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ABSTRACT

Multibeam bathymetry data collected in Hudson Bay in 2004, 2005, 2007 and 2010 during an ArcticNet cruises onboard the CCGS Amundsen show two sectors characterized by a high density of pockmarks and peculiar ring structures. The first sector is situated in northern Hudson Bay close to Mansel Island and is characterised by a ± 2 km long depression in which pockmarks with an average diameter of 100 m and an average depth of 10 m are present. The second sector is divided into two distinct parts; a northern domain characterized by a significant number of pockmarks and a southern one dominated by abundant circular ring-like features. The ring structures are < 200 m in diameter and 10 m deep and have a central peak. The occurrence of these features could be explained by salt doming that fractured bedrock. The occurrence of the ring structures and the pockmarks within the same area suggests that they might be process-related and that fluid escape may be an important characteristic for both types of morphological features. The very good state of preservation of both the pockmarks and the ring structures and the fact that they attenuate iceberg scours suggest that they have been formed recently (after deglaciation, i.e., after ~8500 years).

INTRODUCTION

The Hudson Platform extends over an area of 600,000 km^2, corresponding to ~6 % of Canada's landmass. The platform represents one of the largest Paleozoic sedimentary basins in Canada of which 2/3 is covered by water (Hamblin, 2008). The Hudson Bay Platform is the least studied intracratonic basin in North America even if it bears geological and morphological similarities with other hydrocarbon-prone intracratonic basins such as the Michigan and Illinois basins. However, the preserved sedimentary succession in the Hudson Bay Platform is significantly thinner than those measured in the two other basins (Lavoie *et al*., 2010a). Sporadic exploration for oil and gas started in 1923, and included a few onshore shallow wells in the 1940's. Beginning in 1966, a series of onshore wells (four majors wells in Manitoba and Ontario) and offshore wells (five wells to a varying depth) were drilled by the industry and several seismic data acquisition programs lead by the oil companies and the federal government were undertaken between 1960 and 1990 (Table 1) (Sanford and Norris, 1973; Procter *et al*., 1984; Sanford and Grant, 1990; Sanford et *al*., 1993; Hamblin, 2008). In 2008, as part of the new NRCan program "Geomapping for Energy and Minerals (GEM)" in the Canadian North, the Geological Survey of Canada launched a 5 year-long project, the "Hydrocarbon potential of the Hudson Bay and Foxe basins", which aims to generate new ideas and models about the hydrocarbon potential of these two regions. The re-evaluation of existing geoscientific data through the lens of modern ideas and theories and the application of new scientific technologies and new data acquisition are currently underway (Nicolas and Lavoie, 2009, 2010; Armstrong and Lavoie, 2010;

Zhang, 2010). One of these new data sets is high resolution multibeam bathymetry information collected onboard the CCGS Amundsen in 2004, 2005, 2007 and 2010 within the framework of the ArcticNet research program. These multibeam bathymetric surveys revealed the presence of circular depressions near Mansel Island and in the central part of the Hudson Bay, the latter area being the site of a well-documented uplift (Eaton and Darbyshire, 2010). Here we report and describe for the first time, pockmarks and ring-like structures on the seafloor of Hudson Bay from the analysis of the multibeam data. These new seafloor images provide valuable information on the geometry of these features and their potential links with major geological structures in the Hudson Bay.

Table 1. Summary of the main offshore and onshore wells within Hudson Bay region

Onshore wells	Location (latitude/longitude:NAD27)	Years	Total length (m)
Kaskattama No.1	57.07181N / 90.17484W	1967	896
Pen Island No.1	56.75194N / 88.75417W	19??	1036
Comeault No.1	56.66666N / 90.83333W	1968	648
Whitebear No.1	57.38333N / 92.46670W	1970	427

Offshore wells	Location (latitude/longitude:NAD27)	Years	Total length (m)
Walrus A-71	58.50056N / 87.18015W	1969	1197
Polar Bear C-11	58.50121N / 86.78847W	1974	1576
Narwhal O-58	58.13327N / 84.13416W	1974	1323
Beluga O-23	59.21501N / 88.55755W	1985	2215
Netsiq N-01	59.84668N / 87.51665W	1985	1040

GENESIS OF POCKMARKS

Pockmarks were first observed on echograms where they appeared as notches or small depressions on the seafloor (King and MacLean, 1970). They were then consistently interpreted as erosional channels or gullies (Hovland *et al.*, 1984; Fleischer *et al.*, 2001; Hovland and Svensen, 2006). The advent of side-scan sonar systems allowed determining the true nature of these depressions. Subsequently, pockmarks were defined as circular or elliptical seafloor features with diameters varying from a few metres to more than 300 m (Hovland *et al.,* 1984). Pockmarks on soft seabed have been known since the 1970's and have been found worldwide in water depths ranging from 30 m to over 3000 m (King and MacLean 1970; Hovland and Judd 1988). These features normally occur where the seafloor consists of sandy to silty clay sediments and they are assumed to be the result of fluids expulsion out of the seabed (Hovland, 1989). A significant volume of the interstitial fluids found within shallow, unconsolidated sediment pore space sconsists of methane either from biogenic-process (microbial decay of organic matter) in relatively shallow sediments (<1000 m) or from thermogenic-process in deep-lying organic matter rich hydrocarbon source rocks (Hovland, 1989); besides methane, water and locally liquid hydrocarbons can also fill the available pore space. According to Hovland (1989), two main mechanisms of fluid migration are possible: 1) fluid can migrate upward through fissures and faults or 2) fluid may also transit through the primary pore-permeability system. In most cases, fluid escape seafloor features have been reported in areas of producing hydrocarbon domains worldwide (Logan *et al.*, 2010). The presences of pockmarks in such environments do not necessarily reflect a large pockmarks distribution, but rather the concentration of them within the areas of geophysical surveys (Hovland *et al.*, 1984; Kelley *et al.*, 1994). In some cases, pockmarks may represent an open-window to petroleum systems and provide indirect evidence for the presence of mature source rocks (Hunt, 1996; Pinet *et al.*, 2008).

GEOLOGICAL SETTING OF HUDSON BAY

The Hudson Bay Platform consists of nearly flat-lying and gently deformed sedimentary rocks of Paleozoic and Mesozoic ages surrounded by Precambrian peneplained metamorphic and intrusive rocks of the Canadian Shield, deformed during the Kenoran and Hudsonian orogenies (Fig. 1) (Norris, 1993; Hamblin, 2008). The Hudson Bay Platform is the erosional remnant of two adjacent cratonic basins the Hudson Bay and the Moose River basins. These basins are divided by a broad northeast-trending structural high, named the Cape Henrietta Maria Arch. The Moose River Basin is located within the southeast part of the Hudson Bay Platform and characterised by a 600-700 m thick sedimentary succession whereas the northwest Hudson Bay Basin presents a ~2500 m thick preserved sedimentary succession (Nelson and Johnson, 1966; Norris, 1993; Hamblin, 2008). The northern limit of Hudson Bay Basin corresponds to the northwest-trending Bell Arch, characterized by a series of fault-bounded basement blocks that separate the Hudson Bay Basin from the smaller Foxe Basin (Lavoie *et al*., 2010). The Foxe Basin is an extensive but shallow Paleozoic basin (~1000 m), deepening to the south into the Southampton subbasin (~2000 m), which contains Mesozoic strata (Sanford, B. D. and Grant, A.C., 1990). Most of the present-day physiographic depression forming the Hudson Bay is located in the Hudson Bay Basin (Henderson, 1990). This basin corresponds to a flat-lying to slightly deformed succession formed mainly by carbonates, with subordinate evaporites and clastics, all of Ordovician, Silurian and Devonian ages (Sanford *et al*., 1968; Norris and Sanford, 1969; Sanford and Norris, 1973, 1975; Heywood and Sanford, 1976; Norris, 1986, 1993). The oldest Paleozoic rocks of the Hudson Platform are carbonates of late Middle Ordovician and Late Ordovician age (Norris, 1986) that overlain thin to locally thick veneers of poorly-sorted coarse-grained clastics that cover the Precambrian basement.

Even if no hydrocarbon discoveries have been made in Hudson Bay, Moose River and Foxe basins, many units present in this region are prospective and analogous to known prolific reservoirs in the

Michigan and Williston Basins (Sanford, 1987; Nicolas and Lavoie, 2009). The Late Ordovician black shales (Boas River, Sixteen Miles formations and correlative units) associated to the Tippecanoe Sequence and the Upper Devonian Long Rapids Formation are both characterized by organic-rich shale intervals (Zhang, 2008, 2010; Armstrong and Lavoie, 2010). These potential source rock intervals are separated by an uppermost Ordovician to Upper Silurian shallow subtidal and reefal carbonates and hydrothermal dolostones that provide exquisite reservoir potential over a large area in the region (Hamblin, 2008; Nicolas and Lavoie, 2009). The potential to form structural traps exists, as gentle regional folding of Ordovician to Devonian platform carbonate reservoirs and reefs as well as salt dissolution features have been documented (Sandford *et al.*, 1993). In the deep centres of Hudson Bay basins, the Paleozoic succession is capped by the Long Rapids shale and overlain by Mesozoic strata, which is dominated by fine-grained deposits and may form good regional seals (Hamblin, 2008).

A variable thickness (e.g., from ~5 to 25 m) (Henderson, 1990) of Quaternary sediments composed primarily by till, fine-grained glaciomarine deposits and postglacial mud deposited mostly during the last glaciation and deglaciation (late Wisconsin) covers the Hudson Bay Basin (Josenhans and Zevenhuizen, 1990). On seismic reflection sections, the surficial deposits are largely acoustically unstratified and occur generally as a thin deposits distributed in isolated patchy accumulations on the Paleozoic-Mesozoic bedrock surface (Henderson, 1990).

DATASETS

Multibeam bathymetry data were collected on board the icebreaker CCGS Amundsen at two sites using a Kongsberg-Simrad EM302 system: 1) off the northern part of Mansel Island, 2) in the central part of Hudson Bay (Fig. 1). Water column velocity measurements were made near the sites using a Conductivity-Temperature-Depth probe (CTD) while sound velocities at the head of the multibeam echosounder were recorded continuously during surveys using a velocity sensor. The recorded sound velocity values were used to calibrate the multibeam sounding data which have been taken from a constant sound velocity value. The nominal frequency of the Kongsberg-Simrad EM302 system is 30 kHz and it has an angular coverage sector of up to 150°. This echosounder consists of 135 beams that can be operated in a water depth ranging from 10 to 5000 m. The data provided an integral image of the seafloor with a relative depth accuracy of 2 to 5 m.

RESULTS

Site 1: North of Mansel Island

An area characterized by seafloor depressions associated with fluid escape features has been identified on multibeam bathymetry data (Fig. 2). Data collected north of Mansel Island show circular depressions generally aligned with an average diameter of 100 m, located at an average depth of 200 m and formed in surficial sediments that consist of a 6 to 20 m-thick sorted sand (Henderson, 1990). Several icebergs scours characterized by deep and long north-south striking segments cross the circular depressions. This site is located over a set of east-west trending normal faults which extend over more than 200 km (Sanford and Grant, 1998). The main fault has an average offset of 125 m on the seafloor is crossed by three minors south-north trending faults (Sanford and Grant, 1998).

Site 2: Central Hudson Bay, north of Polar-Bear C-11 and Narwhal 0-58 wells

Multibeam data collected in July 2010 show a sector characterized by an impressive quantity of pockmarks and ring-like features. As for site 1, these features are located at an average depth of 200 m and surficial sediments consist of mixed diamicton and sandy mud (Henderson, 1990). This area is divided into two distinct sectors: one characterized by a significant number of pockmarks which have an average diameter of 100 m and a depth of 20 m to the north (Fig. 3) and another dominated by a large number of circular features showing a ring-like morphology to the south (fig. 4). These structures are more than 200 m in diameter and up to 10 m in depth and are surrounded by dipping off aprons (Fig. 4). A vintage petroleum industry seismic line shows that the reflection pattern is horizontal on each sides of site 2 and chaotic beneath it (Fig. 5). The northern sector is affected by south-north oriented icebergs scours. Scours also occur in the southern sector, but they appear more subtle on and around the ring structures. Site 2 in central Hudson Bay is proximal to a horst-like uplift bounded by series of NNW oriented normal faults that reach ~500 m in vertical throw that can be followed over 300 km (Fig. 6) (Eaton and Darbyshire, 2010). Sites 1 and 2 are located in areas where Quaternary deposits are thicker than 6 m and topped by a fine-grained layer (Henderson, 1990).

DISCUSSION

Age and morphology of the pockmarks and ring-like features

Pockmarks are usually interpreted to be related to the release of fluids from the subsurface. Some pockmarks are not intersected by iceberg scours suggesting that they were formed after deglaciation which occurred ~7.7 kyr BP (Josenhaus et al., 1990). The Holocene deposits covering these sectors (Henderson, 1990) consist of fine sandy to silty clay layers that are shown elsewhere to provide good seals (Dimitrov and Doncheva, 1992). However, the unconsolidated nature of these layers makes them prone to mechanical erosion such as iceberg scouring (i.e., erosion by the keel of an iceberg) that will likely affect the integrity of the seal and thus allow vertical migration of the fluids trapped beneath it.

The ring-like features are found in a sector where iceberg scours appear to be more subtle on the multibeam data (Fig. 7). This suggests that the icebergs scours were likely slightly altered by the formation of the ring-like structures, therefore predating the latter. According to Dimian *et al.* (1983) similar ring-like features have been discovered by the oil industry in the 1970s and 1980s. They have been associated to biohermal reefs, block faulting and salt dissolution that are frequently observed in other North American hydrocarbon-bearing intra-cratonic basins such as the Michigan and Illinois basins. However, the interpretation made by Dimian et *al.* (1983) most be taken with care since the quality of the vintage seismic data is highly variable in Hudson Bay.

In the northern Ontario portion of the Hudson Bay Platform, Suchy and Stearn (1993) associated >200 m diameter and <10 m high Lower Silurian carbonate structures surrounded by dipping off-reef debris aprons to atoll-like stromatoporoid/coral buildups. These oil-stained patch reefs of the Attawapiskat Formation have been documented on land outcrops (Sanford and Norris, 1973; Hamblin, 2008).

Compared to the well-defined V-shaped pockmarks of the central part of Hudson Bay, pockmarks near Mansel Island are rather U-shaped. The V-shaped pockmarks are most likely indicative of the seafloor stability around their flanks while the U-shaped pockmarks suggest that material slumped from the flanks towards the part central part of the depression, thus changing their profile (Dimitrov and Doncheva, 1992). The co-existence of U-shaped and V-shaped pockmarks on the seafloor also suggests that some have been inactive (U-shaped) for a longer period whereas and others have been active recently or are still active (Dimitrov and Doncheva, 1992). It could also be hypothesized that the preservation of the V-shape of some pockmarks relate to early cementation of the flank sediments. Microbial-mediated carbonate precipitation from methane or higher-hydrocarbons chemosynthesis is a common feature of a large number of pockmarks around the globe (Campbell, 2006; Lavoie et al., 2010b)

Origin of the ring-likes features

The distribution of the pockmarks observed on sites 1 and 2 are correlative with two factors: 1) the type of Quaternary sediments and 2) the presence of underlying geological structures. Indeed, we observed that both studied sites have an average surficial deposits thickness varying from 6 m to 20 m and are situated close to major faults. Bank and barrier deposits of up to 200 m thick completely encircle Hudson Basin and mantle the Central Uplift of Cape Henrietta Maria Arch (Hamblin, 2008).

Different source rocks can be suggested if hydrocarbons are responsible for pockmarks' formation. According to Sanford and Norris (1973), the Lower Silurian patch reefs of the Attawapiskat Formation with known oil shows could be one of the major hydrocarbon reservoir units. The presence of a source rock is a fundamental element in the formation of a fluid escape feature. The Lower Silurian Attawapiskat Formation overlies the Upper Ordovician Bad Cache Rapids, Churchill River and Red Head Rapids Formation which contain thin shales informally named "Boas River shale","Sixteen Mile Brook shale" and correlative shales (Zhang, 2008; 2010; Armstrong and Lavoie, 2010). These organic-rich shales have significant source rock potential. Upper Ordovician shales have been identified within three offshore wells situated in the central part of the Hudson Bay (e.g., Walrus A-71, Polar Bear C-11 and Narwhal O-58), all located near the pockmarks and the ring-like features site (Zhang, 2008).

Salt intervals have been observed within the offshore well Narwhal O-58 between 253 to 287 m and between 340 to 356 m below the subsurface. The first intervals intersect siltstone and shale units whereas the second are more massive with thin stringers of variegated siltstone and dolomitic shale (Tillement *et al.,* 1976). These salt intervals that are associated to assumed Pennsylvanian rocks lie on top of the upper red beds of the Kenogami River Formation (Tillement *et al.,* 1976). The change of reflection pattern in the surrounding area of site 2 from horizontal to chaotic could be indicative of salt (Fig. 5). Chaotic to reflection-free patterns are produced by salt layers and domes because of their high velocity internal structure that greatly attenuates the seismic wavefront (Sangree and Widmier, 1979; Yilmaz, 2001). Considering that halokinesis is strongly dependent on the lithostatic pressure, one can suggests that the Laurentide Ice Sheet (LIS) have played a role in the migration of the salt. The >2-km thick LIS that covered Hudson Bay during the Late Quaternary may have generated an important differential loading on the Hudson Bay platform sedimentary pile that forced the salt to flux upward. The incompressibility of the salt will result in its migration throughout the weakness parts of rocks succession (Hudec and Jackson, 2007). Salt migration is often observed by its typical circular structural morphology of diapirs and chimneys. One of the structural characteristic of a salt diapir proposed by Yin and Groshong (2007) as well as Hudec and Jackson (2007) is a ring-like depression feature with a central peak. The upward migration of the salt body through the sedimentary basin will deform and fracture overlying rock layers. On a cross-section, some structural characteristics associated to salt-induced deformations are similar to the ring-like features observed in the Hudson Bay (Fig. 7). Nevertheless, additional work on ice versus rock density equivalence is required to precise the role of the LIS in the formation of the ring-like features. On the other hand, a more classical explanation to the development of these puzzling features could be that salt migration resulted from lithostatic pressure imposed by the existence of a thicker sedimentary pile during the Late Paleozoic to Mesozoic eras. The maximum thickness of the sedimentary succession recorded in the Hudson Bay basin through its geological history will be addressed during the course of this GEM project. Finally, to assess the role played by the thickness of the salt layer (s) in its migration no matter if it has been triggered either by the LIS or a thicker sedimentary pile, additional information is needed.

CONCLUSIONS

Four main conclusions can be drawn for this study:

1. The presence of fluid escape features or pockmarks at two sites indicates that unknown fluids are actively expelled from beneath the thin Quaternary sediments on the seafloor of Hudson Bay.
2. Icebergs scours could have played a role in the formation of the pockmarks. Holocene shallow subsurface sediments recognized as having good sealing properties have most likely been eroded by the passage of icebergs affecting the integrity of the seal, which then allowed the release of hydrocarbons fluids trapped beneath.
3. The relationship between pockmarks and iceberg scours suggests that these fluid escape features were formed in postglacial times.
4. The presence of ring-like features is puzzling. Without additional subsurface information, their precise origin remains uncertain. Salt-related and reef-related formation mechanisms could be two possibilities. The subtle iceberg scours in the area of ring-like features suggests they were formed after deglaciation.

Modern seismic data over both areas where pockmarks have been documented is essential to better understand the provenance of fluids. Information about the physical relationships between the underlying geology of these sectors and the distribution of fluid escape features could be answered with additional mutltibeam bathymetry and seismic data. Finally, for the area located in the central part of the Hudson Basin (site 2), it would be interesting to map more accurately the lateral extent of the salt intervals and of the Lower Silurian reefs in the Hudson Bay, but again seismic data would be a prerequisite.

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FIGURES

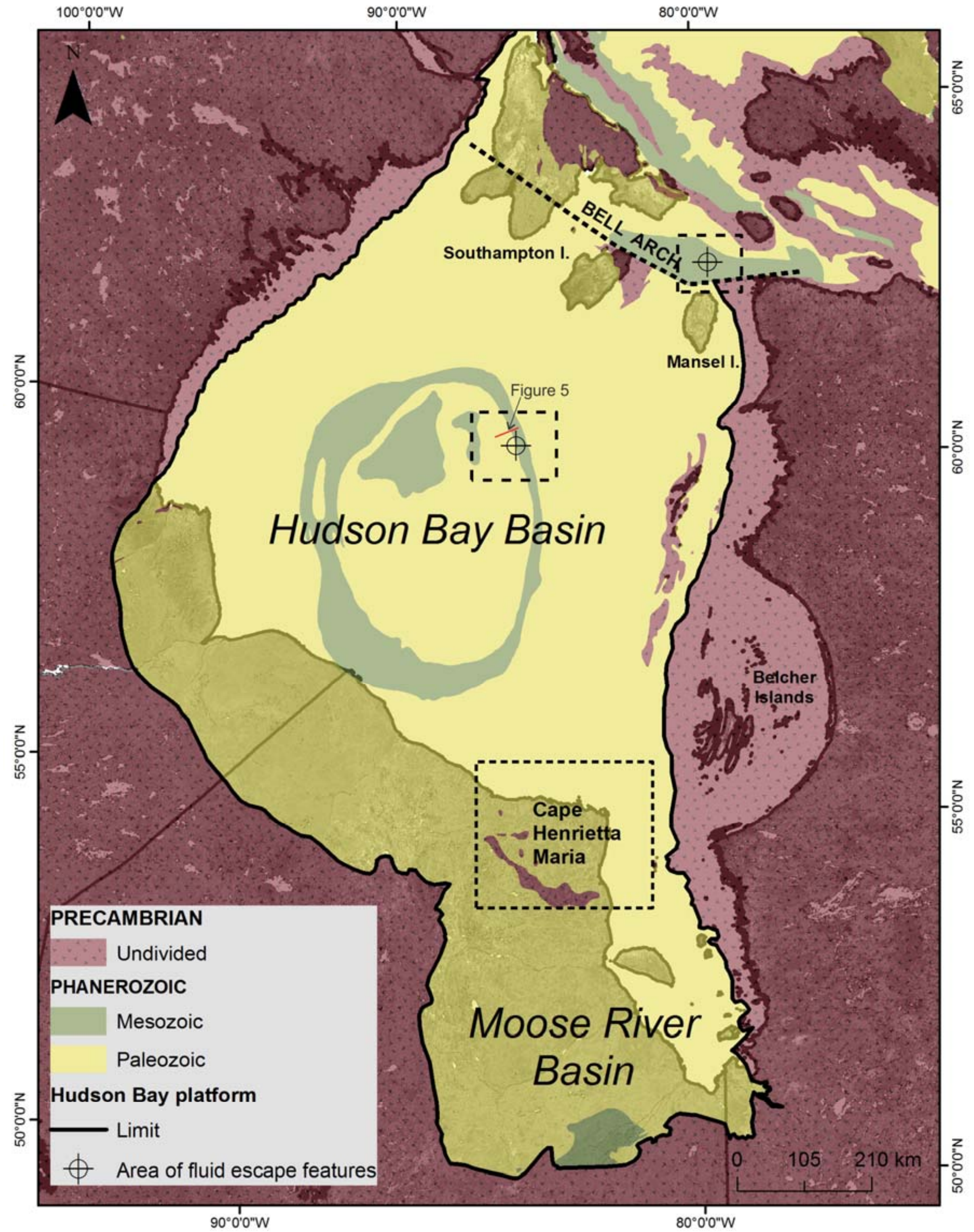

Figure 1. The Hudson Bay platform with the Hudson Bay Basin and the Mooser River Basin separated by the Cape Henrietta Maria Arch. The Hudson Bay Basin is separated from the Foxe Basin by the Arch Bell. Bold dashed-lines boxes locate sites discussed in text.

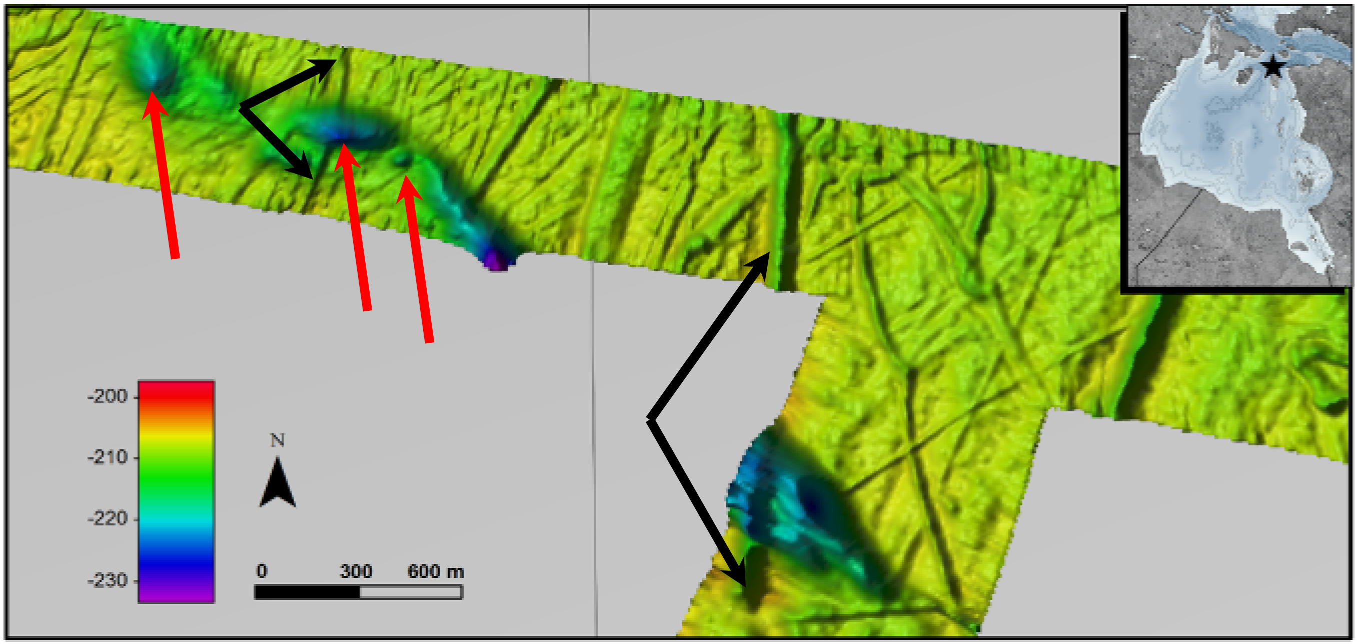

Figure 2. North of Mansel Island site (1) where multibeam data showing circular depressions generally aligned with an average diameter of 100 m, located at an average depth of 200 m. Red arrows show pockmarks whereas black arrows show iceberg scours which cross the pockmarks.

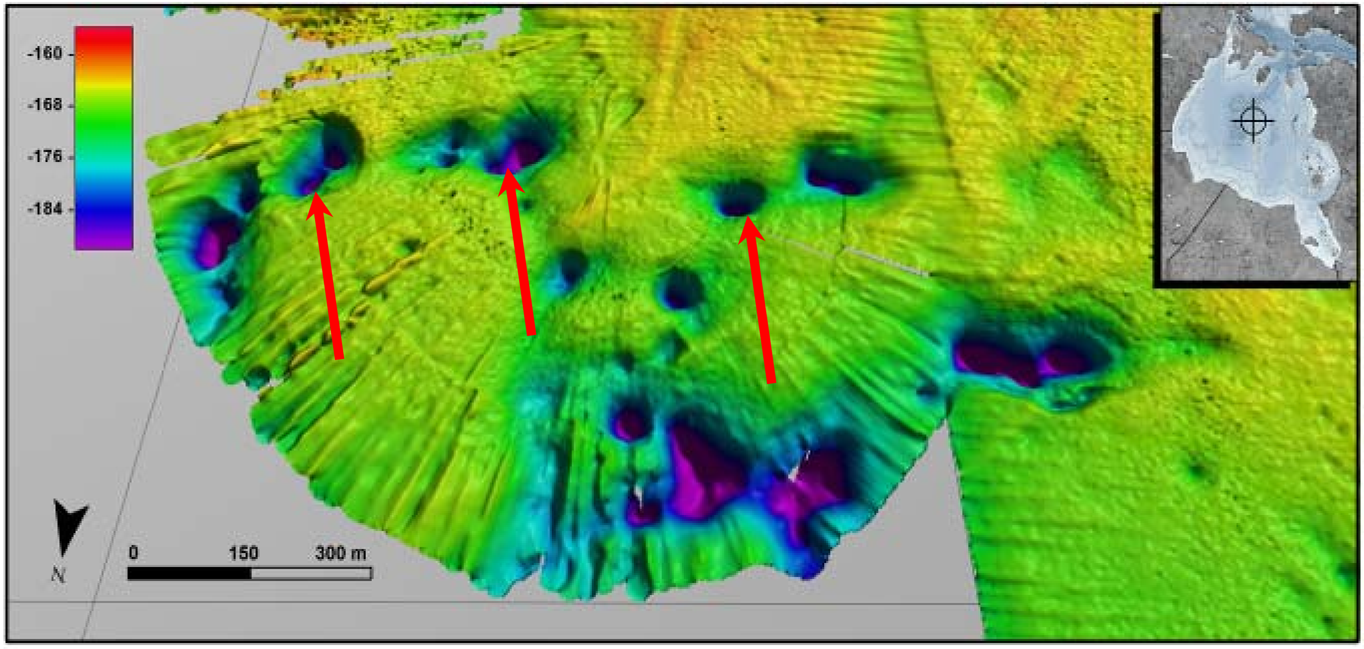

Figure 3. The northern part of the Central Hudson Bay site (2) characterized by many pockmarks which have an average diameter of 75 m and depth of 20 m. Red arrows show pockmarks.

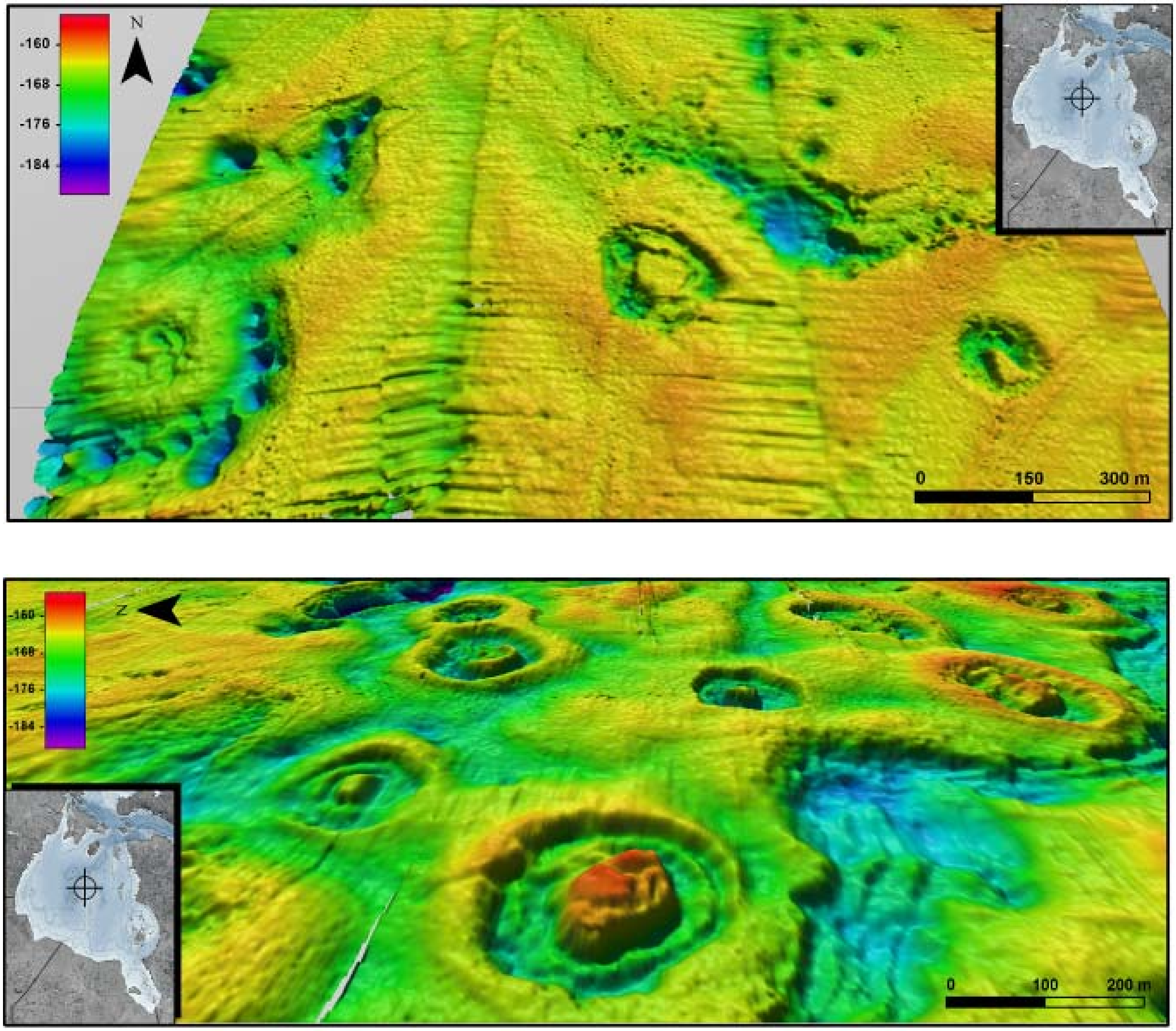

Figure 4. The Southern part of the Central Hudson Bay (site 2) characterized by a large number of ring-like features which are more than 200 m in diameter and up to 10 m high deep and surrounded by dipping off debris aprons.

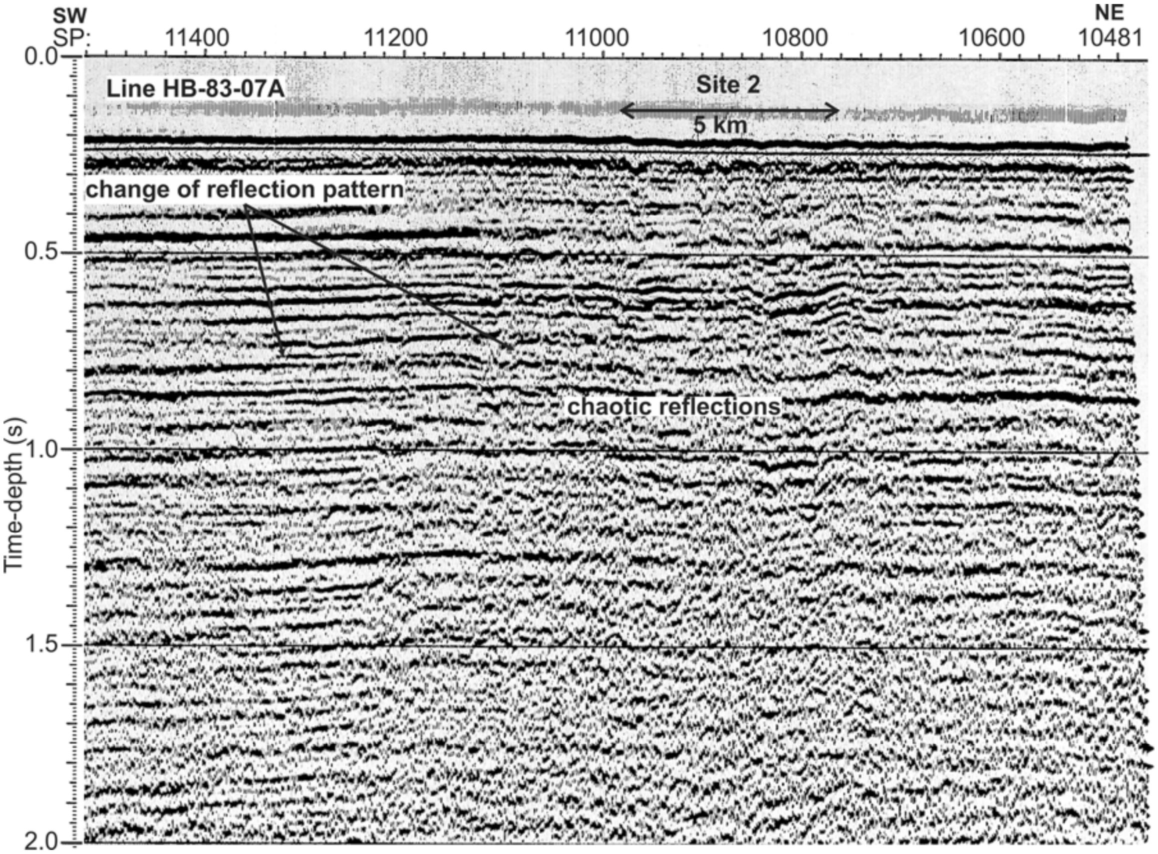

Figure 5. Seismic reflection lineHB-83-07A shot over site 2 for Canadian Occidental Petroleum in 1983. Note the change of reflection pattern beneath site 2. Seismic line is located on Figure 1.

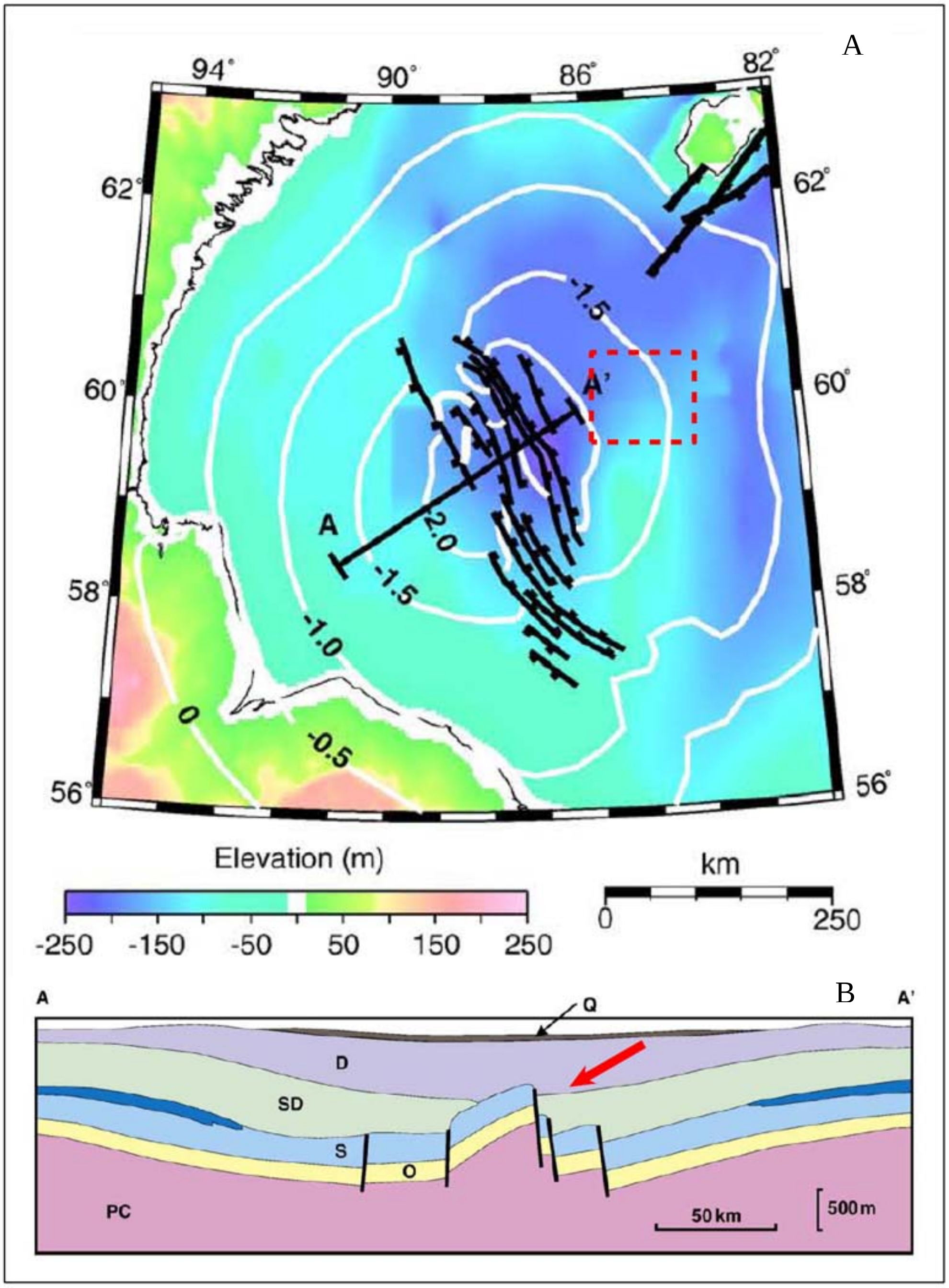

Figure 6. A) Mapped faults in the Central Hudson Bay superimposed on a bathymetry model (from Sanford, 1990 *in* Eaton and Darbyshire, 2010). B) Cross-section A-A' across the centre of the Hudson Bay Basin where the horst-like structure (red arrow) is documented (modified from Eaton and Darbyshire, 2010). PC, O, S, SD, D, and Q denote respectively Precambrian, Ordovician, Silurian, Siluro-Devonian, Devonian, Carboniferous and Quaternary.

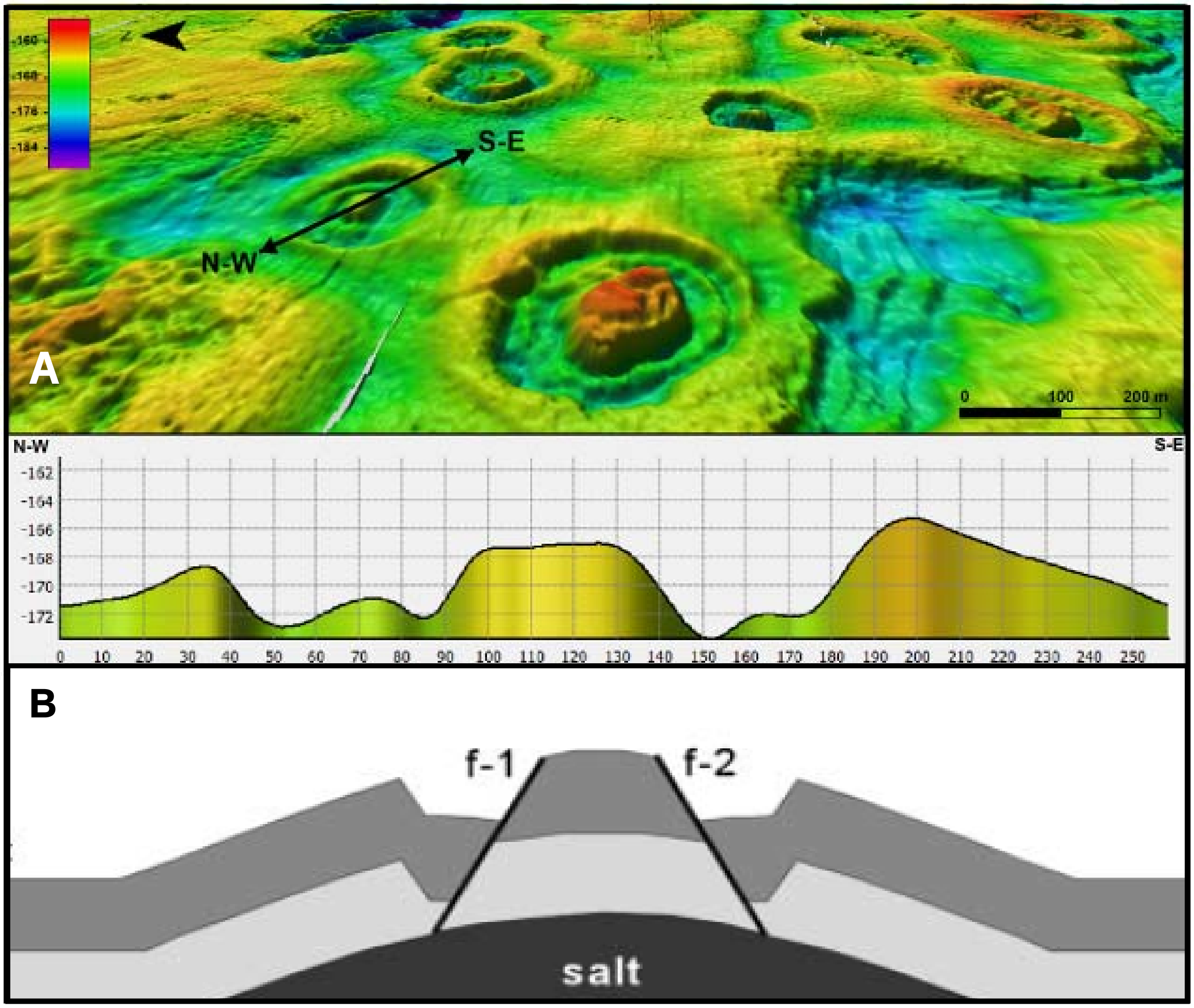

Figure 7. A) Cross-section N-W to S-E across a ring-like feature in the Centre Hudson Bay B) Cross-section perpendicular of the centerline of the flank horst of a salt diapir model dome (modified from Yin and Groshong, 2007)