeg. Unlike other lakes, outlet down-cutting has not been a significant factor on Lake Winnipeg, due to the low and easily erodable barriers that overlie the resistant substrate at the outlet. These new findings of paleoenvironmental change in Lake Winnipeg revealed evidence of unexpectedly dry conditions from 7,500 to 4,000 years BP, with reduced lake area in the north and a desiccated lake basin in the south. Changes in extent of this large lake, now 400 km long, were explained by a combination of (1) expansion due to postglacial differential uplift (tilting), and (2) lake-area reduction due to drier climates associated with the former presence of dry-grassland vegetation. The atmospheric moisture reduction represented by the middle Holocene dry conditions was quantified by comparing lake areas sustainable by grassland climate with computed potential lake areas based on the assumption of open (overflowing) conditions. This approach holds promise for calibrating regional models of climate change and exploring the effects of dry paleoclimates in other large lake basins such as the Laurentian Great Lakes. The ongoing postglacial tilting is of societal concern because it contributes to long-term lakeshore erosion and to the decrease in discharge capacity of the inflowing flood-prone Red River in a populated region.

Flooding:

The Red River flood of 1997 was a major natural disaster that caused immense damage and disruption. Knowledge was needed on how the even larger1826 event, other documented floods of recent centuries, and events predating instrumental and written records, compare to 1997. Was the1826 event extraordinarily rare, or could such a flood recur? Are the impacts of other possible great floods visible in the geological features of the valley? Do climatic or tectonic processes change the flood risk, and have changes to the landscape over the past century increased or decreased the likelihood of an 1826-magnitude event being repeated?

These questions were largely answered by analysis of alluvial sediments that had been mapped along the river, by construction of a remarkably complete and informative tree-ring record, by analysis of cores from Lake Winnipeg, by modeling of the impact of the uplift and through several associated investigations. The result was a picture of a river that naturally undergoes extensive flooding once or twice a century, in a manner that has worsened very gradually due to loss of gradient to uplift.

Construction and Engineering:

The construction industry has struggled for decades with foundation and riverbank stability problems. The new NATMAP geoscience database and improved understanding of the region's depositional history has provided a better realization of the geological causes of these problems. In particular, the new knowledge demonstrated that slope stability problems along the Red and Assiniboine Rivers are a function of higher moisture content of the Lake Agassiz clays in the 'unconfined' environments along the river banks, compared with the 'drier' clays and alluvium found in the rivers' outer meanders or at a distance from the major channels. As well, it was shown that stability problems occurring where construction has taken place over buried, iceberg-scoured channels in the clay, channels that were later infilled by silt, are due to the different reactions of the two substrates to variations in moisture conditions.

Recognized Impacts

The aim of many of the other NATMAP projects was clearly and simply to provide new knowledge of the bedrock and surficial geology that would assist in focussing new or ongoing mineral exploration ventures, and the impacts of such projects could be tracked through the ensuing level of exploration and its successes in the areas newly mapped. In contrast, the much wider scope of the Winnipeg NATMAP project information - standard maps of the region's surficial geology, a geological picture of the structure and history of Lake Winnipeg, forecasts of the sustainability of important groundwater aquifers, the likelihood of and consequences from another major flooding of the Red River - and the variety of its applications, users and sphere of influence, particularly in the longer term, are less amenable to quantification. In general, however, there has been a dramatically increased awareness by various governmental, industrial and environmental communities of the need to incorporate geoscience in their planning.

Certainly, the new geochemical and indicator mineral results that identified several promising areas have continued to influence mineral exploration in the area, although no examples of commercial successes can be attributed explicitly to the NATMAP knowledge at this point.

The improved understanding of the geological influences on Red River flooding have quantitatively assisted the engineering design of the post-1997, billion-dollar flood protection works now under construction and have reduced controversy among members of the general public who sought to lay blame for the flooding. In a similar vein, Lake Winnipeg cottage owners were convinced to drop their suit against Manitoba Hydro., whom they perceived as responsible for shoreline erosion. The NATMAP-related studies indicated that the driving and inevitable, factor was gradual uplift of the terrain in the post-glaciation era, and that Manitoba Hydro could conceivably even be decreasing this erosion through its management of the lake level.

The new understanding of the geological factors influencing construction stability has enabled the geotechnical engineering community to better focus its research in an appropriate direction to help overcome these problems.

In addition to clarifying groundwater sustainability, Lake Winnipeg shoreline erosion, and Red River flooding, the NATMAP results are now fundamental to designing waste disposal and groundwater protection, while also supporting current efforts to understand and manage nutrient loading on Lake Winnipeg.

As well as supporting or guiding several activities that were directly promoted or advanced through the new geoscience knowledge from the multi-discipline research of the Winnipeg project, the successes of particular NATMAP studies and their resulting products have been a direct influence in the development and undertaking of a number of derived or similar investigations or programs in the immediate study area and its peripheries.

With groundwater issues taking on a much higher profile, the 3D geological mapping work begun under NATMAP has more closely involved the Manitoba Geological Survey geologists with the groundwater experts of that province than ever before.

In the United States, a major project to clarify the capacity of water resources in the Fargo - Moorhead region of North Dakota and Minnesota was modelled directly on the Winnipeg NATMAP project. In particular, the multi-agency program developed a 3D model of currently used and potential aquifers and their associated sediments over a 38,000km^2 area incorporating Quaternary, Mesozoic and Paleozoic geology and a lithostratigraphic database compiled from textural and lithologic information obtained from multitudes of sediment samples and drillhole data.

The capabilities developed under the Winnipeg NATMAP work are now being utilized in the Williston Basin Architecture and Hydrocarbon Potential project. In particular, NATMAP 3D methods have been extended to the analysis of hydrocarbon potential and other topics in the parts of the Basin underlying southwestern Manitoba and southeastern Saskatchewan. The primary objective of this extended research was to develop an integrated geoscience dataset incorporating new stratigraphic data, hydrogeological mapping, seismic, gravity and aeromagnetic information, and remotely-sensed imagery over a large area encompassing the Phanerozoic succession of the northeastern Williston Basin.

As part of the Winnipeg NATMAP, MGS and GSC cooperated in the construction of a 3D geological model for all deposits above the Precambrian surface in the Winnipeg region of southeastern Manitoba. As a direct result of this work, especially the realization that mapping of surficial geology benefits immensely from inclusion of subsurface data from wells, MGS has now embarked on a larger project to construct a 3D geological model for all of the Phanerozoic terrane in southern Manitoba to help protect groundwater resources over that region, among several other applications.

Conclusions

The Winnipeg NATMAP was a huge success, and not only from its production of the new maps, 3D model and associated databases. The multi-disciplinary, multi-agency project has provided the scientific foundation for rapid and continuing progress on major issues of immense societal concern in the greater Winnipeg area related to groundwater, shoreline erosion, flooding, mineral resources and engineering. Of at least equal importance, this project enabled the implementation of highly influential new capabilities and inter-agency collaborations, particularly in Manitoba, that are now a model for similar initiatives elsewhere in the world.

Acknowledgements:

The geology of the Winnipeg region NATMAP project was planned and co-led by Harvey Thorleifson, Terrain Sciences Division, GSC (currently Director, Minnesota Geological Survey) and Gaywood Matile, Manitoba Geological Survey. I am indebted to both for their collaboration in the preparation of this material, particularly the use of a comprehensive summary report by Thorleifson that forms the basis of this chapter. Matile kindly provided the figures that accompany the text.

XII - CENTRAL FORELAND NATMAP PROJECT OF THE NORTHERN CANADIAN CORDILLERA

Rationale and Geologic Setting

The Central Foreland NATMAP project area is situated in the foothills of the northern Rocky Mountains of British Columbia and the southern Franklin Mountains of the Yukon and Northwest Territories, approximately between the Peace and Liard Rivers. Geologically, the region straddles the transition from the undeformed sedimentary rocks of the Western Canada Sedimentary Basin and the deformed strata of the foothills of the Rocky Mountains and Franklin Mountains to the west. The Canadian Cordillera, the name for the mountains and plateaus of western Canada, is made up of five distinct, northwest trending geological and morphological belts. The easternmost Foreland Belt comprises a roughly 15 km-thick assemblage of sedimentary strata deposited between 700 and 50 million years ago just west of the old continent. These rocks were then thrust eastward and deformed during mountain building between 100 and 55 million years ago. Previous geological mapping of the area, carried out at a reconnaissance scale in the 1940s to 1960s in the northern part and in the 1970s in the southern part, had been the basis for mineral and hydrocarbon exploration. At least one area remained largely unexplored, despite its recognized potential for base metals, due to the lack of adequate geological maps covering the heavily forested terrain. Since the publication of these maps, major advances were made in understanding the nature and succession of the sedimentary units, largely through new knowledge of the subsurface obtained by industry through seismic surveys or examination of the rocks intersected in test drilling for oil and gas.

The primary objectives of the Central Foreland NATMAP project were to produce modern geological maps of the bedrock and surficial deposits at regional (1:250,000) and more detailed (1:50,000) scales in four map areas stretching roughly 375 km from northeastern British Columbia to southern Yukon and Northwest Territories. Geological mapping would be integrated with existing oil and gas well data and geophysics to develop geological cross-sections depicting lithologic and structural relationships at depth. The new geoscience would provide a better understanding of the likelihood for oil and gas in specific regions of the project area and the potential for their economic development. As well, the study area and adjacent terrains have an abundance of base metal deposits, including potential lead, zinc and silver producers. The project would investigate these sediment-hosted deposits to establish the age of mineralization and relationship to the host rocks and, thereby, to possibly extend the area prospective for such deposits. Till geochemistry, and biostratigraphic programs were integrated with the bedrock and surficial mapping to support and augment the scientific results and maximize logistical efficiency.

The Central Foreland region is rich in oil and natural gas potential and exploration and development activities in the area are accelerating. Such activities must respect environmental sensitivities, such as slope stability concerns, other land use options and the unusually large and diverse populations of indigenous animals. The availability of up to date detailed geological mapping, both on the surface and in the subsurface is, therefore, a vital tool for resource management decisions in the region, such as opening of land for hydrocarbon exploitation, or its removal for protected status.

Project Delivery

The Central Foreland NATMAP project was led by the GSC and jointly conducted by GSC and the government geoscience agencies of BC, Yukon and NWT. During the period from 1998 to 2003, the project benefited from the participation and diverse expertise of over 200 researchers and students from institutions across Canada as well as Russia, Britain and the USA. Government funding included Natural Resources Canada (GSC), Indian and Northern Affairs Canada and the governments of Alberta, BC, Yukon and the Northwest Territories, and financial and in-kind support was provided by 21 corporate partners and consultants, and 12 universities.

The principal aims of the project were the production of an extensive suite of regional bedrock and surficial geology maps. The former document the surface expression of dramatic changes in stratigraphy, sedimentary environments, paleogeography and structural style at depth, all critical for assessing and exploiting the region's hydrocarbon resources. The surficial geology studies, documenting landforms and glacier and lake deposits, are important because they identify terrain types, gravel sources and landslide hazards and provide the geoscience knowledge critical for road, bridge and pipeline locations. As of mid-2006, the project had published 70 surficial and bedrock geology maps at 1:50,000, 1:100,000 and 1:250,000 scales, with approximately 8 others nearing release. Many of these new maps were also released as GIS data sets on CD-ROM.

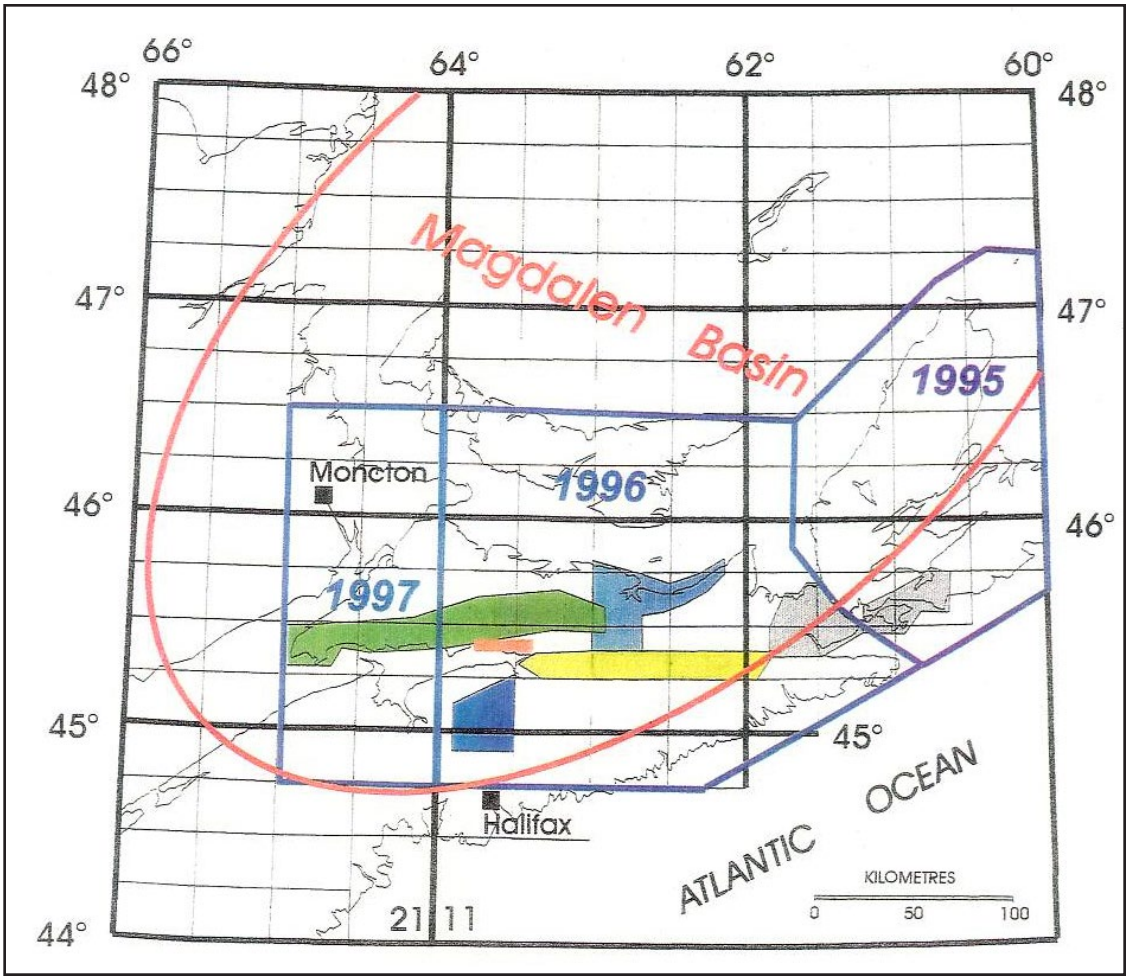

Fig. XII-1: Location of the Central Foreland NATMAP project (inset) and general geology of the Foreland Belt. Areas newly mapped or compiled are indicated in the two component areas of the project. (courtesy of L. Lane, GSC)

Rapid release of data and interpretations was a key goal of the project. Digital compilation and production enabled the project to release Open File maps within weeks of returning from the field. Some 270 presentations at national and international meetings, and over 100 more at annual NATMAP workshops provided a further avenue for rapid technology transfer to customers. Also, more than 40 short Current Research style reports rapidly put significant interpretations into the public domain. These were followed up by over 40 formal synthesis publications, including two dedicated Special Issues of the Bulletin of Canadian Petroleum Geology (Lane, 2004, 2005), the primary source of published geoscientific data for the Canadian petroleum industry.

An important component of the project was the training of young geoscientists. Dozens of university students and young professionals starting out in the petroleum industry worked with, and were formally mentored by, experienced scientists from the participating geoscience agencies. This is partly reflected by the production of 11 theses and 3 postdoctoral fellowships.

The Central Foreland project addressed several key hypotheses by defining and comparing the geology of the Trutch-Toad River map areas in the south and the Fort Liard-La Biche River areas to the north. It had been previously recognized that the size of sedimentary basins and the style of their later deformation changed abruptly near the BC - NWT boundary. A crustal-scale transition reflecting a regional change in the geometry of earlier continental rifting was hypothesized as the cause. A second key hypothesis was that the formation of the Rocky Mountains in the northern BC foothills involved reactivation of Precambrian basement on steep faults (thick-skinned style), in contrast to the structural style farther south where large, far-travelled thrust sheets are characteristic (thin-skinned style). Both hypotheses profoundly influence models of basin evolution, the conditions for resource generation, and the formation of hydrocarbon traps.

Fig. XII-2: Terrain in the northeastern B.C. foothills of the Central Foreland NATMAP project. (courtesy of L. Lane, GSC)

Scientific Results and Implications

Scientific advances through new maps, publications and presentations have provided new interpretations and ideas that help to focus exploration strategies and spur future research. Some key scientific advances and related implications are summarized below:

- Structural inheritance is an important factor in the depositional patterns of Paleozoic and early Mesozoic sedimentary rocks throughout the project area. Thus, the distribution of source and reservoir facies and potential hydrocarbon traps in several important producing formations, is critically influenced by pre-existing structural trends.
- The new, more detailed, maps show that the sinuous traces of large structures in the Liard-La Biche region are actually *en echelon* structures produced by the interference of two distinct structural trends. This not only supports the finding that structural inheritance is important, but helps to define the orientations of the deep pre-existing structures. It also demonstrates that these very large structures are divided into several distinct features that represent separate exploration targets.
- Mississippi Valley type (MVT) lead-zinc deposits at Robb Lake were shown to represent part of a major regional hydrothermal event of Late Devonian or Early Carboniferous age, and not a late event coincident with Cordilleran deformation, as was previously thought.
- The Pool Creek syenite in southeastern Yukon, previously inferred to be Cretaceous in age, was found to be a rare Late Proterozoic pluton (ca. 650 million years), with a much younger syenite intruded nearby, part of a suite of Early Tertiary syenites associated with base metal showings in the area. Both magmatic events provide important evidence for the tectonic setting of this area when these suites were intruded.
- Major new biostratigraphic studies for Paleozoic, Triassic and Cretaceous rocks have greatly improved understanding of the stratigraphy and correlation of units throughout the region, with immediate impacts on petroleum source potential for these successions.
- A new study of the present-day regional geothermal gradient, together with a large body of new outcrop data on the thermal history of the region, has greatly improved our understanding of regional and local variations in thermal history, a key factor in modeling the hydrocarbon generation history of the basin - an important tool for predicting the hydrocarbon content of potential exploration targets.
- Better understanding of sedimentary depositional systems and facies associations has led to better understanding of regional stratigraphic correlations and distribution of potential hydrocarbon source rocks and reservoirs; improved resolution of the region's thermal evolution has led to improved models of the time-temperature evolution in the thermal kitchen where hydrocarbons are produced; improved resolution of structural inheritance in influencing younger deformation styles has led to better models of hydrocarbon trapping systems. Source, reservoir, generation and trapping are the four essential components of a basin model for hydrocarbon exploration. The Central

Foreland project has reduced uncertainty in all four components which will lead to reduced risk, increased success rates and reduced cumulative environmental impacts throughout the project area.

- The release of new data that suggests significant hydrocarbon prospectivity in deep Devonian targets beneath the Cordilleran Foreland has been followed up by a BC Government report, extensively citing Central Foreland products, that expands on the prospectivity of this untested target. (Current production in the region is sourced from shallower Carboniferous and Triassic targets.)
- The Robb Lake MVT deposit, the largest of a suite of sediment-hosted lead-zinc deposits in the central Cordilleran Foreland, is now known to result from a large-scale hydrothermal event of Late Devonian or Early Carboniferous age, as distinct from much later Cordilleran hydrothermal systems. This new knowledge will improve the focus of MVT exploration throughout the region.
- Detailed mapping in western La Biche River (Yukon) has led to additional follow up work in adjacent Coal River, a poorly known part of Selwyn Basin. This work has significantly extended the prospective area for Sedex- type base metal deposits in both map areas.
- Surficial studies of ice flow history showing direct interaction of continental and Cordilleran glaciers has documented that a previously inferred ice-free corridor along the mountain front could not have existed in this region. This finding has helped to force alternative interpretations of human migration patterns during Late Pleistocene time.

The value of this new geoscientific knowledge has been acknowledged by some corporate customers:

- "The NATMAP team at the GSC office in Calgary has played an essential role in assisting Gulf Canada and other E & P companies to collect field data and evaluate the natural gas potential." (Gulf, 2001)
- "The advantage of the NATMAP project to AEC is having the range of expertise that the GSC offers in performing these studies. ... The advantage to AEC is not solely the cost savings of not having a crew in the field for several days, it is the value of another person's interpretation. ... Current Research papers on these studies are important because they provide rapid publication of the work in time for industry to apply the new knowledge to their exploration programs." (AEC, 2001)
- "At a more regional level, functions such as the NATMAP workshops provide a forum for evolving ideas on the geological evolution of northeastern British Columbia and the southern Territories. It is through these events and informal discussions that geological themes evolve, that are applicable to all disciplines of exploration." (IIT Inc., 2001)
- Follow up studies with direct relevance to the economic development of the region have built on NATMAP results. Such studies include a University of Calgary Master's thesis on regional thermal maturity patterns in northeastern BC; a BC Government study of the petroleum potential of deep Devonian strata in northeastern BC drawing heavily on project publications; and maps and publications produced by the Yukon Government describing new mineral potential in Coal River and western La Biche map areas.

From an environmental standpoint:

- Geochemical studies revealed that numerous small streams emanating in springs within the Mattson Formation are too acidic to drink. The acidity is attributed to a natural phenomenon - the dissolution by groundwater of the naturally occurring iron-sulphide mineral, pyrite, to form sulphuric acid. This finding alone will have little direct impact on the local community. It does, however, provide important baseline information on the natural acid drainage of the area, to be taken into account when granting land use or resource development permits and the attached requirements for environmental impact mitigation or subsequent site reclamation. The area affected by this natural acid drainage is believed to extend into the proposed Nahanni National Park reserve expansion area and may impact on existing mineral exploration activities there.
- In response to long standing community concerns about recent changes in Fisherman Lake and a suspicion that these changes were related to hydrocarbon exploration and development over the past 40 years, the project undertook a pilot study of gas seeps and water chemistry in the lake. Fisherman Lake, near Fort Liard, is a traditional summer camp site for the local community and the home of several families year round. Many community members are reluctant to eat fish from the lake, fearing that it may be contaminated. Analyses of the isotopic composition of the gas showed that it is naturally occurring biogenic gas produced by the decay of vegetation in the lake bed; and the changes are part of a natural process called eutrophication. The NATMAP study recommended that further analyses be undertaken to broaden the scope of the sampling, and to determine the timing of these chemical changes using siliceous diatoms recovered in lake sediment samples, and a follow up study was initiated.
- Landslides are an important local hazard for community developments such as roads, pipelines and petroleum drill pads, particularly in the Liard, Kotaneelee and La Biche Ranges, where ongoing exploration and development activities are regularly disrupted by slope failures. During landslide mapping, it was recognized that certain

bedrock units were more likely associated with large landslides than others. Taking advantage of digital map compilation, a new map product for areas affected by extensive landslides was developed, showing bedrock geology with landslides superimposed. Such maps are particularly useful for engineers and planners engaged in siting excavations and foundations where landslides might cause structural failure.

New surficial and bedrock geological maps and reports of the Fort Liard and La Biche River map areas have been used extensively in the ongoing MERA process for the proposed expansion to Nahanni National Park Reserve. The proposal includes areas covered by the new mapping.

Recognized Impacts

While the intent of government geoscience agencies is to have their new geoscience knowledge contribute in a significant way to the nation's economic development while minimizing environmental degradation, the direct impact of geological mapping is usually difficult to quantify. Resource exploration responds to a complex mix of factors, such as commodity prices, refining capacity, regulatory framework, First Nations land claims and recent discoveries in the area. Also, approximately two-thirds of petroleum industry managers are reluctant to formally acknowledge external sources or influences of the information they consult. Thus, any direct links between the Central Foreland NATMAP results and exploration levels and successes is incomplete. Nonetheless, the following impacts have been documented by industry and attributed to the new geoscience knowledge produced by the project.

- The project's publications have formed the geological underpinning that have led to investments in land acquisition and wells drilled valued in hundreds of millions of dollars, and of cost savings and improved exploration focus worth over $1 million between 1998 and 2006.
- At a typical cost of $6 to $12 million each, 48 new wells have been drilled to date in, or within a few kilometres of, areas newly mapped in the project; implying a direct influence on expenditures on the order of $400 million.
- "Maps from the NATMAP Foreland project have been an integral part of Burlington Resources technical analysis of the Trutch and adjacent areas of the foothills.... The above work has formed the geological underpinning to justify recent expenditures at BC land sales. These expenditures have totaled greater than $25 million .... during the course of the mapping." (Burlington Resources, March 2001)
- Central Foreland NATMAP Project: Stratigraphic and Structural Evolution of the Canadian Foreland – Part 1. Bulletin of Canadian Petroleum Geology. "The Besa-Prophet area (NE BC) is anticipated to open for Oil and Gas land postings in 2002. Six 50,000 scale sheets mapped during the NATMAP project cover this area. For industry to cover this area would have taken months of field work over several field seasons, and likely the work would never cover an entire sheet. Even partial coverage would cost us close to $500,000." (AEC, Dec 2001)
- Gulf Oil stated that the surface maps published by the NATMAP team provide an essential base to begin subsurface exploration and that this level of mapping would take a resource company years to complete at a cost of hundreds of thousands of dollars;
- Nexen reported that the new detailed maps within the La Biche River and Fort Liard areas helped with analysis of prospective structures in the Liard, Kotaneelee and La Biche Ranges. Collection of this data by the company on its own would have involved expenditures of at least $250,000;
- The Pink Mountain map sheet in the southern Trutch area was used by AEC in its seismic interpretation of lands it held at the time of release.

Conclusions

The many new maps and reports of the Central Foreland NATMAP Project have provided the essential geoscience groundwork to better understand the stratigraphic history and structural evolution of the northeastern BC - southern Territories region. In fulfilling its NATMAP goals, this field-based bedrock and surficial mapping project has:

- supported Canada's hydrocarbon and mineral industries by directly influencing their economic activities, measured in hundreds of millions of dollars, that resulted in successful natural gas developments within and adjacent to the project area;
- successfully collaborated with industry, academia and other government geoscience agencies to promote efficient technology transfer of much new geoscientific knowledge;
- fostered and enhanced the training of dozens of Canadian geoscience students and young professionals; and
- been a corporate leader in the development and application of digital databases, map production technologies and GIS products.

Acknowledgements:

The Central Foreland NATMAP project of the northern Canadian Cordillera was developed and carried out initially under the leadership of Mike Cecile (1998-99), GSC Calgary. The leadership then passed to Larry Lane, GSC Calgary, who undertook this role to the project's completion in 2003. Andrew Legun of the B.C Geological Survey and Lee Pigage of the Yukon Geological Survey coordinated

the work of their respective agencies. Lane's final report on the project that forms the basis for this chapter, and his further valuable contributions to this summary are gratefully acknowledged.

XIII - ANCIENT PACIFIC MARGIN NATMAP PROJECT: STRATIGRAPHIC, TECTONIC AND METALLOGENETIC PORTRAIT OF THE WESTERN NORTH AMERICAN MARGIN

Rationale and Geologic Setting

The Ancient Pacific Margin NATMAP project provides a comprehensive analysis of a belt of complexly deformed and metamorphosed rocks that extends roughly 2000 kilometres north-northwest from southern British Columbia through Yukon Territory into east-central Alaska. The project was a response to demands of the mineral industry for new mapping, new geophysics, new metallogenic studies and new syntheses of the belt's poorly understood component terranes, spurred by discoveries in the mid-1990s of high-grade volcanogenic massive sulphides deposits near Finlayson Lake, Yukon. This would be accomplished through bedrock mapping in areas that provide access to the critical stratigraphic, igneous and metamorphic assemblages that are most likely to bridge pre-existing knowledge gaps. Despite an interest since the late 1800s in the potential of parts of the area to host economic mineral deposits, with local exceptions, few detailed studies had been undertaken on these critical terranes and geological data were largely inadequate to address these questions. At the project outset in 1999, the only bedrock record of large parts of Yukon and B.C. underlain by these rocks was reconnaissance level mapping by the Geological Survey of Canada (GSC) of 1930-1970 vintage. Poor geological exposure throughout much of the region, the lithologic and structural complexity, a scarcity of fossils plus deformational events that reset most geochronological systems had severely hindered correlations over any distance. The NATMAP project would bring up to modern standards all or part of several key 1:250,000-scale bedrock maps along the belt. In addition, the Ancient Pacific Margin project would include more detailed (1:50,000) mapping in parts of Yukon known to be prospective for massive sulphides, metallogenic studies along the belt and studies of the surficial deposits to identify favourable areas for placer gold exploration. While investigations of the surficial geology of the area go back to the Klondike goldrush (1896-98) that exploited the rich unconsolidated placer gravels of late Tertiary and Quaternary age, the NATMAP project would provide the region's first systematic surficial geologic mapping.

The assemblage of rocks targeted by the NATMAP project makes up one of three fundamental tectonostratigraphic subdivisions of the Cordillera - the name for the mountains of western Canada. This zone of pericratonic rocks - rocks with a continental or cratonic affinity - lies wedged between the strata of the western margin of ancestral North America - the Ancient Pacific Margin - and those of oceanic origin accreted from the west. These ancient Pacific margin rock assemblages are important to our understanding of how the western edge of North America interacted with the oceanic plates, an understanding that was incomplete and highly controversial. Though commonly referred to as a 'passive margin', the outer plate margin was actually a dynamic interface between the continent and the shifting plates of the proto-Pacific Ocean. Within the pericratonic belt are stratigraphic assemblages marked by profound changes in type and thickness, and so rich in volcanic components that it is difficult to establish whether they correlate with strata of the continental margin or one of the terranes of oceanic affinity. Deformation and metamorphism has obscured stratigraphic relationships, thereby posing a significant challenge to deciphering paleogeography with time.

The Ancient Pacific margin rocks host a variety of mineral deposits, including sediment- and volcanic-hosted massive sulphides, porphyries, skarns, gold, placer gold and industrial minerals. The aim of the NATMAP project would be to provide regional and deposit-scale maps that would generate innovative geological thinking - the fundamentals for new exploration strategies. The new knowledge would be gained through reconnaissance (1:250,000-scale) and detailed (1:50,000-scale) bedrock mapping, complemented by fundamentally important research in geochronology, geochemistry and structural analysis, locally augmented by airborne gamma-ray/aeromagnetic surveys over areas where bedrock exposure is limited. Analysis of LANDSAT TM satellite imagery would be tested as a potential mapping tool for bedrock and surficial geology, a potentially important new tool for rugged terrains such as these. Mapping of the surficial geology at scales of 1:50,000 and 1:100,000 would be carried out in conjunction with the bedrock mapping and at more detailed scales around known placer gold deposits. Metallogeny studies would focus on the genesis of certain mineral deposits and their relationship to the regional geological framework and similar deposits in Canada's northwest and Alaska. The new maps and reports would fill gaps in the fundamental geoscience database of the Cordillera, produce new insights into the evolution and metallogeny of the pericratonic terranes and provide new information and insight to underpin mineral exploration models for the region.

Project Delivery

In the mid-1990s, mapping projects were being carried out by the GSC, the British Columbia Geological Survey (BCGS) and the Yukon Geology Program (YGP) in the same part of the pericratonic belt - the Yukon-Tanana Terrane (YTT) - and it was recognized that the work of each would be enhanced by cooperation at the working level. The Ancient Pacific Margin NATMAP project was jointly coordinated by

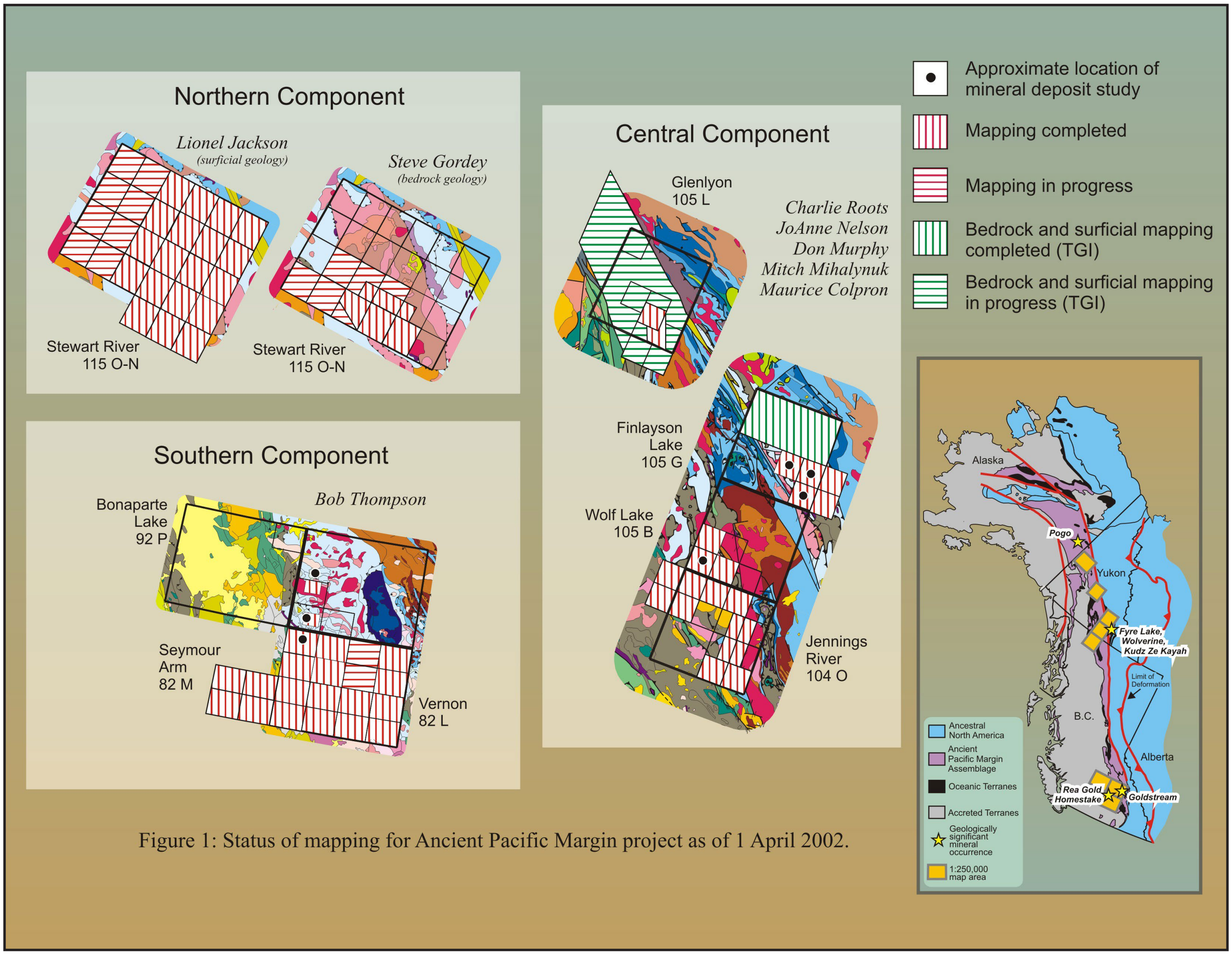

Fig. XIII-1: Location and general geology of the three component areas of the Ancient Pacific Margin NATMAP project.

the GSC with participation and funding by these agencies, and additional important contributions from the University of Alberta, the University of British Columbia, the Alaska State Survey and the United States Geological Survey (USGS). The five year period of the project (1999-2004) would see a strategic deployment of these resources within three separate, 1:250,000 scale project areas along the pericratonic belt: a southern component in southeastern B.C.: a divided central component with mapping occurring in three separate areas – an area straddling the B.C./ Yukon boundary, an area in southeastern Yukon, and an area in southcentral Yukon – and a northern component abutting the Alaska boundary in central Yukon. Each area was selected to add critical information for specific aspects of the overall project objectives. In several instances, the new mapping would abut areas recently mapped, or being mapped, by BCGS and YGP to take advantage of the new geoscience knowledge gained in those geologically related regions.

Specifically, work in the southern component would focus on improving understanding of the southern Cordillera, the key element of which would be the mapping of certain stratigraphic assemblages to determine whether physical linkages between geographically separated and apparently disparate units exist. As one example, can rocks of the Lardeau Group, with extensive mineral potential and production, be correlated with other strata of similar age in the map area, thereby increasing the economic potential for the latter units? In the central component, bedrock mapping would be carried out in areas key to the understanding of the geological evolution and metallogeny of the Yukon-Tanana terrane and affiliated assemblages in B.C. and Yukon, rocks that host important and various types of sulphide mineral deposits, including the new discoveries in the Finlayson Lake area, Yukon. The northern component - the Stewart River map area - encompassed the most poorly known part of the Yukon-Tanana terrane and was in dire need of updated geoscience to help assess the bedrock-hosted mineral potential of the region. On the other hand, more than 70% of Yukon's

Fig. XIII-2: Stewart River terrain, Ancient Pacific Margin NATMAP project, northern component. (courtesy of S. Gordey, GSC)

placer gold is found in the Stewart River map area due to a congruence of bedrock sources and minimal glaciation of the placer deposits. However, a detailed understanding of the paleoclimatic and geomorphic conditions under which these placers formed, plus their specific relationship to the bedrock sources, are essential for the construction of models to aid in the exploration for new gold placers.

Scientific Results and Implications

The various multidisciplinary studies carried out under the Ancient Pacific Margin NATMAP project have contributed major advances towards an understanding of the lithological complexities, structural framework and evolutionary history of the Cordilleran pericratonic assemblages of BC and Yukon, plus a new understanding of the extent of regional glaciation that is important to the placer story.

In addition to the new bedrock geology maps and compilations, their accompanying reports and databases, most of the bedrock scientific results were presented in a special compendium of nineteen scientific papers published in 2006 (Colpron and Nelson, 2006). Many of the new geoscience insights are related, on the one hand, to recognition of distinct components within major assemblages which were earlier believed to be homogeneous or too complexly deformed to be subdivided. On the other hand, units and assemblages in different parts of the belt that were considered distinct are now shown to be correlative over considerable distances.

As well, the surficial geology and Late Cenozoic history of the Stewart River area was presented by Jackson et al. (2009). The following broad scale highlights have been drawn directly from the preface, summary and other papers of these compendium volumes.

- All the pericratonic terranes throughout the NATMAP project region are recognized to have originated along the outer margin of ancestral North America. Some parts, however, are now interpreted to be an extension of this margin, and more or less in their original location. Still other parts are recognized to have been split from the continental margin in the Middle to Late Devonian and evolved independently until they were reattached to the westward growing continent some 100 million years later.
- New depositional relationships among terranes are now recognized, which challenge the earlier-held belief that each of these terranes, separated from one another by major faults, preserves a geological record distinct from its neighbouring terranes. As examples, depositional relationships exist between the Yukon-Tanana and Slide Mountain terranes, Yukon; Paleozoic arc rocks along the BC-Yukon border correlate with the Harper Ranch group of southern BC and form the depositional basement to the Upper Triassic volcanic arc rocks of the Quesnellia terrane.
- The Yukon-Tanana terrane of the northern Cordillera is by far the largest of the pericratonic terranes, underlying southern Yukon and northern British Columbia, and extending into easternmost Alaska. Previous models of this terrane described it as a dismembered structural complex with no internal stratigraphy. Studies under the NATMAP project have led to recognition of an internal stratigraphy, provided the basis for reinterpreting the terrane's Paleozoic tectonic evolution and also a geological context for the volcanogenic massive sulphide deposits. The new tectono-stratigraphic framework results in a much simpler distribution of terranes compared to the previous interpretations of only a decade earlier.
- Discoveries and relationships portrayed in the new geologic maps have led to a provocative new model for the southern British Columbia portion of the ancestral Pacific margin that differs in three important respects from previous accretion models: the Okanagan 'high', a block of North American continental crust 200km wide and several hundred km in length, defined the western side of the ancestral continental margin until early Paleozoic time; the overlying sequence that represents accreted crust was emplaced stratigraphically, rather than by tectonic events; in some areas in the southern Cordillera, the ancient continental crust is still within roughly 5km of the present surface.
- The Eagle Bay assemblage of the Kootenay terrane of south-central B.C. hosts several polymetallic precious and base metal massive sulphide deposits, a number of which have had limited ore production. Regional lithogeochemical and isotopic studies conducted under the NATMAP project provide new insights into the local- and regional-scale volcanic controls on this sulphide mineralization.

- New knowledge was gained on the tectonic setting and host rocks of other important massive sulphide districts in the pericratonic belt including the Finlayson Lake district, Delta and Bonnifield districts, Alaska Range and Goldstream.
- Surficial deposit studies revealed that glacial ice advance down the Stewart River valley stopped well short of the limit previously believed. Thus, basins beyond the confluences of Rosebud and Black Hills Creeks with the Stewart were never disturbed by glaciation or glaciofluvial flushing so their Tertiary-age placers have remained in place and could offer opportunities for new, economic deposits of placer gold.
- Investigation of high terrace gravels supports the hypothesis that the original flow direction of the Yukon River was to the south. As the reversal to its present day northerly flow postdated the deposition of White Channel gravels, these gravels could exist beyond their apparent termination at the mouth of the Yukon River, thus expanding the area for potential auriferous placers.
- The discovery of some remarkable paleoenvironmental records, particularly in the placer exposures of Thistle Creek where fossil permafrost dates back more than 600 000 years and numerous tephras are exposed, greatly improved knowledge of the area's paleoecology and climate history.

Recognized Impacts

- Prior to the NATMAP project, Almaden Minerals Ltd. had been exploring in the Big Salmon Complex of Yukon Tanana terrane in the map area immediately west of the Central Component straddling the B.C. - Yukon boundary. The new geoscience produced during the NATMAP project provided Almaden with a better understanding of the stratigraphy and tectonic setting of the Big Salmon Complex that also applied to their map area, and allowed them to focus their more detailed prospecting and sampling efforts to specific rock units. Those results then led to expansion of two mineral properties where subsequent private sector exploration programs have advanced both these prospects.
- The new NATMAP geoscience information provides a greater level of confidence for the discovery of new mineral occurrences of potential economic significance, so that numerous geochemical anomalies defined by the private sector through stream sediment geochemical data in the BC-Yukon border region are receiving further evaluation.
- New mapping in the Finlayson lake district provided a stratigraphic context for the known occurrences and new discoveries in that area – and outline the spatial extents of the prospective stratigraphic horizons.
- A significant geophysical signature came to light from the airborne magnetic survey flown to complement and help guide the NATMAP project geological mapping in the Stewart River area. Staking of the region and subsequent reconnaissance soil surveying by a prominent local prospector demonstrated that a copper-gold-molydenum metal signature is coincident with the geophysical anomaly. The property - known as the Lucky Joe copper-gold occurrence - was optioned to Copper Ridge Exploration in 2002 which conducted additional claim staking, ground magnetic surveys and reconnaissance soil sampling. Following a subsequent option in 2003, Kennecott Canada spent over $1 million on geochemistry and geological mapping, followed by an induced-polarization survey and diamond drilling of 5 holes.

Conclusions

The multi-faceted studies conducted in association with the NATMAP project have led to a much improved, and much needed, characterization and understanding of the several component terranes that represent rocks originally emplaced in the zone between the margin of North America and the oceanic zone to the west – the Ancient Pacific Margin – and their subsequent, complex, deformational history. The new geoscience has allowed recognition of distinct components within major assemblages that were believed to be homogeneous or too complexly deformed to be subdivided, while some units and assemblages that were considered distinct and localized are now shown to be correlative over great distances into different parts of the belt. These revelations, combined with new insights into the evolution and metallogeny of the NATMAP project subareas, will be the basis for future mineral exploration models in both bedrock and placer settings for the entire region.

Acknowledgements:

The Ancient Pacific Margin NATMAP project was carried out under the leadership of Robert Thompson, GSC Pacific Division, in collaboration with JoAnne Nelson (BC Geological Survey) and Don Murphy (Yukon Geology Program, now Yukon Geological Survey). In addition to the references cited, important information for this summary was gleaned from Thompson's annual progress reports to the NATMAP Steering Committee. He also assisted with this author's compilation of funding information for the project. Charlie Roots, GSC Pacific, located in the Yukon Geological Survey office, provided valuable information on impacts stemming from the new geoscience coming out of the Yukon-northern BC components of the project, plus the names and contact information for many companies and individuals exploring in this region. Of those, thanks are extended to Ed Balon of Almaden Minerals Ltd., Jason Dunning of Expatriate Resources Ltd., Gerry Carlson of Copper Ridge Explorations Inc. and Jim Sparling of StrataGold Corp., for

their remarks on how their companies have been using the new geoscience knowledge and their favourable impressions of the NATMAP project in general. I appreciate the valuable comments Murphy provided to improve an earlier draft, and thanks are extended to Steve Gordey, GSC Pacific Division, who led the bedrock geology component of the northern component of the Ancient Pacific Margin project, for providing the figure. Lionel Jackson, GSC Vancouver, who led the surficial geology studies component in the Stewart River area, was of immense help in aiding my understanding of the results and implications of this facet of the project, and offered much appreciated comments on the final draft.

XIV - EASTERN CANADA APPALACHIAN FORELANDS AND PLATFORM NATMAP PROJECT

Rationale and Geologic Setting

The Eastern Canada Appalachian Forelands and Platform NATMAP project (also known as 'The Bridges") was designed to upgrade our knowledge of the complex assemblage of Early Paleozoic age (~530-390 million years) platform sedimentary rocks and coeval, but deformed, Appalachian volcanic and sedimentary rocks that are exposed on the northern and southern shores of the St. Lawrence system, between southern Quebec, northern New Brunswick and western Newfoundland. This region originally marked the southern margin of the ancient paleocontinent of Laurentia, formed from the breakup of the supercontinent of Rodinia in late Proterozoic time (~ 550 million years). The northeasterly - trending belts of Paleozoic sedimentary rocks were deposited in the relatively shallow waters on the submerged margin of Laurentia (the St. Lawrence and Newfoundland Platform), in deeper waters farther offshore (now preserved in Taconic allochthons), and in a series of foreland basins that lie along and within the Appalachian foreland. While the limestones and associated lithologies nearest the continental margin, now exposed both in Quebec along or near the north shore of the St. Lawrence River, and in northwest Newfoundland, remained largely undisturbed since their deposition, the more southerly sedimentary sequences were highly deformed by three major tectonic events. As a gross simplification of the situation, those rocks now encountered in the Humber Zone of western Newfoundland, northern Gaspé and southern Quebec were deformed partly in the Taconian Orogeny (470-450 million years) and the Salinic Orogeny (~ 435-420 million years), whereas rocks that belong to the adjacent Gaspé belt in northern New Brunswick, central and southern Gaspé, southeastern Quebec and western Newfoundland were largely deformed during the later (390 million years) Acadian Orogeny. Alleghanian deformation (~310 million years) likely affected the successions in western Newfoundland and southern Gaspé. The Bridges project aimed to provide the first regional, integrated geoscience framework for these various depositional belts that cross five provincial jurisdictional frontiers, as well as the much younger and undisturbed Quaternary age (<2.5 million years) deposits that overlie these belts in certain areas.

This overall scenario was confronted with several challenges. 1) Although the stratigraphic and structural history of the western Newfoundland shallow platform succession part of the study area had been well documented by Newfoundland geoscience groups, the coeval deep marine successions in the Humber Arm Allochthon were poorly known and only mapped at 1:250,000 scale. Thus, a regional synthesis of the local- to provincial-scale flavour of the tectono-stratigraphy for the entire sedimentary belts of the complete region was lacking. 2) Some of the GSC's and provincial bedrock and surficial geology maps from the early 1970s and '80s were seriously outdated when compared with those of the shallow Lower Paleozoic platform areas from studies by the Newfoundland provincial survey in the mid '80s. 3) Tectonic models to account for the variability of the continuous or separated deformation events were still a matter of debate and dispute. 4) Offshore and onshore seismic coverage was deficient, of poor quality and outdated. These challenges had major implications for the resource industry when it initiated a new cycle of oil and gas exploration in the Canadian Appalachian Region in the early 1990's. The new geoscience data would provide the resource industry (oil and gas, mining and groundwater) with modern information and models to help plan and carry out future exploration ventures.

In order to achieve these objectives, several diverse geoscience studies were discussed between the GSC and its provincial partners and undertaken: 1) new conventional bedrock and Quaternary mapping at 1:20 000 to 1:50 000 scales, 2) thematic geoscience studies, including lithostratigraphy and biostratigraphy, palynology, thermal maturation studies, structural analysis, geophysics (seismic reflection acquisition, reprocessing and reinterpretation, high-resolution aeromagnetic surveys), geochronology, diagenesis and geochemistry (organic and mineral), and 3) a significant joint effort to produce 4 regional (1:125 000 and 1: 250 000) geological strip-map and cross-section syntheses. As it was impossible to cover the entire area with new mapping, five narrow tectonostratigraphic corridors were selected from southern Quebec to western Newfoundland, representing the entire regional variability of the geological framework, for in-depth analysis of the geological architecture of this large segment of the Canadian landmass.

Project Delivery

The Bridges NATMAP project was undertaken between 1999 and 2004. Three provincial geological surveys were involved in the project along with the Geological Survey of Canada (GSC). Under a 5 -year agreement signed between the GSC and the Geological Survey of New Brunswick (GSNB), the GSC provided funds to support mutually

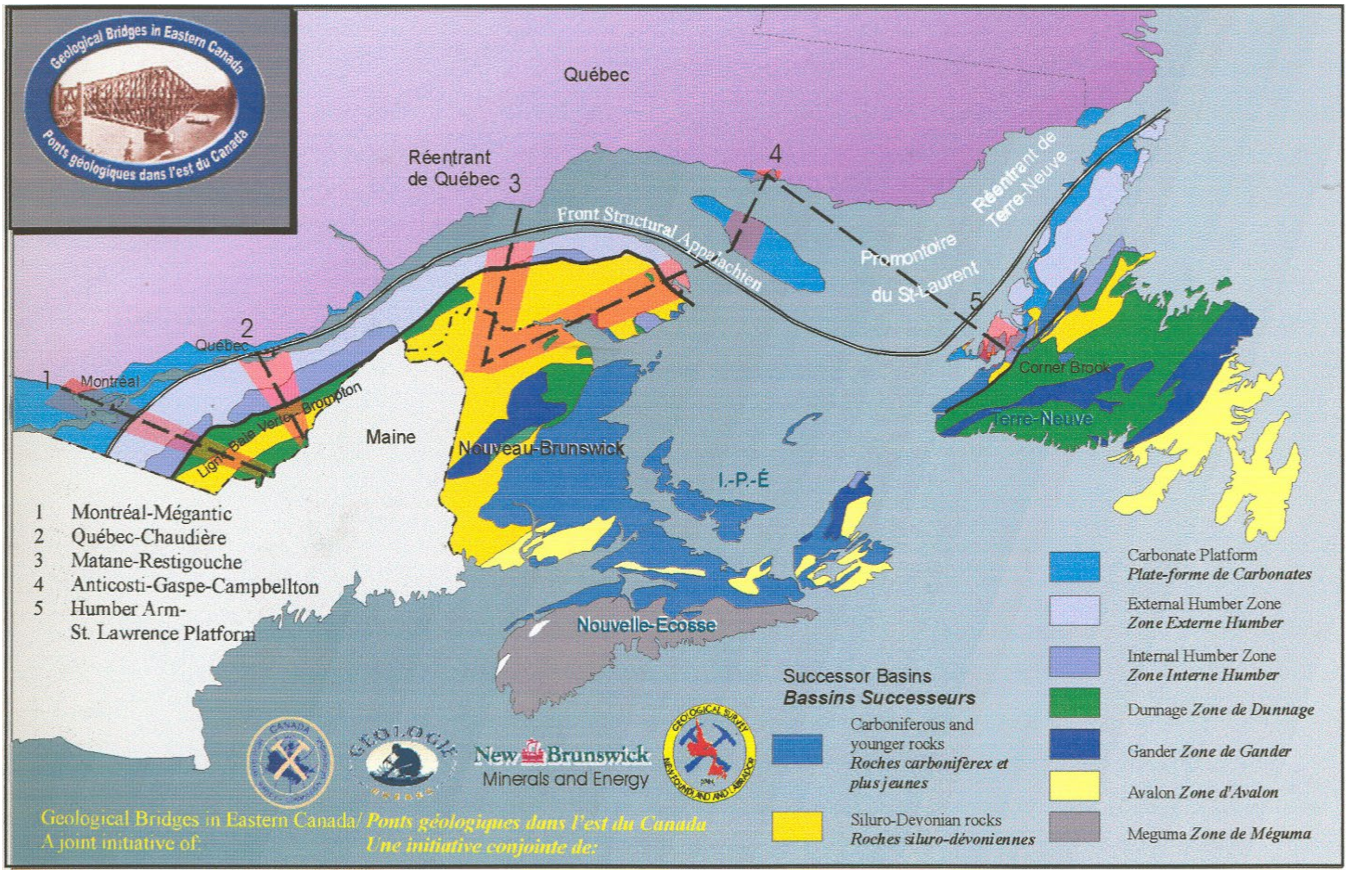

Fig. XIV-1. Location of the five project transects and general geology of the Eastern Canada Appalachian Forelands NATMAP project. (courtesy of D. Lavoie, GSC)

planned mapping activities in the Gaspé Belt in northern New Brunswick. Yearly informal agreements were reached with the Service Géologique de Québec (SGQ) and the Geological Survey of Newfoundland and Labrador (GSNL) in which respective bedrock mapping projects and thematic studies were discussed; these outlined joint, cost-sharing or in-kind supported activities in their respective jurisdictions. To augment the scientific capacity of the GSC and provincial surveys, formal agreements were signed with 10 Canadian universities at various times during the project to tackle some specific thematic aspects of the overall project.

Over the five years of the active project, a total of 40 new geological maps (bedrock and surficial) were produced and released by the GSC or the provincial surveys. The Bridges-associated GASL (GeoAtlas of the St. Lawrence) virtual library was put on-line with access to the new geoscience databases produced by the project. The main scientific conclusions were synthesized in three special issues of geoscience journals

- The new hydrocarbon system synthesis for the eastern part of the Gaspé Belt was released as a special issue of the *Bulletin of Canadian Petroleum Geology* (Lavoie and Bourque, 2001).
- The new tectonostratigraphic models for the Cambrian-Ordovician belts (St. Lawrence Platform and Humber Zone) were presented in a suite of 12 papers regrouped in a special issue of the *Canadian Journal of Earth Sciences* (Lavoie et al., 2003). The first regional integrated stratigraphic framework for the entire Humber Zone in eastern Canada was also presented.
- The new ideas and models for the Silurian-Devonian Gaspé Belt were covered in a group of 10 papers published as a special issue of the *Canadian Journal of Earth Sciences* (Lavoie et al., 2004). Of critical interest were the efforts by all partners to present a joint stratigraphic and structural framework for the Gaspé Belt on both sides of the Quebec – New Brunswick border.
- The GSC, SGQ and the GSNB jointly produced four major regional geological strip-maps and cross-sections. These represent the flagship products of the project as they clearly present the new ideas for the geological framework but, perhaps more importantly, they testify to the new synergy in geoscience research in eastern Canada.

Scientific Results and Implications

- The Lower-Middle Paleozoic rocks of the St. Lawrence Platform and the Lower-Middle Paleozoic Appalachians were among the first rocks to be studied by William Logan after the creation of the GSC in 1842. Most of the belt had been mapped to local scales in the intervening years, but the coverage of some areas dated from the 1930-1960 period, well before the advent of modern geodynamic models. Most of GSC's regional efforts in the plate tectonic era of the 1970-late 1990's period then shifted to the Canadian Rockies or Canada's north. Because the Appalachian region spans all the provincial jurisdictions of eastern Canada, no coherent federal or provincial efforts for regional correlation had been carried out, other than the famous Appalachian tectonostratigraphic map from Memorial University, which was based on obsolete map information at many places. Over the five years of the NATMAP BRIDGE project, major new ideas and models, plus regional syntheses were proposed and developed as a result of the new geoscience data and interpretation:
- A new regional stratigraphic synthesis for the entire Cambrian-Ordovician and Silurian-Devonian depositional belts from southern Quebec, through northern New Brunswick and the Gaspé Peninsula, up to western Newfoundland is now available.
- Precise biostratigraphic ages based on micropaleontology are now available for previously undated segments of the Cambrian to the Devonian. These were invaluable for the coherence of the new stratigraphic framework.
- The Salinic Orogeny, although known earlier, is now clearly recognized as a significant late Early Silurian (440 m.y.) deformational event with a northerly-directed compressive episode reaching northern Gaspé.
-
- A joint effort between the NATMAP project and a GSC-led hydrogeology project in southern Quebec resulted in new bedrock and Quaternary geology maps west of Montreal that help to locate areas of recharge and of high sensibility for the Quaternary and Ordovician fractured bedrock aquifers identified by both groups.
- New organic matter maturation data and analysis of potential source rocks permitted unequivocal documentation of a significant oil and gas potential for the Gaspé Belt in northern New Brunswick
- The new models and data were presented in 43 peer-reviewed papers in geoscience journals and in 41 federal-provincial current research reports and open files. A total of 217 formal abstracts were submitted to various geoscience meetings, and the NATMAP GSC leadership was directly behind the organization of 5 national and north-American geoscience symposiums and special sessions.
- Of critical importance was the training of new geoscientists through fieldwork and graduate research. The project supported 10 honours B.Sc., 10 M.Sc. and 5 Ph.D. theses.

The results of the NATMAP Bridges project upgraded to modern standards the geoscience knowledge of various aspects of the origin and evolution of significant segments of the Lower-Middle Paleozoic continental margin of Laurentia. As usual, as the data become more abundant, some questions are solved but others come to mind.

The economic future of the natural resource industry in the area covered by this NATMAP project had been in serious jeopardy since the late 1990s. The two major ore producers were facing serious problems. Mining reserves at the Bathurst Mining Camp in northern New Brunswick were dwindling rapidly, with little hope of replacement apparent in the mine area or in the camp itself. The camp had been the target of several projects over the previous decade and the mapping fieldwork and geophysical activities outside the mining camp were primarily designed to find new base metal (copper-lead-zinc) reserves. The world-class Murdochville copper mine was also facing a rapid depletion of its ore reserves. A major industry-SGQ initiative in the Gaspé Peninsula had failed to identify new economic deposits to feed the smelter in Murdochville.

The Gaspé Peninsula was one of the first areas in North America where drilling for oil and gas took place (1860). For many years, extensive efforts by local operators had failed to document significant volumes of hydrocarbons in the Lower to Middle Paleozoic rocks of the Canadian Appalachians (the one exception was Shell's 1964 discovery of the 12BCF St. Flavien gas field). In 1995, however, successful drilling of an oil reservoir in western Newfoundland prompted renewed interest for the entire area. Modern geoscience map data from the Newfoundland survey, together with subsurface information from joint GSC-academia research projects were the elements that fuelled the initial exploration spark.

- The NATMAP project new data supported critical analysis of the mid-1990's industry-sponsored research by GSC and collaborators on the hydrocarbon potential of the Gaspé Belt in easternmost Gaspé Peninsula. The resulting new interpretations and their implications were published in a special issue of the Bulletin of Canadian Petroleum Geology (Lavoie and Bourque, 2001); this publication is acknowledged by many as the main element in the renewed interest for the hydrocarbon potential of the Gaspé Belt.
- The NATMAP project generated data that will ultimately open up a new exploration frontier in the Gaspé Belt of northern New Brunswick. Detailed organic matter data and Rock-Eval analysis have shown that the area around Campbellton-Dalhousie is favourable to the preservation of oil and gas, and good quality source rocks have been identified.

These initial results were complemented in the following GSC activities:

- Detailed field work along seismic lines reprocessed by the GSC led to the recognition that large areas previously mapped as oceanic rocks of the Dunnage zone actually belong to the Humber Zone. These rocks, that underlie the Gaspé Belt in Témiscouata, are a potentially good source for hydrocarbons.
- Detailed field, diagenetic and geochemical studies of a dolomitic outcrop in western Gaspé led to the first identification of hydrothermal dolomites in Lower Silurian rocks in the Appalachians. These hydrothermal dolomites are major oil and gas reservoirs in the Ordovician of central and eastern USA. Since the publication of this finding, all operators in the area now list the Lower Silurian hydrothermal dolomite as one of their targets for drilling.

The NATMAP project generated new hydrocarbon-oriented data and ideas that, if not the major elements in the current hectic exploration activities in all prospective sedimentary belts from southern Quebec to western Newfoundland, are among the major ones as recognized by the provincial and industrial stakeholders.

Recognized Impacts

The Bridges NATMAP project was initiated at a time of limited resource exploration for base metals and hydrocarbons in the Lower Paleozoic rocks of eastern Canada. This low was coincident with a global depression in the price of the various commodities but also in the reduced appeal of the Canadian Appalachians that was plagued by an overall outdated regional map coverage, obsolete tectonostratigraphic frameworks and, especially, a lack of exploration success. The earlier provincial mapping and thematic geoscience efforts were focussed, to some extent, in other frontier areas (northern Quebec, for example) or in support of the declining mining communities (Bathurst, Murdochville). Over the life span of the project, new data and models were generated and proposed. The joint federal-provincial-academia geoscience efforts in the Lower Paleozoic domains of eastern Canada provided the much-needed science that currently supports the regional-scale hydrocarbon exploration. Moreover, the new governance model defined under that project served as the building stone upon which regional geoscience projects were based and are still undertaken.

New Brunswick:

- Subsequent mineral exploration was largely focused along parts of two transects in response to anomalies that showed up in the geochemical and geophysical surveys and subsequent mapping. Over 900 mineral claims were staked and approximately $525K was spent in exploration expenditures.
- The results of thermal history studies done in support of the mapping show that part of the project area is in the "oil window"; subsequent work that documented the presence of hydrothermal dolomites, has defined potential reservoirs. Little hydrocarbon exploration had been carried out in northern NB but these data suggested that there is potential for hydrocarbons south of the Restigouche estuary. As a result, Petrolia conducted a seismic survey on its leased property, while hydrocarbon exploration on the Quebec side of the Restigouche is underway.

Québec:

- The project was significant for the current hectic hydrocarbon exploration activity where all prospective lands are currently under exploration licenses. 2004 hydrocarbon exploration expenditures in the Province of Quebec reached a record $25 million and numbers for 2005 were fully expected to be even higher. This has to be contrasted with the almost total lack of exploration investments at the start of the project. The price of oil played a critical role in enhancing the value of the exploration dollars, although without the new geoscience data and models, these dollars would have certainly been spent somewhere else. In 2002 (natural gas) and 2005 (oil), the province of Quebec entered, albeit modestly, the community of hydrocarbon producing jurisdictions.

Newfoundland:

- The NATMAP project was defined to address a major knowledge gap in western Newfoundland as the Humber Arm Allochthon, the type-area of the Appalachian Humber Zone, had been published only at a regional scale (1:250 000). The new detailed mapping (1:50 000) resulted in a very different image of the area with its world-wide famous 'Mélanges' now unequivocally assigned to specific stratigraphic units. The new stratigraphic framework is now tied with the continental coeval successions and integrated into the regional evolution scenario, defined earlier by researchers at Memorial University and the Geological Survey of Newfoundland and Labrador. Follow up investigations, based on this scenario and the considerable earlier work by mappers at GSNL, resulted in the recognition of the hydrocarbon potential of these rocks.

Conclusions

The Bridges NATMAP project resulted in a new synergy of geoscience efforts during an overall period of declining public geoscience funding and the associated reduction in expertise; these collaborative models are still used in ongoing, broader geoscience initiatives in eastern Canada. The NATMAP project has made major contributions to our knowledge of the fundamental geological architecture and evolution of the Lower Paleozoic rocks in eastern Canada. The various syntheses that originated from the collective work of the GSC and its provincial partners from Quebec, New Brunswick and Newfoundland raised our models to useful modern standards. The various local and regional maps and cross-sections, reports and databases played an unequivocal role in the ongoing major hydrocarbon exploration activities in the Paleozoic rocks of eastern Canada and some of the new data and findings were, from the words of the industry, major elements in the development of producing hydrocarbon fields in Gaspé. The NATMAP data are currently being synthesized with more recent joint federal-provincial endeavours in the same area (TGI 2 Appalachian Energy Project and Gulf of St. Lawrence Energy Resource Evaluation Project) with the national and international hydrocarbon industry actively using the public geoscience for its exploration projects in this area. As a preliminary conclusion of the nearly 10 years (1999-2009) of joint federal-provincial geoscience research, the first independent hydrocarbon resource evaluation for the entire Gulf of St. Lawrence and adjacent Paleozoic onshore was released in the fall of 2009 (Lavoie et al., 2009).

Acknowledgements:

The Appalachian Forelands and Platform NATMAP project was carried out under the joint leadership of Denis Lavoie and Daniel Lebel, GSC Quebec. Leadership for studies undertaken by the provincial geoscience agencies was provided by Steve McCutcheon (NB Geological Surveys Branch) and Steve Colman-Sadd (Geological Survey of Newfoundland and Labrador -GSNL). The author greatly appreciates the considerable help provided by Lavoie who wrote most of the text of this summary chapter. Lavoie's excellent report was used as an example of the format, style and content for preparing several of the other chapters in this volume. McCutcheon kindly prepared summary information on the New Brunswick component studies and their influence on subsequent mineral exploration, and his colleague, Reg Wilson, added useful information on the petroleum potential aspect. Dave Livermore and Ian Knight, both of GSNL, made suggestions on the final draft to improve the understanding of the contributions of that agency. Pierre Verpaelst, Géologie Québec, offered some important insights into how the NATMAP project contributed to, or influenced, related studies in Quebec.

REFERENCES

Andrews, A. and Lawton, S. 1988. Prospectors Need Better Maps, says PDAC. PDAC Digest, Autumn 1988.

Bernknopf, R.L., Wein, A.M., St-Onge, M.R., and Lucas, S.B., 2007. Analysis of Improved Government Geological Map Information for Mineral Exploration: Incorporating Efficiency, Productivity, Effectiveness and Risk Considerations: Geological Survey of Canada Bulletin 593 – USGS Professional paper 1721, 45 p.

Bhagwat, S.B. and Ipe, V.C., 2000. Value of Geologic Quadrangle Maps of Kentucky: Illinois State Geological Survey, Special Report 3, 39 p.

Bleeker, W. and Davis, W.J., 1999. The 1991-1996 NATMAP Slave Province Project: Introduction. Canadian Journal of Earth Sciences, vol. 36, pp. 1033-1042.

Boulton, R.B., 1999. Refinement and Validation of a Costs, Benefits and Impact Model for TGI: R.B. Boulton and Associates, unpublished, 23 p.

Colpron, M. and Nelson, J. eds., 2006. Paleozoic evolution and metallogeny of pericratonic terranes at the ancient Pacific margin of North America, Canadian and Alaskan Cordillera. Geol. Assoc. Canada Special Paper 45.

Coope, J.A., D'Anglejean, B., Gordy, P.L., Strangway, D.W., Sutherland Brown, A. and Tanguay, M.C., 1983. An Examination of the Output of the Geological Survey of Canada by the Canadian Geoscience Council. Part 1. Geological Survey of Canada Paper 82–06, 59 p.

Cranstone, D.A., 2002. A History of Mining and Mineral Exploration in Canada and Outlook for the Future: Natural Resources Canada, 49 p.

Dawson, W., 1864. Toronto Leader: May 6, 1864.

Fulton, R. J., Blais-Stevens, A., Sun, C., Eilers, R G., Betcher, R., Elson, J. A., Veldhuis, H., Fraser, W. R., 2004. Surficial materials of the Virden area, Manitoba and Saskatchewan. Geological Survey of Canada, Bulletin no. 546, 104 p., 1 CD-ROM

Gartner, J. 2000. Evaluation of the Geological Survey of Canada's National Geoscience Mapping Program (NATMAP). Gartner Lee Limited project #99508, unpublished.

Intergovernmental Geoscience Accord, 1996. 53rd Annual Mines Ministers' Conference, Yellowknife, Northwest Territories, September 17, 1996, unpublished, 12 p.

Intergovernmental Working Group on the Mineral Industry, 1999. Funding Government Geological Surveys: How Much is Enough? A Report to Mines Ministers by a Task Force Appointed by the Intergovernmental Working Group on the Mineral Industry, 56th Annual Mines Ministers' Conference, Charlottetown, PEI, September, 1999, unpublished 16 p.

Jackson, L. E., Jr., Leboe, E. R., Little, E. C., Holme, P. J., Hicock, S. R., Shimamura, K. and Nelson, F. E. N., 2008. Quaternary stratigraphy and geology of the Rocky Mountain Foothills, southwestern Alberta. GSC Bulletin 583, 61 p.

Jackson, L.E, Jr., Froese, D.G., Huscroft, C.M., Nelson, F.E., Westgate, J.A., Telka, A.M., Shimamura, K. and Rotheisler, P.N, 2009. Surficial geology and Late Cenozoic history of the Stewart River and northern Stevenson Ridge map areas, west-central Yukon Territory. GSC Open File 6059, 414 p.

Jones, B.,ed., 2001. The Nechako MATMAP Project of the central Canadian Cordillera. Canadian Journal of Earth Sciences, Special Volume 38, Number 4.

Lambert, I.B., 1999. Sustaining Economic Benefits from Mineral Resources: Returns on Government Investment in Geoscience: Bulletin of the Australasian Institute of Mining and Metallurgy, no.3, p. 84–87.

Lane, L.S., ed. 2004. Central Foreland NATMAP Project: Stratigraphic and Structural Evolution of the Canadian Foreland – Part 1. Bulletin of Canadian Petroleum Geology. Vol. 52, 4. p 273-375.

Lane, L.S., ed. 2005. Central Foreland NATMAP Project: Stratigraphic and Structural Evolution of the Canadian Foreland – Part 2. Bulletin of Canadian Petroleum Geology. Vol. 54, 1. p. 1-100.

Lavoie, D. and Bourque, P-A., eds., 2001. Hydrocarbon plays in the Silurian-Devonian Gaspé Belt, Québec Appalachians. Bulletin of Canadian Petroleum Geology, v. 49, no. 2, 177-365.

Lavoie, D., Malo, M. and Tremblay, A., eds. 2003. The Cambrian-Ordovician successions along the ancient continental margin of Laurentia – recent advances. Canadian Journal of Earth Sciences Special Issue, v. 40, p. 131-133.

Lavoie, D., Malo, M. and Tremblay, A., eds. 2004. Eastern Canada Silurian-Devonian Gaspé Belt NATMAP Project. Canadian Journal of Earth Sciences Special Issue, v. 41, p. 483-653.

Lavoie, D., Dietrich, J., Pinet, N., Castonguay, S., Hannigan, P., Hamblin, T., and Giles, P.S., 2009. Hydrocarbon resource assessment, Paleozoic basins of eastern Canada. Open File 6174, Geological Survey of Canada, 275 pages

Logan, W.E., 1863. Geology of Canada: Geological Survey of Canada. Report of Progress from its Commencement: Dawson Bros., Montreal, 983 p.

Lucas, S.B., Syme, E.C. and Ashton, K.E., 1999a. New perspectives on the Flin Flon Belt, Trans-Hudson Orogen, Manitoba and Saskatchewan: an introduction to the special issue on the NATMAP Shield Margin Project, Part 1. Canadian Journal of Earth Sciences, vol. 36, pp. 135-140.

Lucas, S.B., Syme, E.C. and Ashton, K.E., 1999b. Introduction to Special Issue 2 on the NATMAP Shield Margin Project: The Flin Flon Belt, Trans-Hudson Orogen, Manitoba and Saskatchewan. Canadian Journal of Earth Sciences, vol. 36, pp. 1763-1765.

Lynch, G., 2001. Structural denudation of Silurian-Devonian high-grade metamorphic rocks and post-orogenic detachment faulting in the Maritimes Basin, northern Nova Scotia. GSC Bulletin 558, 64 p.

Maurice, C., Lamothe, D. and Roy, C., 2009. Measuring the Economic Impacts of Geoscience Work by Géologie Québec: Géologie Québec PRO 2009-06, 10 p.

Mossop, G.D., 1989. Earth Sciences in the Service of the Nation: A Report on the Geological Survey of Canada. Canadian Geoscience Council published as GSC Paper 89-25, 29 p.

NATMAP, 1992 (unauthored). NATMAP: Canada's National Geoscience Program. GSC Pamphlet GS4000-5.

Percival, J.A., 2004. Insights on Archean continent-ocean assembly, western Superior Province: from new structural, geochemical and geochronological observations (Introduction by J.A. Percival). Precambrian Research, Special Issue, vol. 132, pp. 209-326.

Percival, J.A. and Helmstaedt, H., 2006. The Western Superior Province Lithoprobe and NATMAP transects (Introduction by J.A. Percival and H. Helmstaedt). Canadian Journal of Earth Sciences, Special Issue, vol. 43, pp. 743-1117.

Smith, C.H., 1999. William Logan's 1850 History of the Geological Survey of Canada: Geoscience Canada, v.26, p. 111–120.

St-Onge, M.R., *ed*., 1990. NATMAP: Canada's National Geoscience Mapping Program. Report of a Workshop Held March 8–10, 1990: Geological Survey of Canada Open File 2256, 83 p.

Thorleifson, L.H., Garrett, R.G. and Matile, G., 1994. Prairie kimberlite study – indicator mineral geochemistry. Geological Survey of Canada, Open File 2875.

USGS, 1987 (unauthored). National Geological Mapping Program: Goals, Objectives and Long-Range Plans. U.S. Geological Survey Circular 1020, 29 p.

Vodden, C.E., 1992. No Stone Unturned: The First 150 Years of the Geological Survey of Canada: Energy, Mines and Resources Canada, 52 p.

Appendix A: Guidance and Management of the NATMAP Program

At the inception of the Program in 1990, the NATMAP Steering Committee was formed to develop the program, provide guidance and management of the selection of the component mapping projects, to recommend funding levels, to annually review their progress and make decisions on their continuance, and to review new project proposals as earlier projects came to an end. The Steering Committee considered its developmental role as successfully completed in April 1995 and recommended it be replaced by the NATMAP Coordination Committee, with members who would serve three-year terms. Membership of both committees included representatives of the Geological Survey of Canada, provincial and territorial surveys, Canadian university geoscience departments, Canada's minerals and petroleum exploration industries and the Canadian geotechnical and environmental engineering industry. The Chief Geoscientist of the GSC (Earth Sciences Sector, NRCan) and a senior management representative of GSC were included as *ex-officio* members. Both committees, in turn, were supported by the two-person NATMAP Secretariat in the GSC.

Membership of the NATMAP Steering and Coordination Committees was as follows.

Membership of the NATMAP Steering Committee

(June 1990 – March 1995)

Geological Survey of Canada: Sandy Colvine (Co-chair), Jean-Serge Vincent

Provincial and Territorial Governments: Dave McRitchie (Co-chair), Manitoba Geological Surveys Branch; Scott Swinden, Newfoundland Geological Surveys Branch; Steve Morison, Dept of Indian and Northern Affairs, Yukon Territory

Industry: John Gartner (1990-94), Gartner Lee Limited; John Heslop, International Thunderwood Explorations Ltd (PDAC rep); Jeff Jeffery (MITEC rep 1990-92); Richard Moore, Falconbridge Ltd. (MITEC rep 1992-95); Dave Watkins, Minnova Inc. (1990-94)

Universities: Herb Helmstaedt, Queen's University; Ron Clowes (1990-92), University of British Columbia (LITHOPROBE Secretariat)

Ex-Officio: Jim Franklin, Chief Scientist, Geological Survey of Canada; Chris Findlay (1990-93), Director-General, Geological Survey of Canada; Mike Berry (1993-95), Director-General, GSC

NATMAP Secretariat: Mike Cherry (seconded to GSC from the Ontario Geological Survey); Dan Richardson, GSC

Membership of the NATMAP Coordination Committee

(April 1995 - 2002)

Geological Survey of Canada: Sandy Colvine (1995-96); Jean-Serge Vincent (1995-98); Grant Mossop (1996-2001); Aïcha Achab (1998-2001); Mike Cecile (2002); Daniel Lebel (2002)

Provincial and Territorial Governments: Dave McRitchie, Manitoba Geological Surveys Branch (1995-96); Bill McMillan, British Columbia Geological Surveys Branch (1995-1999); Scott Swinden, Newfoundland Geological Surveys Branch (1995-1999); Fran Haidl, Saskatchewan Energy and Mines (1999-2002); Jennifer Pell, Indian and Northern Affairs Canada, NWT (1995-97); Carolyn Relf, Indian and Northern Affairs Canada, NWT (1997-98); John Armstrong, Indian and Northern Affairs Canada, NWT (1998-2002)

Industry: Doug Van Dine, Van Dine Geological Engineering Services (1995-2002); Ed Debicki, INCO Exploration and Technical Services (MITEC rep, 1995-97); John Heslop, International Thunderwood Explorations Ltd (PDAC rep, 1995-97); Richard Moore, Falconbridge Inc. (PDAC rep, 1996-2002); Richard Alcock, Falconbridge Inc. (CAMIRO rep, 1997-2002); Robert Scammell, Burlington Resources Canada Ltd. (1998-2002)

Universities: Phillippe Erdmer, University of Alberta (1995-2002); Herb Helmstaedt, Queen's University (1995-97); Sandra Barr, Acadia University (1998-2002).

Ex-officio: Jim Franklin, GSC, Chief Geoscientist, ESS (1995-97); Richard Grieve, GSC, Chief Geoscientist, ESS (1997-2002); Mike Berry, GSC (1995-96); Murray Duke, GSC (1996-2002)

NATMAP Secretariat: Mike Cherry, GSC (1995-99); Dan Richardson, GSC, Interim Coordinator (1999-2002)

Appendix B: Funding Sources by NATMAP Project

In the *Funding NATMAP* section of the Introduction, Table 1 and Figure 1 present a breakdown of the total NATMAP Program funding by the various funding sources – NATMAP, GSC, Provinces/Territories, etc. The following tables take the information for each of these categories and show how each funding agency contributed specifically to the thirteen NATMAP projects. While every attempt was made to be complete and accurate with these numbers, the variability in reporting found in the source documents has led to some uncertainties in these compilations. Therefore, in the tables which follow, in some cases, 'best estimates' have been used, whereas in others, no information is included.

Table B-1: Total funding ($K) by project and source

Project	NATMAP	GSC A-Base	GSC PAS	Provinces Territories	OGDs	University	Industry	Other	Total
Shield Margin	1285.0	6098.1		6942.4	15.0	3300.0	1001.5		18642.0
Slave Province	1320.0	6515.7	Information not available						7835.7*
Quaternary of Southern Prairies	902.5	2040.1		2703.7	154.9	8.1	78.1		5887.4
Eastern Cordilleran	838.0	3233.7		248.0		243.4	1348.3	5.0	5916.4
Oak Ridges Moraine	692.5	960.0		2600.0	50.0	118.0	75.0	20.0	4515.5
Magdalen Basin	832.5	3060.1		2595.3		642.2	61.0		7191.1
Nechako	1090.0	3002.7		5218.4	46.3	565.3	847.5		10770.2
Western Churchill	1138.6	6231.5		2314.5		99.0	313.0		10096.6
Western Superior	1131.6	2233.4	8.4	6699.0		3957.0	4.0		14033.4
Greater Winnipeg	530.0	2840.0		1330.0	770.0	125.0			5595.0
Central Foreland Geoscience Transect	880.5	4993.2	225.0	579.6	15.0	899.5	3177.7		10770.5
Ancient Pacific Margin	650.0	5466.6	450.0	2221.0	53.0	155.1	93.1		9088.8
Appalachian Foreland & St. Lawrence Platform Architectures	537.5	2612.3	445.0	5443.0		814.0	694.0		10545.8
TOTALS	11828.7	49287.4	1128.4	38894.9	1104.2	10926.6	7693.2	25.0	120888.4

* The Slave Province NATMAP project total funding is lower than actual, due to incomplete reporting in some aspects.

Table B-2: NATMAP funds ($K) by year and project

Project	91-92	92-93	93-94	94-95	95-96	96-97	97-98	98-99	99-00	00-01	01-02	02-03	03-04	Total
Shield Margin	250.0	250.0	350.0	255.0	180.0									1285.0
Slave Province	220.0	350.0	350.0	300.0	100.0									1320.0
Quaternary of Southern Prairies		118.0	210.0	217.0	200.0	150.0	7.5							902.5
Eastern Cordilleran			148.0	184.0	184.0	189.0	133.0							838.0
Oak Ridges Moraine			117.5	175.0	175.0	215.0	10.0							692.5
Magdalen Basin			85.0	220.0	245.0	200.0	82.5							832.5
Nechako					181.0	300.0	265.0	232.0	112.0					1090.0
Western Churchill							315.0	300.0	200.0	180.0	143.6			1138.6
Western Superior						10.0	250.0	250.0	225.0	225.0	171.6	8.4		1140.0*
Greater Winnipeg							165.0	165.0	150.0	50.0				530.0
Central Foreland Geoscience Transect								250.0	203.0	225.0	202.5	225.0		1105.5*
Ancient Pacific Margin								20.0	202.5	225.0	202.5	225.0	225.0	1100.0*
Appalachian Foreland & St. Lawrence Platform Architectures									110.0	225.0	202.5	225.0	220.0	982.5*
TOTALS	470.0	718.0	1260.5	1351.0	1265.0	1064.0	1228.0	1217.0	1202.5	1130.0	922.7	683.4	445.0	12957.1**

* The NATMAP Program formally ended in FY2001-02. The four projects that continued in 2002-03 and 2003-04 had been notionally approved to receive NATMAP funds in those years, so were then funded under the GSC's PAS (Program Approval System) to enable their completion. The totals presented above, therefore, represent the total GSC NATMAP project costs. Annual funding support provided for the NATMAP Secretariat function from 1991-92 to 2001-01 (~$20K per year) is not included

Table B-3: GSC A-Base funds* ($K) by year & project (Includes GSC MDA funds)

Project	91-92	92-93	93-94	94-95	95-96	96-97	97-98	98-99	99-00	00-01	01-02	02-03	03-04	totals
Shield Margin	1710.5	1492.5	1005.0	1341.5	548.6									6098.1
Slave Province	1680.5	1720.4	1303.8	1002.0	809.0									6515.7
Quaternary of Southern Prairies		220.0	453.0	449.4	531.2	386.5								2040.1
Eastern Cordilleran			552.0	503.0	592.0	826.3	760.4							3233.7
Oak Ridges Moraine				345.0	280.0	335.0								960.0
Magdalen Basin			704.0	870.5	677.2	448.9	359.5							3060.1
Nechako					462.5	756.0	698.5	667.5	418.2					3002.7
Western Churchill							1340.0	1610.0	1581.5	900.0	800.0			6231.5
Western Superior							215.0	500.0	566.0	565.0	387.4			2233.4
Greater Winnipeg							605.0	550.0	720.0	965.0				2840.0
Central Foreland Geoscience Transect								922.4	848.1	910.3	937.4	1175.0	200.0	4993.2
Ancient Pacific Margin									680.0	1112.5	1694.0	1071.6	908.5	5466.6
Appalachian Foreland & St. Lawrence Platform Architectures									827.0	727.5	738.0		319.8	2612.3
TOTALS	3391.0	3432.9	4017.8	4511.4	3900.5	2752.7	3978.4	4249.9	5640.8	5180.3	4556.8	2246.6	1428.3	49287.4

Table B-4: Provincial and Territorial Funding ($K) by year & project

Project	91-92	92-93	93-94	95-96**	96-97	97-98	98-99	99-00	00-01	01-02	Totals
Shield Margin	m+s 1625	m+s 1650	m+s 1600	m 802.4 s 182.0							6942.4
Slave Province	information not available										
Quaternary of Southern Prairies		m 102 s 140 a 140	m 102 s 140 a 140	m 289.4 s 4.9	m 95.4	m 734 s 360 a 280					2703.7
Eastern Cordilleran				a 75.0	a 7.0	a 124					248.0
Oak Ridges Moraine			o 40.0	o 415.0	o 375.0	o 1300					2600.0
Magdalen Basin			ns 204 nb 55	ns 280 nb 64.4	ns 79.0 nb 65.0	ns 60.0 nb50.0	ns 996 nb 302				2595.3
Nechako				b 404.8	b 689.7	b 596.9	b 623.5	b 294.5	b 2609		5218.4
Western Churchill						inac 752.0	nwt 310 inac 460	inac 492.5	inac110 cngo100	inac 60 cngo 30	2314.5
Western Superior						o 470.0 m 1200	o 461 m 735	o 933 m 707	o 1016 m 525	o 253 m 399	6699.0
Greater Winnipeg						m 155	m 140	m 185	m 185	m 665	1330.0
Central Foreland Geoscience Transect							b 170	b 107 inac 6	b 21 y 216.6 l 10	b 2 y 23.5 nwt 23.5	579.6
Ancient Pacific Margin								y 416 b 550 us 112	y 492 b 219	y 432	2221.0
Appalachian Foreland & St. Lawrence Platform Architectures								nb 987.5 nl 248.5 q 145	nb1007 nl 128 q 1080	nb 482 nl 185 q1180	5443.0
TOTALS	1625.0	2032.0	2281.0	2517.9	1311.1	6081.9	4197.5	5184.0	7718.6	3735.0	38894.9*

Abbreviations: a = Alberta; b = British Columbia; cngo = Canada Nunavut Geoscience Office; inac = Indian and Northern Affairs Canada; m = Manitoba; nb = New Brunswick; nl = Newfoundland and Labrador; ns = Nova Scotia; nwt = Northwest Territory; y = Yukon Territory; o = Ontario; q = Quebec; s = Saskatchewan; us = US Geological Survey

* These figures include funding by INAC and USGS, as well as the provincial geological surveys, so the total differs from the "Provinces/Territories" figure of Table 1 and Figure 1.

Table B-5: Other Government Departments (OGD) contribution ($K) by year & project

Project	91-92	92-93	93-94	94-95	95-96	96-97	97-98	98-99	99-00	00-01	01-02	TOTAL
Shield Margin					15.0							15.0
Slave Province												
Quaternary of Southern Prairies					7.4	147.5						154.9
Eastern Cordilleran												
Oak Ridges Moraine				35.0		15.0						50.0
Magdalen Basin												
Nechako								14.3	32.0			46.3
Western Churchill												
Western Superior												
Greater Winnipeg							5.0	30.0	355.0	380.0		770.0
Central Foreland Geoscience Transect									15.0			15.0
Ancient Pacific Margin									53.0			53.0
Appalachian Foreland & St. Lawrence Platform Architectures												
TOTALS				35.0	22.4	162.5	5.0	44.3	455.0	380.0		1104.2

Table B-6: University contribution ($K) by year & project - includes NSERC

Project	91-92	92-93	93-94	94-95	95-96	96-97	97-98	98-99	99-00	00-01	01-02	TOTAL
Shield Margin	Not available			2400.0	900.0							3300.0
Slave Province	Information not available											
Quaternary of Southern Prairies					8.1							8.1
Eastern Cordilleran				58.0	133.0	39.0	13.4					243.4
Oak Ridges Moraine			10.0	28.0	35.0	45.0						118.0
Magdalen Basin			70.0	135.0	139.0	168.2	130.0					642.2
Nechako					27.0	98.8	118.6	174.9	146.0			565.3
Western Churchill							15.0	22.0	12.0	32.0	18.0	99.0
Western Superior							2400.0		1091.0	313.0	153.0	3957.0
Greater Winnipeg							20.0	35.0	35.0	35.0		125.0
Central Foreland Geoscience Transect								211.9	233.5	239.0	215.1	899.5
Ancient Pacific Margin									31.6	10.0	113.5	155.1
Appalachian Foreland & St. Lawrence Platform Architectures									270.0	278.0	266.0	814.0
TOTALS			80.0	2621.0	1242.1	351.0	2697.0	443.8	1819.1	907.0	765.6	10926.6

Table B-7: Industry contribution ($K) by year & project

Project	91-92	92-93	93-94	94-95	95-96	96-97	97-98	98-99	99-00	00-01	01-02	02-03	03-04	Total
Shield Margin				1001.5										1001.5
Slave Province	Information not available													
Quaternary of Southern Prairies					48.1	30.0								78.1
Eastern Cordilleran			100.0	609.0	279.3	260.0	100.0							1348.3
Oak Ridges Moraine				45.0	30.0									75.0
Magdalen Basin					55.0	3.0	3.0							61.0
Nechako					507.5	257.5	22.9	59.1	0.5					847.5
Western Churchill							142.0	98.0	73.0					313.0
Western Superior							1.0		2.0	1.0				4.0
Greater Winnipeg														
Central Foreland Geoscience Transect								1760.0	1005.5	349.0	63.2			3177.7
Ancient Pacific Margin									21.0	62.1	10.0			93.1
Appalachian Foreland & St. Lawrence Platform Architectures									232.0	370.0	70.0		22.0	694.0
TOTALS			100.0	1655.5	919.9	550.5	268.9	1917.1	1334.0	782.1	143.2		22.0	7693.2