Geo-mapping for Energy and Minerals program: activities in the Sverdrup Basin, Canadian Arctic Islands

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Abstract: Advancements in the establishment of the geological framework of the Sverdrup Basin resulting from the Geo-mapping for Energy and Minerals program can be grouped under the main topics of tectonostratigraphy, crosslinking of biostratigraphy and chronostratigraphy, integration of igneous records with newly refined stratigraphy, and effects of global climatic environments on hydrocarbon source rocks in geological time. New discoveries of volcanic ash beds throughout much of the Triassic stratigraphic section required new tectonic interpretations involving a magmatic arc northwest of the basin that was likely involved in the opening of the Amerasia Basin. Modern approaches to biostratigraphy calibrated by radiometric age dating of volcanic ash beds made global correlations to chronostratigraphic frameworks and tectonic models possible. Correlation of the stratigraphy and recent geochronology of the High Arctic large igneous province (HALIP) places the main pulse of mafic magmatism in a postrift setting. Finally, the depositional setting of source rocks in the Sverdrup Basin is explained in terms of oceanographic factors that are related to the global environment. All of these advancements, including hints of undefined and relatively young structural events, lead to the conclusion that the hydrocarbon potential of the Sverdrup Basin has not been fully tested by historical exploration drilling.

Résumé : Les progrès réalisés dans la définition du cadre géologique du bassin de Sverdrup grâce au programme Géocartographie de l'énergie et des minéraux peuvent être regroupés sous les principaux thèmes suivants : la tectonostratigraphie; les liens croisés entre la biostratigraphie et la chronostratigraphie; l'intégration des archives ignées et de la stratigraphie nouvellement précisée; et les effets des environnements climatiques globaux sur les roches mères d'hydrocarbures au cours des temps géologiques. La découverte de nouvelles couches de cendres volcaniques dans une grande partie de la coupe stratigraphique du Trias a nécessité la formulation de nouvelles interprétations tectoniques mettant en jeu un arc magmatique au nord-ouest du bassin, lequel a probablement été impliqué dans l'ouverture du bassin amérasien. Les approches modernes de la biostratigraphie étalonnée par la datation radiométrique des couches de cendres volcaniques permettent des corrélations des cadres chronostratigraphiques et des modèles tectoniques à l'échelle globale. La corrélation de la stratigraphie et de la géochronologie récente de la grande province ignée du Haut-Arctique permet de situer la principale impulsion d'activité magmatique mafique dans un contexte post-rift. Enfin, le milieu de dépôt des roches mères dans le bassin de Sverdrup peut être expliqué à l'aide de facteurs océanographiques liés à l'environnement global. Tous ces progrès, y compris des indices de l'existence d'événements structuraux non définis et relativement récents, permettent de conclure que le potentiel en hydrocarbures du bassin de Sverdrup n'a pas été entièrement vérifié par les anciens forages d'exploration.

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Contents

INTRODUCTION

The Geo-mapping for Energy and Minerals (GEM) Western Arctic project was tasked with re-examining the geological framework for areas of the Canadian continental margin bordering the Arctic Ocean. The fundamental stratigraphy of the Sverdrup Basin was established by previous generations of Geological Survey of Canada (GSC) scientists over many decades prior to the GEM program. These GSC scientists produced a rigorous description, correlation, and fossil-based age definition of stratigraphic units. The GSC was uniquely equipped with the requisite expertise to undertake GEM-supported research and developed new fields of study in the process.

An overarching theme of the GEM program in studying the Sverdrup Basin was to allow researchers to apply modern laboratory techniques and advancements in geological theory, but this could only be achieved by undertaking new targeted field observations and rock sampling. Sedimentary geochemistry, radiometric geochronology, micropaleontology, and tectonostratigraphy were integrated to provide an up-to-date paleoenvironmental and tectonic framework for the Sverdrup Basin, from initial subsidence in the Carboniferous to uplift in the Cenozoic. The elements of this framework were combined to examine how the Arctic Ocean formed by continental drift.

This paper does not present new research. Instead, it describes the contribution of the GEM program to advancing the understanding of Sverdrup Basin's geological framework. The bibliography provided in Appendix A is a catalogue of publications on the Sverdrup Basin that have been produced as part of the GEM program.

MODERN TECTONIC FRAMEWORK

Prior to GEM, there was no direct evidence of a complex geodynamic setting for the Sverdrup Basin; therefore, interpretations about the basin's origin quite necessarily involved postorogenic and passive margin processes. It was mainly detrital zircon U-Pb age data coupled with new field observations, more specifically recognition of volcanic ash beds in the Triassic section, that required updated tectonic concepts. These ideas led to a new understanding of the setting for the Sverdrup Basin in terms of continental configuration and, more importantly, explained why the Sverdrup Basin formed. In general, the new model places the basin behind a continental subduction zone, in a retro-arc position (Fig. 1), and the various stages of the basin are attributed to subduction dynamics, ultimately resulting in rifting, continental breakup, and formation of the Arctic Ocean as a back-arc basin (Fig. 2, 3; Hadlari et al., 2016, 2018; Midwinter et al., 2016; Alonso-Torres et al., 2018).

MULTIDISCIPLINARY APPROACHES TO CRETACEOUS STRATIGRAPHY

Significant updates to the stratigraphy of the Sverdrup Basin were achieved using an integrated multiproxy approach. New quantitative techniques were developed for the next-generation analysis of biostratigraphic data from the Sverdrup Basin; for example, the Hassel Formation in the Sverdrup Basin was determined to be time equivalent to the putative Hassel Formation in the Eclipse Trough (Bylot Island) on

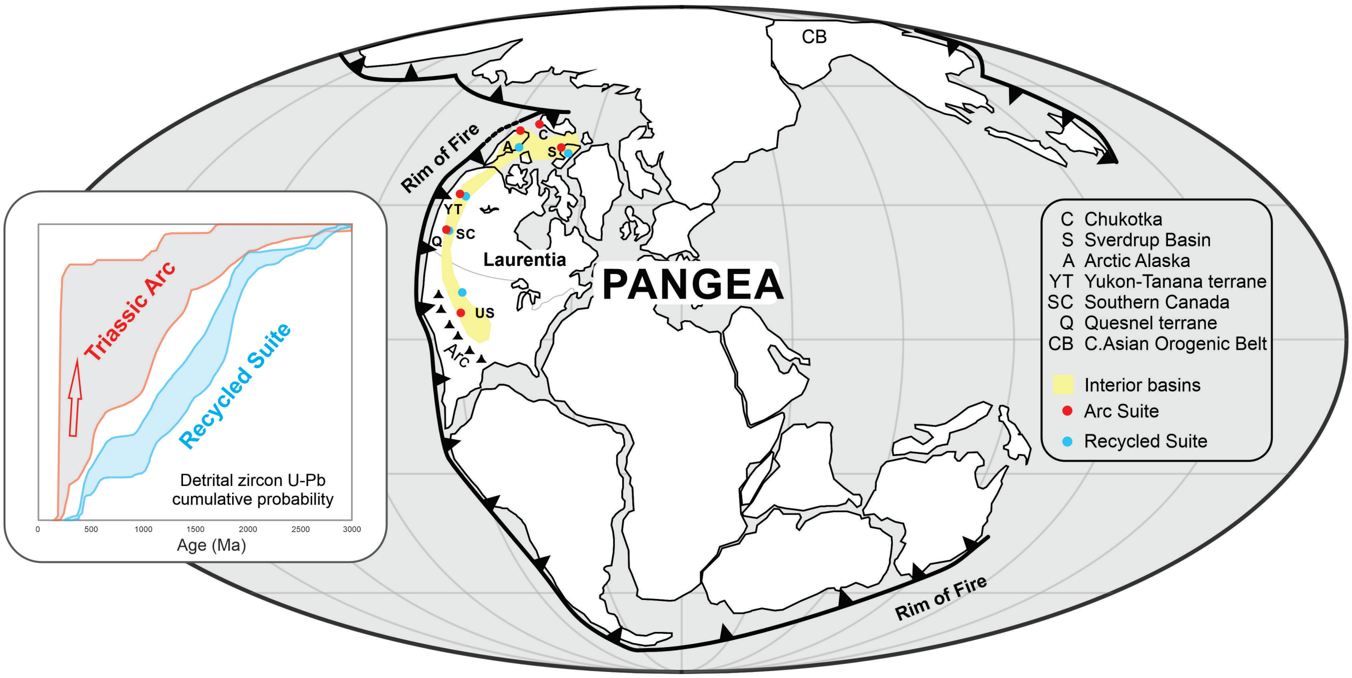


Figure 1. Global tectonic reconstruction of Pangea *from* Hadlari et al. (2018).

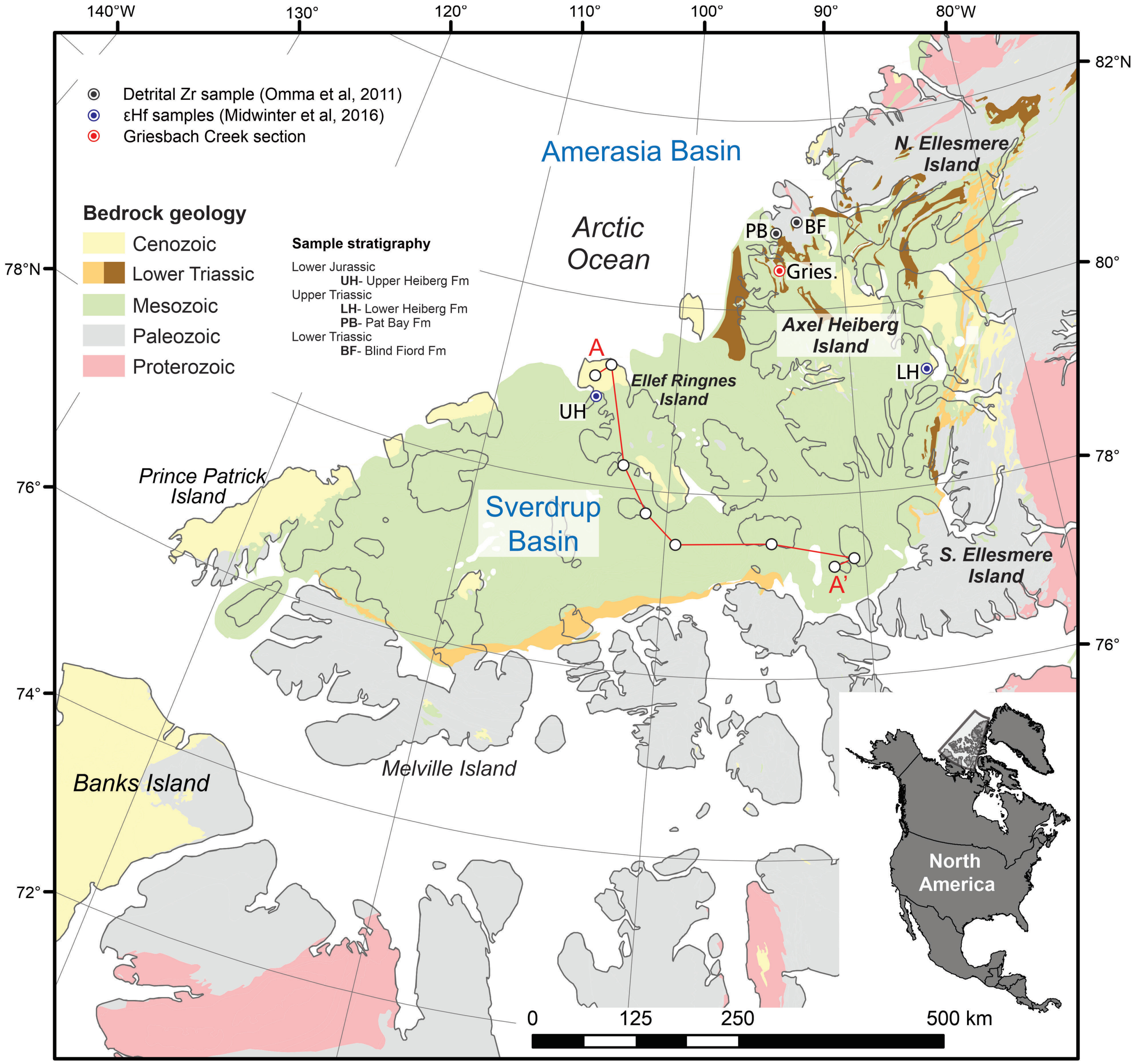


Figure 2. Map of the Sverdrup Basin *from* Hadlari et al. (2018).

the basis of a statistical comparison of fossil pollen assemblages (J.M. Galloway et al., 2012). In another example, assemblage-level biostratigraphic signatures for Upper Jurassic–Lower Cretaceous strata were developed using quantitative palynology (Fig. 4; J.M. Galloway et al., 2013). Demonstration of a sub-Hauterivian unconformity in the basin was useful for tectonic frameworks (J.M. Galloway et al., 2013, 2015).

Figures 5 and 6 are examples showing the integration of measured sections, paleontology, chemostratigraphy, and geochronology. These sections were previously measured and studied, but new field-sampling strategies for modern laboratory techniques yielded valuable results, mainly because volcanism spans a much wider time range than previously documented (Herrle et al., 2015; Davis et al., 2017).

The integrated approach also yielded results from volcanic stratigraphy because some rocks previously mapped as volcanic flows are actually sills. Flows are the same age as interbedded sedimentary strata, whereas sills could be emplaced at any time after sedimentary deposition; therefore, distinguishing between flows and sills is of critical importance for assessing paleomagnetic and geochronological data. New insight into the chronostratigraphy of the Sverdrup Basin, implications for normal and reverse

Contents

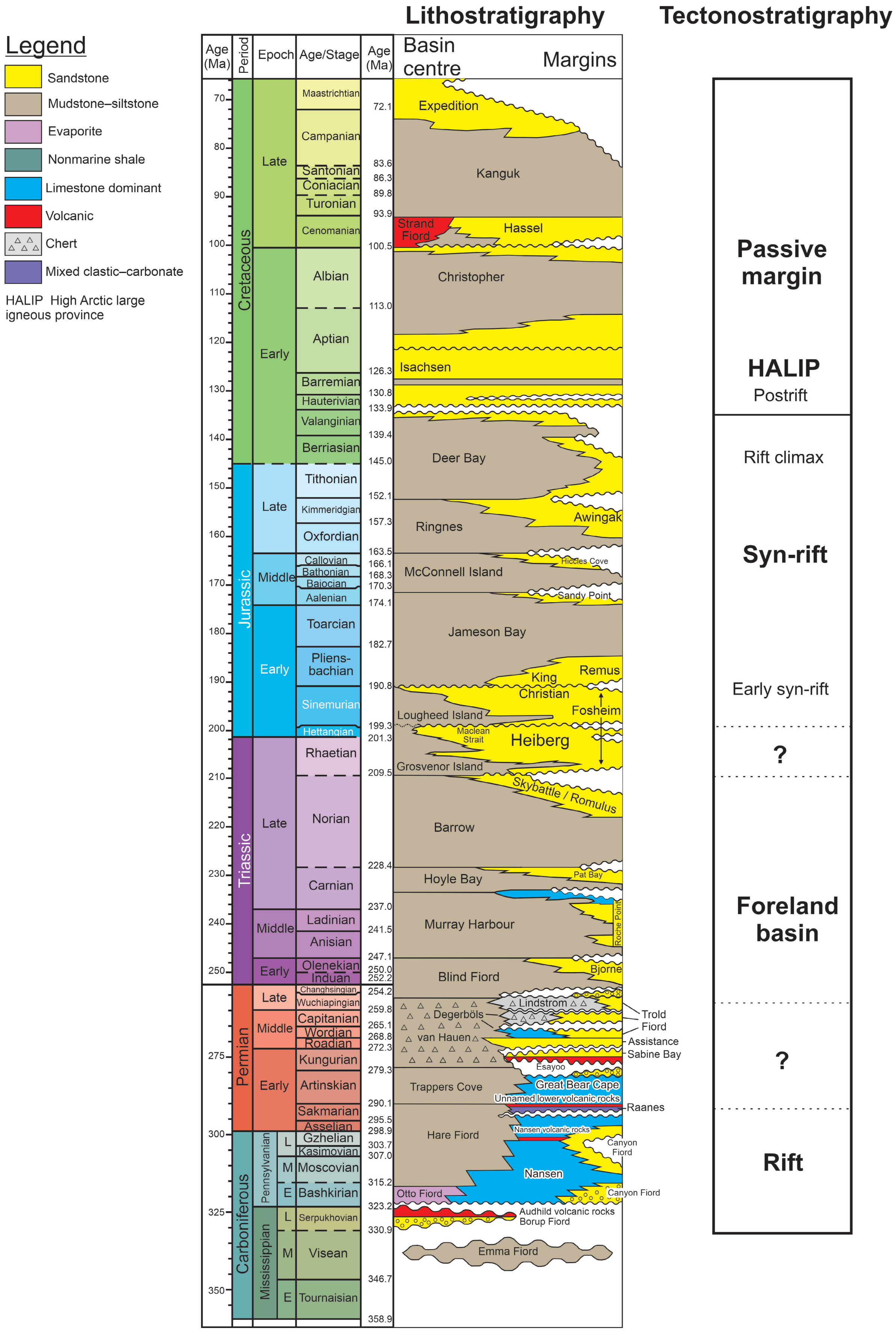

Legend
Sandstone
Mudstone–siltstone
Evaporite
Nonmarine shale
Limestone dominant
Volcanic
Chert
Mixed clastic–carbonate
HALIP High Arctic large igneous province
Lithostratigraphy
Tectonostratigraphy
Age (Ma)
Period
Epoch
Age/Stage
Age (Ma)
Basin centre
Margins
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
275
300
325
350
Cretaceous
Jurassic
Triassic
Permian
Carboniferous
Pennsylvanian
Mississippian
Late
Early
Late
Middle
Early
Late
Middle
Early
Late
Middle
Early
L
M
E
L
M
E
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Albian
Aptian
Barremian
Hauterivian
Valanginian
Berriasian
Tithonian
Kimmeridgian
Oxfordian
Callovian
Bathonian
Bajocian
Aalenian
Toarcian
Pliens-bachian
Sinemurian
Hettangian
Rhaetian
Norian
Carnian
Ladinian
Anisian
Olenekian
Induan
Changhsingian
Wuchiapingian
Capitanian
Wordian
Roadian
Kungurian
Artinskian
Sakmarian
Asselian
Gzhelian
Kasimovian
Moscovian
Bashkirian
Serpukhovian
Visean
Tournaisian
72.1
83.6
86.3
89.8
93.9
100.5
113.0
126.3
130.8
133.9
139.4
145.0
152.1
157.3
163.5
166.1
168.3
170.3
174.1
182.7
190.8
199.3
201.3
209.5
228.4
237.0
241.5
247.1
250.0
252.2
254.2
259.8
265.1
268.8
272.3
279.3
290.1
295.5
298.9
303.7
307.0
315.2
323.2
330.9
346.7
358.9
Expedition
Kanguk
Strand Fiord
Hassel
Christopher
Isachsen
Deer Bay
Ringnes
Awingak
Hiccles Cove
McConnell Island
Sandy Point
Jameson Bay
Remus
King Christian
Fosheim
Lougheed Island
Maclean Strait
Heiberg
Grosvenor Island
Skybattle / Romulus
Barrow
Hoyle Bay
Pat Bay
Roche Point
Murray Harbour
Blind Fiord
Bjorne
Lindstrom
Degerböls
van Hauen
Trold Fiord
Assistance
Sabine Bay
Esayoo
Great Bear Cape
Trappers Cove
Unnamed lower volcanic rocks
Raanes
Nansen volcanic rocks
Hare Fiord
Canyon Fiord
Nansen
Otto Fiord
Canyon Fiord
Audhild volcanic rocks
Borup Fiord
Emma Fiord
Passive margin
HALIP
Postrift
Rift climax
Syn-rift
Early syn-rift
?
Foreland basin
?
Rift

Figure 3. Stratigraphy and tectonic stages of the Sverdrup Basin (Hadlari et al., 2016, 2018).

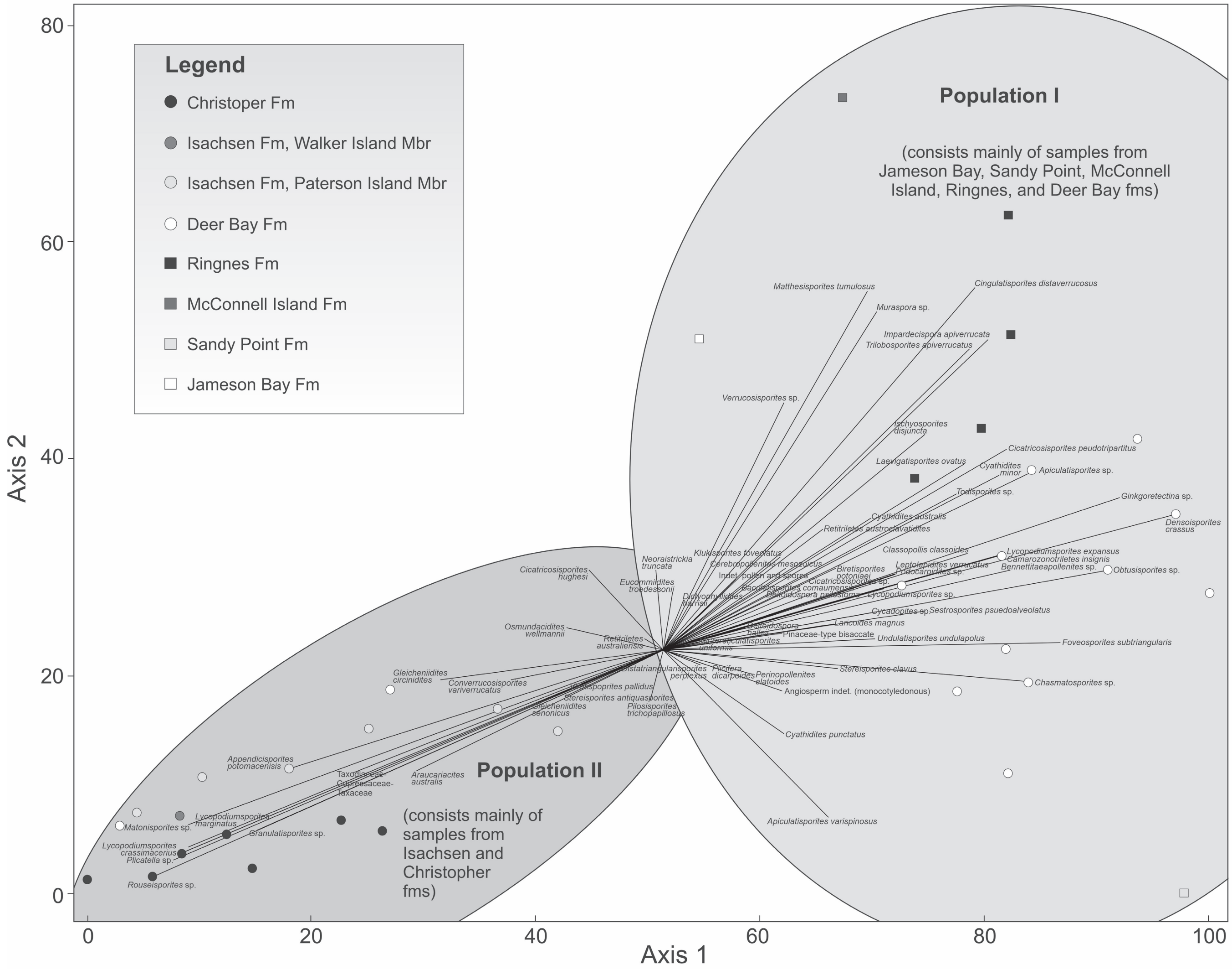


Figure 4. Multidimensional scaling analysis of fossil pollen and spores in Hoodoo Dome (*from* J.M. Galloway et al., 2013).

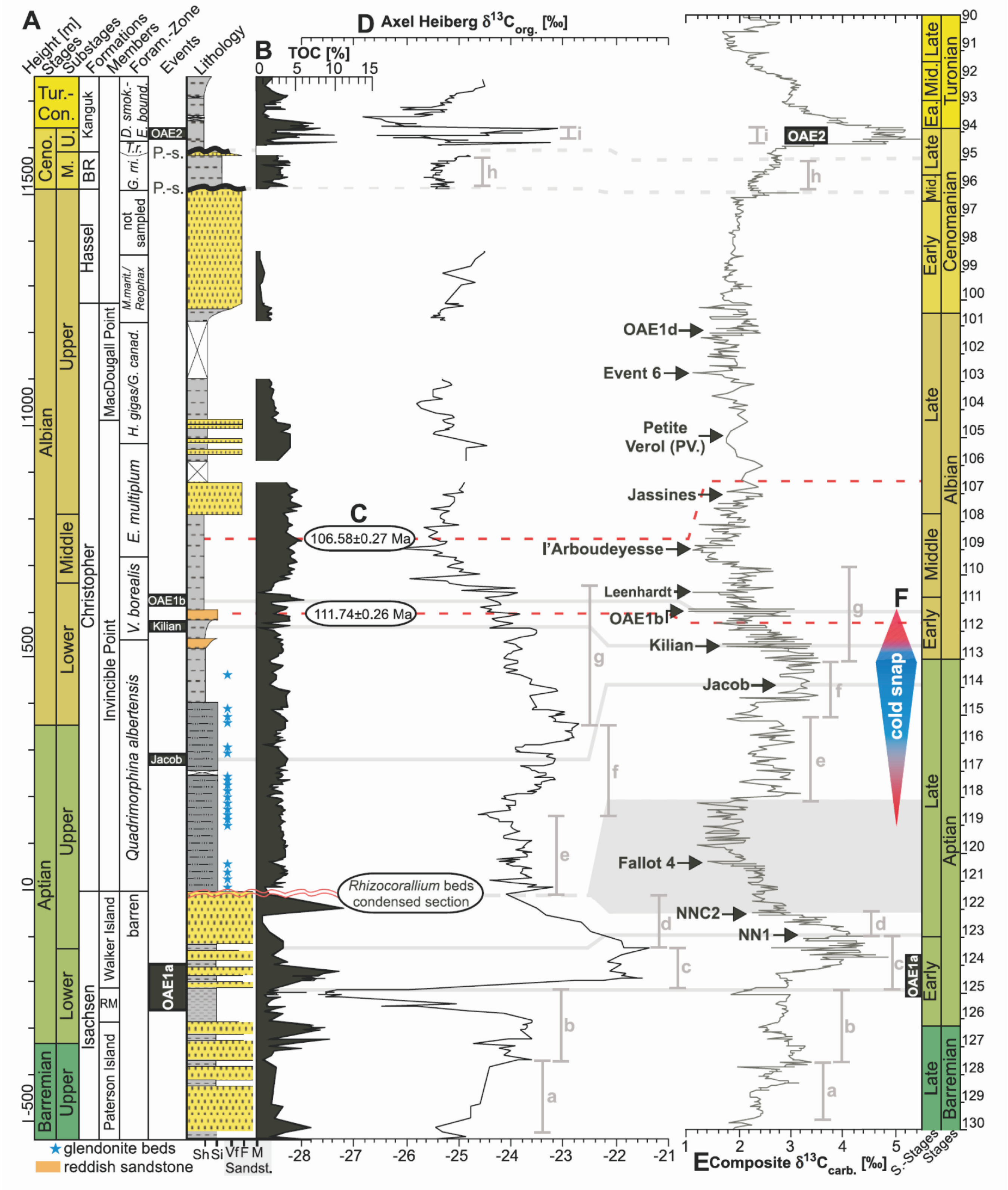

A
Height [m]
Stages
Substages
Formations
Members
Foram.-Zone
Events
Lithology
Tur.-Con.
Ceno.
U.
M.
Albian
Upper
Middle
Lower
Aptian
Upper
Lower
Barremian
Upper
1500
1000
500
0
-500
Kanguk
BR
Hassel
Christopher
MacDougall Point
Invincible Point
Isachsen
Walker Island
RM
Paterson Island
D. smok.-E. bound.
T.r.
G. rri.
not sampled
M.marit./Reophax
H. gigas/G. canad.
E. multiplum
V. borealis
Quadrimorphina albertensis
barren
OAE2
P.-s.
OAE1b
Kilian
Jacob
OAE1a
B
TOC [%]
0
5
10
15
C
106.58±0.27 Ma
111.74±0.26 Ma
Rhizocorallium beds condensed section
D
Axel Heiberg $\delta^{13}C_{org.}$ [‰]
-28
-27
-26
-25
-24
-23
-22
-21
a
b
c
d
e
f
g
h
i
OAE1d
Event 6
Petite Verol (PV.)
Jassines
l'Arboudeyesse
Leenhardt
OAE1b
Kilian
Jacob
Fallot 4
NNC2
NN1
E
Composite $\delta^{13}C_{carb.}$ [‰]
1
2
3
4
5
F
cold snap
S.-Stages
Stages
Turonian
Late
Mid.
Ea.
Cenomanian
Late
Mid
Early
Albian
Late
Middle
Early
Aptian
Late
Early
Barremian
Late
90
91
92
93
94
95
96
97
98
99
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
121
122
123
124
125
126
127
128
129
130
★ glendonite beds
reddish sandstone
Sh
Si
Vf
F
M
Sandst.

Figure 5. Early Cretaceous stratigraphy of Axel Heiberg Island, Nunavut, calibrated using geochronology (figure and caption *from* Herrle et al., 2015). A: Stratigraphy, biostratigraphy, lithostratigraphy, paleoceanographic events, and lithology. B: Total organic carbon (TOC, %). C: U-Pb geochronology ages (red dashed lines indicate absolute age tie points). D: Organic carbon isotopes. E: Carbonate carbon isotope composite age-calibrated curve (*from* Gradstein et al., 2012) and major mid-Cretaceous paleoceanographic events. F: Position of the late Aptian to early Albian cold snap based on TEX_{86} sea-surface temperatures from the Mazagan Plateau, France (*from* McAnena et al., 2013). Correlative intervals based on $\delta^{13}C$ fluctuations are indicated by segments *a–i*. Grey areas and red wavy lines represent condensed intervals (*Rhizocorallium* beds). Black wavy lines represent disconformities (paleosols) of middle and upper Cenomanian. Benthic foraminifera stratigraphy *after* Schröder-Adams et al. (2014). Blue stars show glendonite beds; grey lines represent correlative paleoceanographic events. RM = Rondon Member; BR = Bastion Ridge; OAE = oceanic anoxic event; P.s. = paleosol; Sh = shale; Si = siltstone; Vf = very fine-grained sandstone; F = fine-grained sandstone; M = medium-grained sandstone; *V. borealis* = *Verneuilinoides borealis*; *E. multiplum* = *Evolutinella multiplum*; *H. gigas* = *Haplophragmoides gigas*; *G. canad.* = *Gaudryina canadensis*; *M. mant.* = *Miliammina manitobensis*; *G. iri.* = *Gaudryina irinensis*; *T. r.* = *Trochammina rutherfordi*; *D. smok.* = *Dorothia smokyensis*; *E. bound.* = *Evolutinella boundaryensis*.

paleomagnetic polarity chrons, and timing of magmatic activity in the High Arctic large igneous province (HALIP) were discussed, clarified, and revised in Evenchick et al. (2019).

GLOBAL CLIMATE, LOCAL ENVIRONMENT, AND HYDROCARBON SOURCE ROCKS

A series of GEM papers has shown the impact of mercury and fly ash during the latest Permian extinction event (Grasby et al., 2011, 2015a, b, 2017). These toxic byproducts were released from burning coal as magma from the Siberian large igneous province rose through sedimentary strata (Fig. 7). The discovery of fly ash in the Canadian Arctic was a serendipitous discovery of GEM research, when organic-rich upper Permian rocks were examined for their hydrocarbon source-rock potential.

The GEM field-based studies demonstrated that the Early Triassic was severely nutrient limited due to global hothouse conditions causing a stratified ocean (Fig. 8), which limited source-rock formation. Return to normal temperatures led to high marine productivity and the formation of major circum-Arctic petroleum source rocks (Grasby et al., 2013, 2016).

Palynological analysis revealed a cold snap of late Valanginian age in the Canadian High Arctic that resulted in vegetation composition changes (J.M. Galloway et al., 2015). Analysis results also demonstrated that during the overall Cretaceous warm period, cold snaps affected biological productivity in circum-Arctic regions (Grasby et al., 2017).

HIGH ARCTIC LARGE IGNEOUS PROVINCE (HALIP)

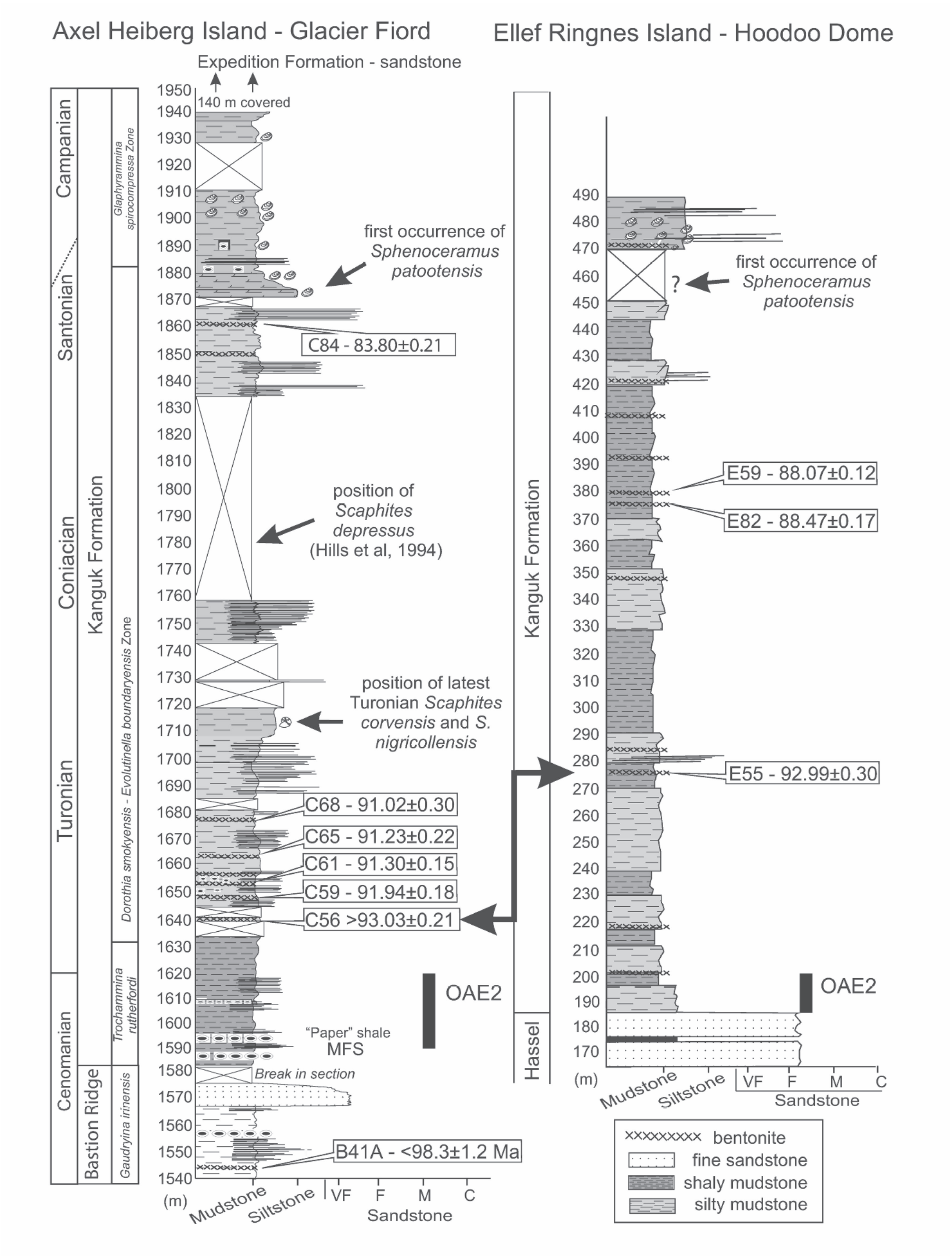
The HALIP was probably initiated ca. 128 to 126 Ma by a plume that arrived after the Arctic Ocean had started to form, with the main initial pulse of magmatism occurring at 124 to 120 Ma (Fig. 9). Results from field mapping identified new volcanic horizons and provided more robust age constraints, which showed that the record of igneous activity in the HALIP was more protracted than previously thought (Evenchick et al., 2015; Herrle et al., 2015). Following the first pulse, magmatism persisted throughout the Late Cretaceous to ca. 80 Ma.

The integration of biostratigraphy and geochronology techniques has allowed fossil horizons to be calibrated in terms of radiometric ages (Herrle et al. 2015; Davis et al., 2017). Igneous geochronology places the magmatic events in time (Evenchick et al., 2015; Dockman et al., 2018). Relating stratigraphic ages and magmatic ages allowed the correlation of events in the sedimentary basin with the magmatic record of HALIP. Examination of this new tectonic framework revealed that the HALIP postdates both rifting and the breakup event, when parts of Russia and Alaska started to drift away from the northwestern Canadian Arctic margin.

ORE AND PETROLEUM SYSTEMS

Many GEM products have important implications for resource potential, from the metallogeny of HALIP rocks (Jowitt et al., 2014; Saumur et al., 2016) to the timing of

Figure 6. Late Cretaceous stratigraphy of Axel Heiberg and Ellef Ringnes islands, calibrated using geochronology (*from* Davis et al., 2017). MFS = maximum flooding surface; OAE = oceanic anoxic event; Vf = very fine-grained sandstone; F = fine-grained sandstone; M = medium-grained sandstone; C = coarse-grained sandstone.


Axel Heiberg Island - Glacier Fiord
Ellef Ringnes Island - Hoodoo Dome
Expedition Formation - sandstone
140 m covered
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Kanguk Formation
Bastion Ridge
Glaphyrammina spirocompressa Zone
Dorothia smokyensis - Evolutinella boundaryensis Zone
Trochammina rutherfordi
Gaudryina irinensis
first occurrence of Sphenoceramus patootensis
C84 - 83.80±0.21
position of Scaphites depressus (Hills et al, 1994)
position of latest Turonian Scaphites corvensis and S. nigricollensis
C68 - 91.02±0.30
C65 - 91.23±0.22
C61 - 91.30±0.15
C59 - 91.94±0.18
C56 >93.03±0.21
OAE2
"Paper" shale MFS
Break in section
B41A - <98.3±1.2 Ma
(m)
Mudstone
Siltstone
VF F M C
Sandstone
1950 1940 1930 1920 1910 1900 1890 1880 1870 1860 1850 1840 1830 1820 1810 1800 1790 1780 1770 1760 1750 1740 1730 1720 1710 1700 1690 1680 1670 1660 1650 1640 1630 1620 1610 1600 1590 1580 1570 1560 1550 1540
Kanguk Formation
Hassel
490 480 470 460 450 440 430 420 410 400 390 380 370 360 350 340 330 320 310 300 290 280 270 260 250 240 230 220 210 200 190 180 170
?
first occurrence of Sphenoceramus patootensis
E59 - 88.07±0.12
E82 - 88.47±0.17
E55 - 92.99±0.30
OAE2
(m)
Mudstone
Siltstone
VF F M C
Sandstone
xxxxxxxxx bentonite
fine sandstone
shaly mudstone
silty mudstone

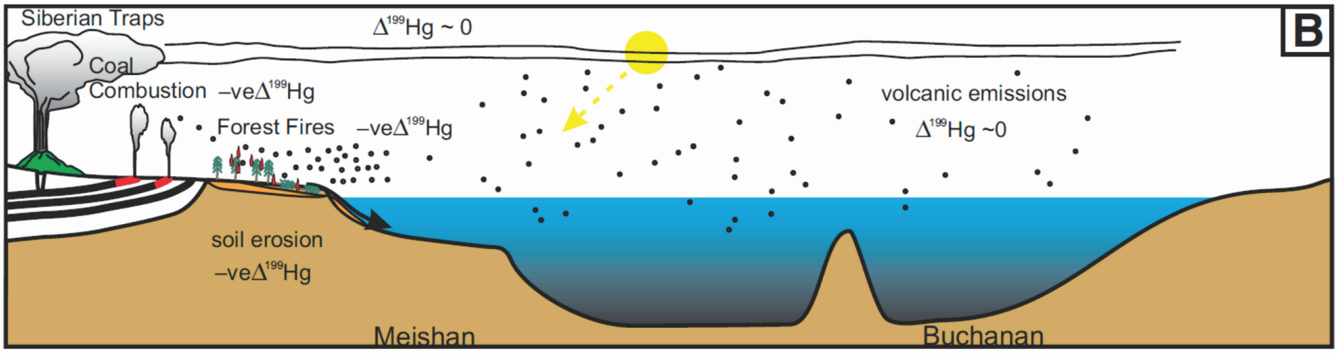


Figure 7. Mercury flux in late Permian marine environments (*from* Grasby et al., 2017). Negative (−ve) and positive (+ve) Δ^{199}Hg source signatures are indicated. Pangea sections: Meishan, China; and Buchanan Lake, Sverdrup Basin, Canadian Arctic Archipelago.

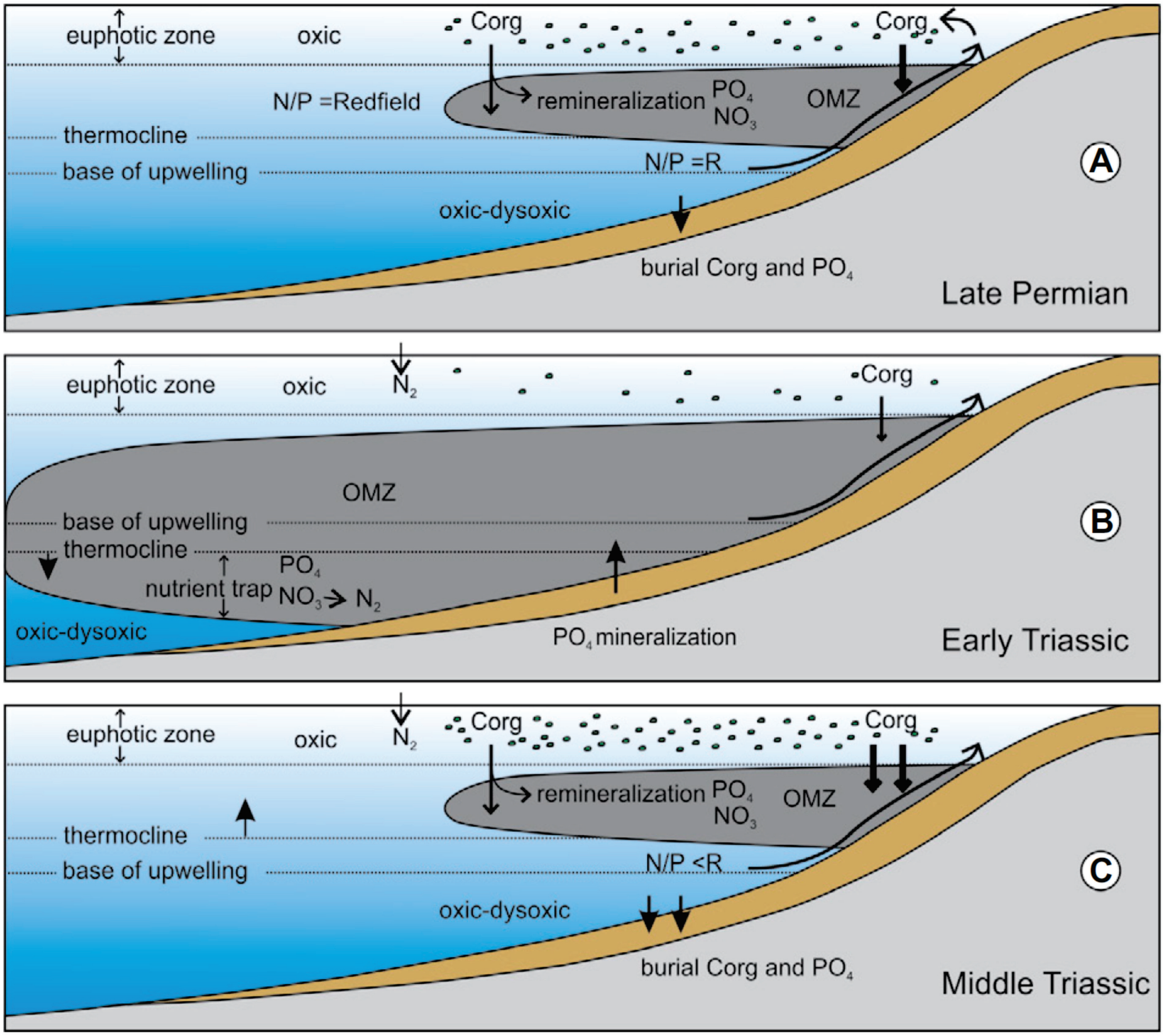


Figure 8. History of upwelling along northwestern margin of Pangea (*from* Grasby et al., 2016). **a)** Late Permian; **b)** Early Triassic; **c)** Middle Triassic. N/P = nitrogen/potassium = Redfield ratio; OMZ = oxygen minimum zone.

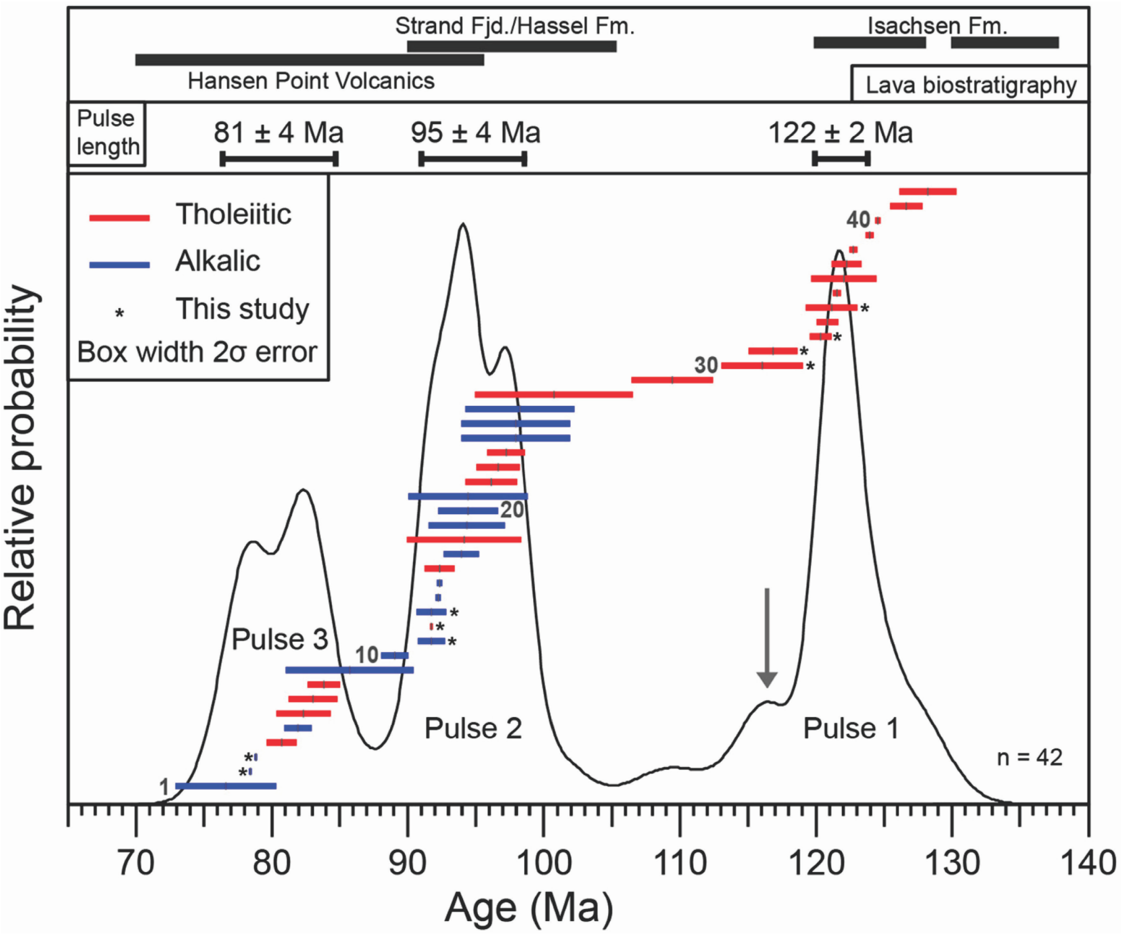


Figure 9. Magmatic pulses of the High Arctic large igneous province (*from* Dockman et al., 2018).

salt movement and formation of hydrocarbon traps (e.g. J.M. Galloway et al., 2013; Dewing et al., 2016a). Some excellent examples of GEM products that are directly related to resource potential are highlighted below.

A basinwide summary of the thermal maturity of the Middle Triassic source-rock interval(s) in the Schei Point Group indicates that Middle Triassic source rocks in the western Sverdrup Basin are in the oil, rather than gas, window (Dewing and Obermajer, 2011). This implies that the large natural gas discoveries in the western Sverdrup Basin had a deeper origin.

Canada's largest conventional natural gas field at Drake Point, on Melville Island, contains 5.3 TCF of gas trapped in an anticline (Fig. 10; Dewing et al., 2016b). New results show that the anticline formed in two phases: the first phase was a previously unrecognized folding event at ca. 100 Ma; the second occurred during the Eurekan Orogeny at ca. 55 Ma. The geochemical characteristics of the gas at Drake Point indicate that the gas migrated from a source rock dominated by type III (terrestrial) kerogen. This implies a source deeper than the Middle Triassic strata, possibly as deep as the Permian van Hauen Formation. If gas was generated from deep source rocks, then many traps in the Sverdrup Basin were not fully assessed during exploration drilling carried out in the 1970s to 1980s.

Examination of the Polaris mine explains the location of the Polaris Zn-Pb deposit in terms of fault reactivation (Reid et al., 2013a). An older (Early Devonian) set of reverse faults was reactivated in Late Devonian time as strike-slip faults (Fig. 11). This created local pull-apart basins that focused fluid flow. This model helps predict areas of highest mineral-exploration potential that may have a similar geological setting.

SUPPORT FOR UNIVERSITY RESEARCH

By supporting research at universities, the GEM program was able to expand the scope of Sverdrup Basin activities by adding external expertise and laboratory capabilities to complement core GSC activities. Professors at various universities led research groups: B. Beauchamp at the University of Calgary (Tullius et al., 2014; Anfinson

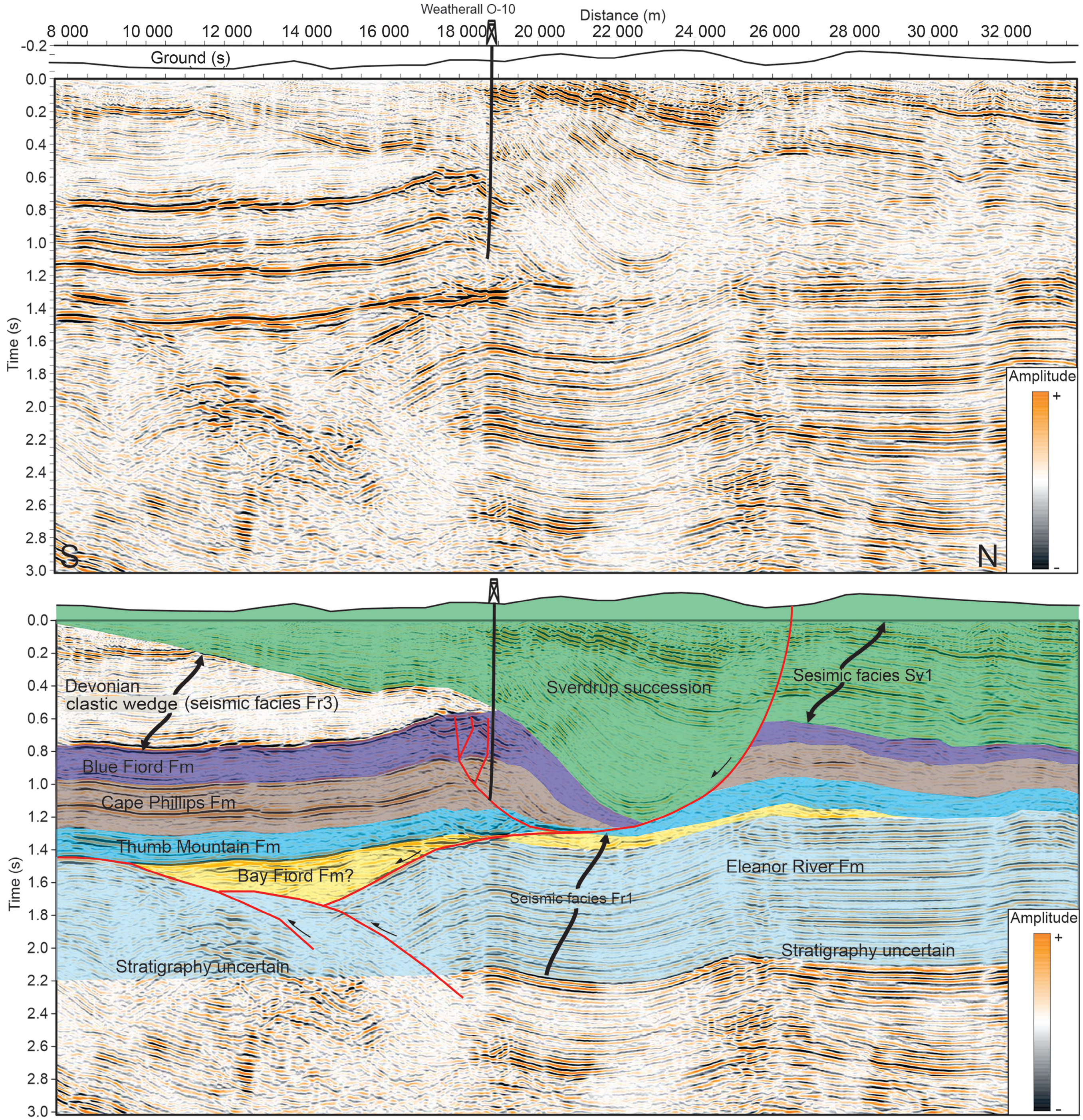


Figure 10. Interpreted seismic section from Melville Island, showing lower Paleozoic rocks below a hanging-wall anticline formed within strata of the Sverdrup Basin (for location and full discussion *see* Dewing et al., 2016b).

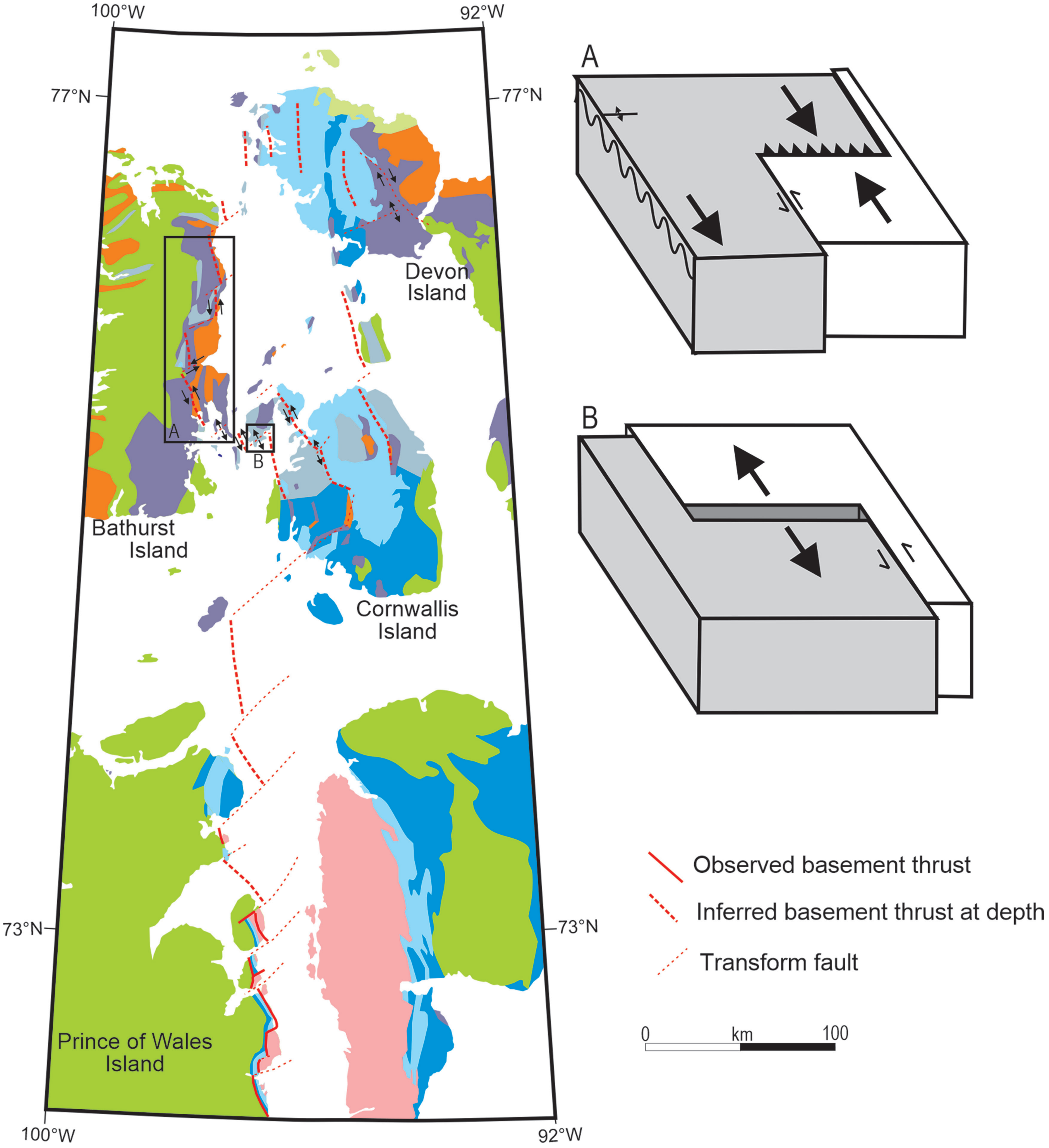


Figure 11. Late Devonian fault motion at Polaris Zn-Pb mine site *from* Reid et al. (2013b). Interpreted trace of leading edge of basement blocks shown as red dashed lines. Basement blocks that step to the west cause compression (block A), whereas those that step to the east cause local pull-apart basins (block B). Locations of blocks A and B are shown by boxes on the map.

et al., 2016; Williscroft et al., 2017; Alonso-Torres et al., 2018; B.J. Galloway et al., 2018; Beauchamp et al., 2019); C.J. Schröder-Adams at Carleton University (Pugh et al., 2014; Schröder-Adams et al., 2014); R.W.C. Arnott at the University of Ottawa (Midwinter et al., 2016, 2017a, b); G. Pearson at the University of Alberta (Dockman et al., 2018); and R. Stephenson at the University of Aberdeen (Stephenson et al., 2013).

INTERNATIONAL COLLABORATION

Formal agreements were negotiated with four international research institutes to support collaborative field-based research related to the Sverdrup Basin. These were the University of Hull (Bond and Grasby, 2017), University of Leeds (e.g. Grasby et al., 2015a, b), Bundesanstalt für Geowissenschaften und Rohstoffe (J.M. Galloway et al., 2018; Piepjohn et al., 2018), and Uppsala University (Deegan et al., 2016).

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APPENDIX A

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