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Structural and Stratigraphic Controls on Carbonate-Hosted Base Metal Mineralization in the Mesoproterozoic Borden Basin (Nanisivik District), Nunavut

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Abstract

Field mapping of carbonate-hosted base metal showings in the Milne Inlet graben of the Mesoproterozoic Borden basin, Nunavut, has identified the main geologic settings for mineralization in the district that hosts the past-producing Nanisivik deposit. All known showings are associated with faults, fractures, or dikes; these include major, graben-bounding structures with significant displacement, extensive synsedimentary and reactivated intragraben structures, and comparatively minor structures with negligible displacement. These brittle structural features, together with stratigraphic factors and primary lithofacies, control the distribution of base metal showings, and define four main settings for sulfide concentrations. The most volumetrically impressive mineralization (1) for example, Nanisivik orebody, is spatially constrained by erosional highs on an unconformity surface that separates host dolostone and overlying shale; (2) and (3) widespread but volumetrically limited fault- and fracture-controlled showings are spatially associated with intragraben fracture and dike systems—some of these showings (2) are stratigraphically limited to dolostone immediately above shale, whereas others (3) appear to be stratigraphically random and show a close spatial association with structural features; and (4) lithofacies-controlled mineralization that displays replacement textures is present in the immediate vicinity of graben-bounding faults. The most distinctive features of the district are the predominance of structural controls on the spatial distribution of sulfides, the nonplatformal, nonpassive-margin origin of the main dolostone host, the fundamental spatial control imposed by unconformity shape at the most important showings, and association of some highly prospective showings with long-lived crustal-scale faults.

Introduction

THE NANISIVIK deposit was a major (19 million metric tons (Mt) ~10% Zn + Pb) carbonate-hosted Zn-Pb orebody that was mined from 1976 to 2002. It resides in the 50th to 75th percentile of size for known Mississippi-Valley-type (MVT) deposits and is among the 30 largest MVT deposits by combined Zn + Pb (Leach et al., 2005). In spite of decades invested in exploration and production of this orebody, both its age and the geologic controls on its formation remain enigmatic. The Nanisivik ore deposit belongs to a large but virtually unstudied base metal district. Nanisivik has been important in the evolution of models for Mississippi-Valley-type (MVT) mineralization, and so clarifying the geologic constraints on its formation and those of geographically associated sulfide bodies will be a significant contribution to the global understanding of carbonate-hosted ore deposits.

Early models for mineralization at Nanisivik invoked karst-related porosity and void-filling mineral precipitation (Ford, 1981; Olson, 1984; Ghazban and Ford, 1993). This concept was eventually obviated by a model in which trapped hydrocarbon gas reacted with sulfate- and metal-bearing fluids and carbonate host rocks to produce ore by progressive replacement (Arne et al., 1991; Sutherland and Dumka, 1995; Sherlock et al., 2004). The gas-cap model presented a compelling explanation for the unusual morphology of the Nanisivik orebody (a strikingly flat-topped manto) and the rhythmic banding of much of the ore. The nature of the gas- and fluid-trapping feature that dictated the location of the deposit remained ambiguous, however, and so one of the most important criteria in exploration for similar deposits remained poorly understood.

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Base metal (Zn + Pb ± Ag ± Cu) mineralization that may be related to Nanisivik is present throughout the ~300-km-long, northwest-trending Milne Inlet graben, the main structural domain of the unmetamorphosed Mesoproterozoic Borden basin on Baffin Island, Nunavut (Fig. 1). The showings and deposits in the Milne Inlet graben have been known for a hundred years and exploration has taken place intermittently since the 1960s (Clayton and Thorpe, 1982; Sutherland and Dumka, 1995; Sangster, 1998), but the general setting and geologic history of the mineralized rock units at Nanisivik and throughout the district remained poorly defined until recently. Basic descriptions of the regional showings and their stratigraphic and lithologic contexts are either not publicly available or nonexistent, and controls on the localization and driving mechanisms that formed the district's deposits remain unknown. This paper addresses the spatial controls on mineralization in the district and is part of a research program designed to address information gaps in the structural, stratigraphic, diagenetic, and metallogenic evolution of this important yet understudied and underexplored base metal district.

Geologic Setting of the Milne Inlet Graben

Stratigraphy

The Borden basin is one of the putatively aulacogenic ~1.2 Ga Bylot basins of the Canadian high Arctic (Fahrig et al., 1981; Jackson and Iannelli, 1981; Fig. 1). In the Borden basin, known mineralization is hosted by the unmetamorphosed Mesoproterozoic Bylot Supergroup (Fig. 2). This ~6-km-thick succession was deposited in rift grabens (Jackson and Iannelli, 1981) that may have evolved into a distal foreland basin (Sherman et al., 2002). The Borden basin consists of three troughs (Fig. 1). The Milne Inlet graben is both the

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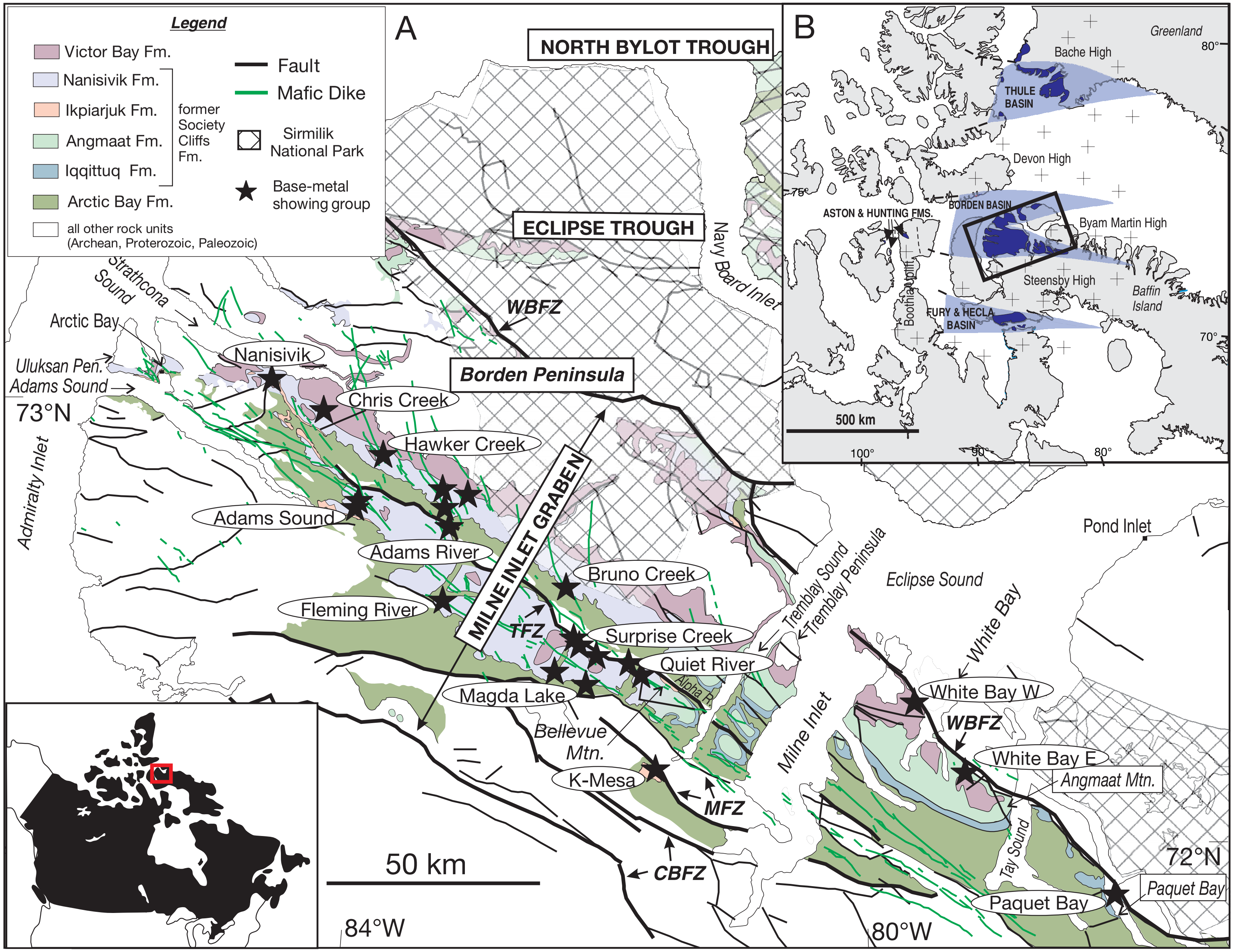

FIG. 1. A. Location map of the Milne Inlet graben and its main base metal showing groups (geology modified after Scott and deKemp, 1998; Turner, 2009). Only the stratigraphic units germane to this study are shown (other Mesoproterozoic units, Paleozoic units, and crystalline basement are in white). CBFZ = Central Baffin fault zone, MFZ = Magda fault zone, TFZ = Tikirarjuaq fault zone, WBFZ = White Bay fault zone. B. Location of the Borden basin among the Mesoproterozoic Bylot basins of Nunavut (after Jackson and Iannelli, 1981; LeCheminant and Heaman, 1989). Dark blue shows present-day exposure; pale blue indicates inferred former basin configuration (after Jackson and Iannelli, 1981). Black rectangle is area depicted in (A).

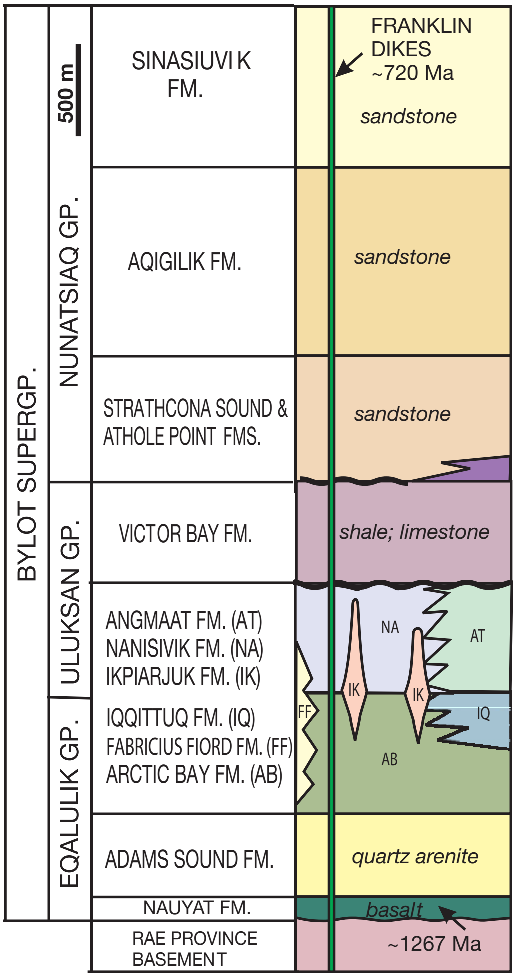

FIG. 2. Stratigraphy of the Bylot Supergroup in the Milne Inlet graben (after Turner, 2009).

largest trough and the only one known to contain massive sulfide deposits and associated showings.

Rifting of the Archean basement gneiss (Rae province) is recorded by the Eqalulik Group, which consists of a basal subaerial tholeiitic basalt (Nauyat Formation), which is correlated with ~1.27 Ga Mackenzie dike swarm and the Coppermine basalt (LeCheminant and Heaman, 1989). The volcanic rocks are overlain by fluvial to shallow-marine quartz arenite of the Adams Sound Formation (Jackson and Iannelli, 1981) and shale of the Arctic Bay Formation. A conformably overlying dolostone has been provisionally dated at ca. 1.2 Ga (Kah et al., 2001, unpub. data). The dolostone was formerly known as the Society Cliffs Formation but has recently been divided into four distinct formation-scale units (Figs. 1-3; Turner, 2009a).

The middle phase of the basin's depositional history is relevant to the later development of sulfide bodies and can be divided into five time intervals (Fig. 4; Turner, 2009a).

1. The lower to middle Arctic Bay Formation represents a westward-deepening shale basin.

2. Development of a carbonate ramp (Iqqittuq Formation) took place after Arctic Bay Formation shale deposition in the southeastern one-third of the Milne Inlet graben. The ramp transitioned northwestward to shale deposited in a coeval deep-water basin (upper part of the Arctic Bay Formation). In this deep-water shale-dominated area, in the vicinity of faults and fractures, local, large, deep-water carbonate mounds (Ikpiarjuk Formation) developed. Mounds are especially well developed in the extreme northwest, near Nanisivik and Arctic Bay, and are exposed as pale, massive, cliff-forming dolostone (Turner, 2009a). Mounds prograded over surrounding, coeval shale on the basin floor, achieved topographic relief well above the surrounding sea floor and have upper surfaces that slope gently away from elongate central zones where mound thicknesses reach >200 m. Mound lithofacies are important because they form much of the thickness of the type section of the former Society Cliffs Formation (as originally established near Arctic Bay; Fig. 5), underlie the orebody at Nanisivik, and, because they were misinterpreted, were a persistent impediment to understanding the range of lithofacies constituting the former Society Cliffs Formation.

3. The platformal Angmaat Formation gradationally overlies the Iqqittuq Formation in the southeastern Milne Inlet graben and is characterized by cyclic subtidal to peritidal facies rimmed by an outboard barrier of tepee-oolite shoals at Tremblay Sound. The Angmaat Formation grades northwestward onto the Borden Peninsula to laterally equivalent, dark-weathering, laminated, deep-water dolostone of the Nanisivik Formation, the host rock of the Nanisivik orebody. This basinal dololaminite facies locally lapped onto and engulfed defunct mounds of the Ikpiarjuk Formation, in most cases erasing the relict topography that mounds had retained from the previous time interval. Some mound flanks, particularly at Nanisivik, are associated with haloes of mound-derived debris that interfinger with Nanisivik Formation laminite and were probably shed erosionally after mound growth had ceased. Some mounds may have remained topographically elevated after laminite deposition and were eventually buried by shale of the overlying Victor Bay Formation.

4. Deposition of the Angmaat and Nanisivik Formations was followed by subaerial exposure of the entire Milne Inlet graben. Erosional topography of at least 200 m is discernible from air photos and from cross sections through the contact, and regional stratigraphic thickness variations suggest that as much as 500 m of Nanisivik Formation dolostone may have been removed in the western end of the graben (Turner, 2009a). Recent work suggests that although the contact is unconformable and exhibits pronounced erosional irregularity, neither exposure-related karst features nor alteration by meteoric water are well developed in the Angmaat or Nanisivik Formations. The unconformity is most readily recognized in the western part of the Milne Inlet graben, where it is the Nanisivik Formation that underlies shale of the Victor Bay Formation. The apparent westward thinning of the Nanisivik Formation and the present-day northeast dip of units below the unconformity suggest that regional uplift and northeast-down rotation of lower Bylot Supergroup strata in the Milne block took place during this exposure interval, with the most pronounced uplift in the northwest. This unconformity records very significant differential uplift (many hundreds of meters) and remains to be adequately explained from a tectonic viewpoint.

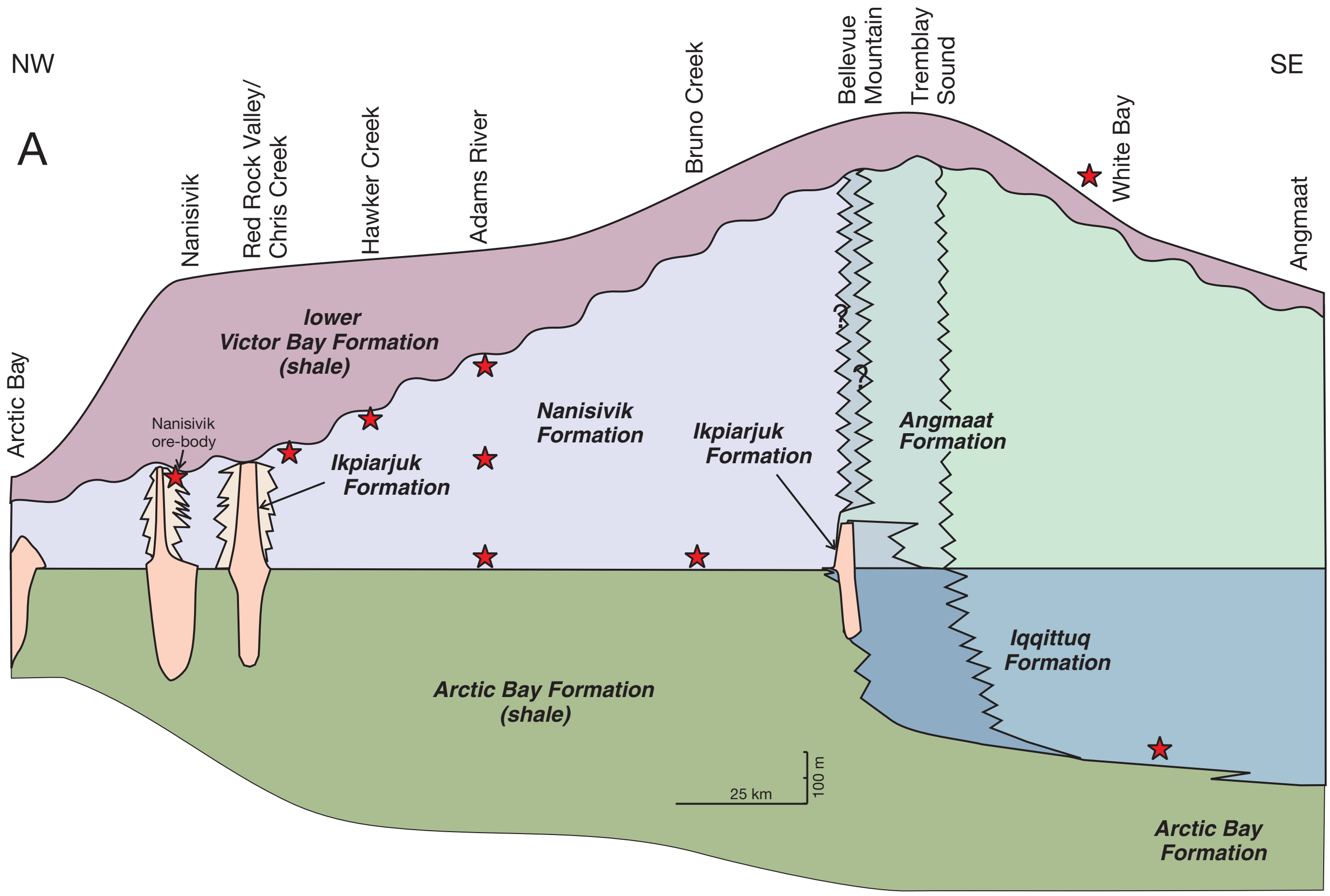

FIG. 3. Northwest-southeast diagrammatic panel showing disposition of four major carbonate units (former Society Cliffs Formation) and associated shale units in the Milne block of the Milne Inlet graben (from Turner, 2009). Red stars diagrammatically show positions of showings and of the Nanisivik orebody.

5. After the erosional hiatus that followed deposition of the Nanisivik and Angmaat Formations, the Milne Inlet graben was rapidly inundated by seawater and the lower Victor Bay Formation (shale) was deposited in deep water. In the Milne Inlet graben, the Victor Bay Formation consists of shale overlain by a southwest-deepening and -thinning carbonate succession that locally contains large stromatolite reefs (Jackson and Iannelli, 1989; Narbonne and James, 1996; Sherman et al., 2001, 2002).

Events late in the deposition of the Victor Bay Formation record a second episode of uplift in the western part of the Milne Inlet graben, which exposed western carbonate rocks of the Victor Bay Formation to subaerial karstification, and simultaneously drowned the eastern end of the Milne Inlet graben, resulting in deposition of the eastern, deep-water Athole Point Formation (Sherman et al., 2002). This event reversed the basin's polarity to eastward deepening and was followed by deposition of locally to distantly derived terrigenous-clastic–dominated strata of the Nunatsiaq Group onto a paleotopographically complex surface (Knight and Jackson, 1994; Sherman et al., 2002).

Mafic dikes of the Franklin swarm (ca. 720 Ma; Heaman et al., 1992; Pehrsson and Buchan, 1999; Denyszyn et al., 2009) intruded along preexisting graben-related fracture systems in the Neoproterozoic (Figs. 1, 2). Most of the structures that host the gabbro dikes show no evidence of fault displacement; they were deep-seated regional fracture systems inherited from the early graben and experienced episodic reactivation and fracture propagation into overlying units.

Marine inundation at the end of the Proterozoic resulted in epicratonic deposition of a comparatively thin succession of terrigenous and carbonate rocks in the Borden basin area, as part of the geographically extensive, long-lived early to mid-Paleozoic Arctic platform and Franklinian basin (e.g., Trettin, 1969). Flat-lying lower Paleozoic rocks angularly overlie the Bylot Supergroup. In the Early to Middle Ordovician, two significant evaporite units were deposited in part of this Paleozoic basin, with a southern limit that way probably 200 km north of the Milne Inlet graben's exposure area. Although the lower to middle Paleozoic succession of the central Arctic Islands is known to contain carbonate-hosted base metal mineralization (Cornwallis district, including the Polaris deposit; Dewing et al., 2007a, b), showings of the Cornwallis district have never been considered to be related to those of the Borden basin. Base metal showings have never been reported from Paleozoic rocks of northern Baffin Island.

Known mineralization in the Milne Inlet graben is hosted almost exclusively by the Mesoproterozoic Nanisivik and

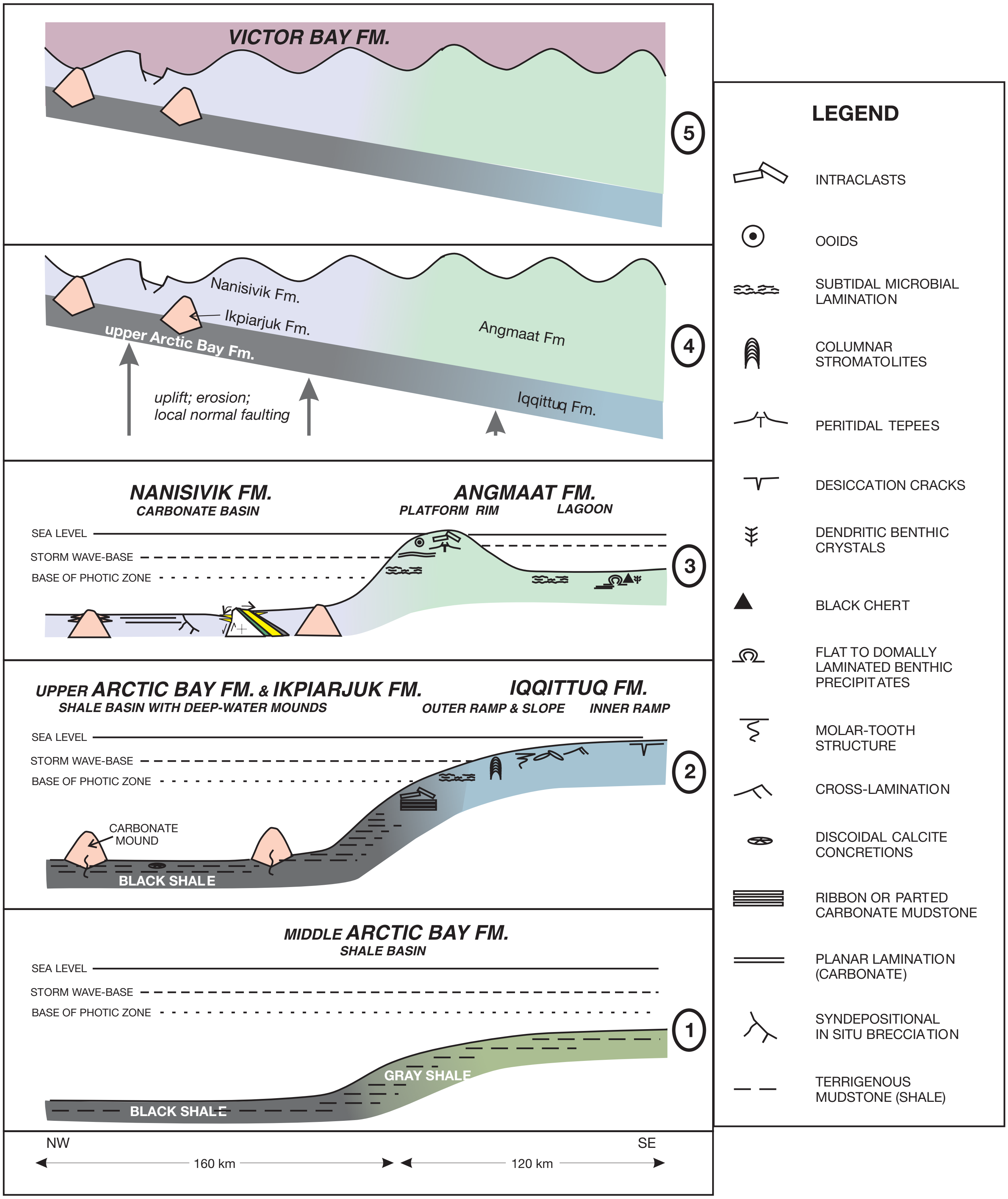

FIG. 4. Stratigraphic, sedimentologic, and structural evolution of the Milne Inlet graben from the Arctic Bay to the Victor Bay Formation. Colors of rock units are as in Figure 2; cross symbol = basement, green = Nauyat Formation, yellow = Adams Sound Formation. Yellow wedges flanking diagrammatic fault in panel 3 indicate localized terrigenous material shed from uplifted fault blocks into deep-water environments of the Nanisivik Formation.

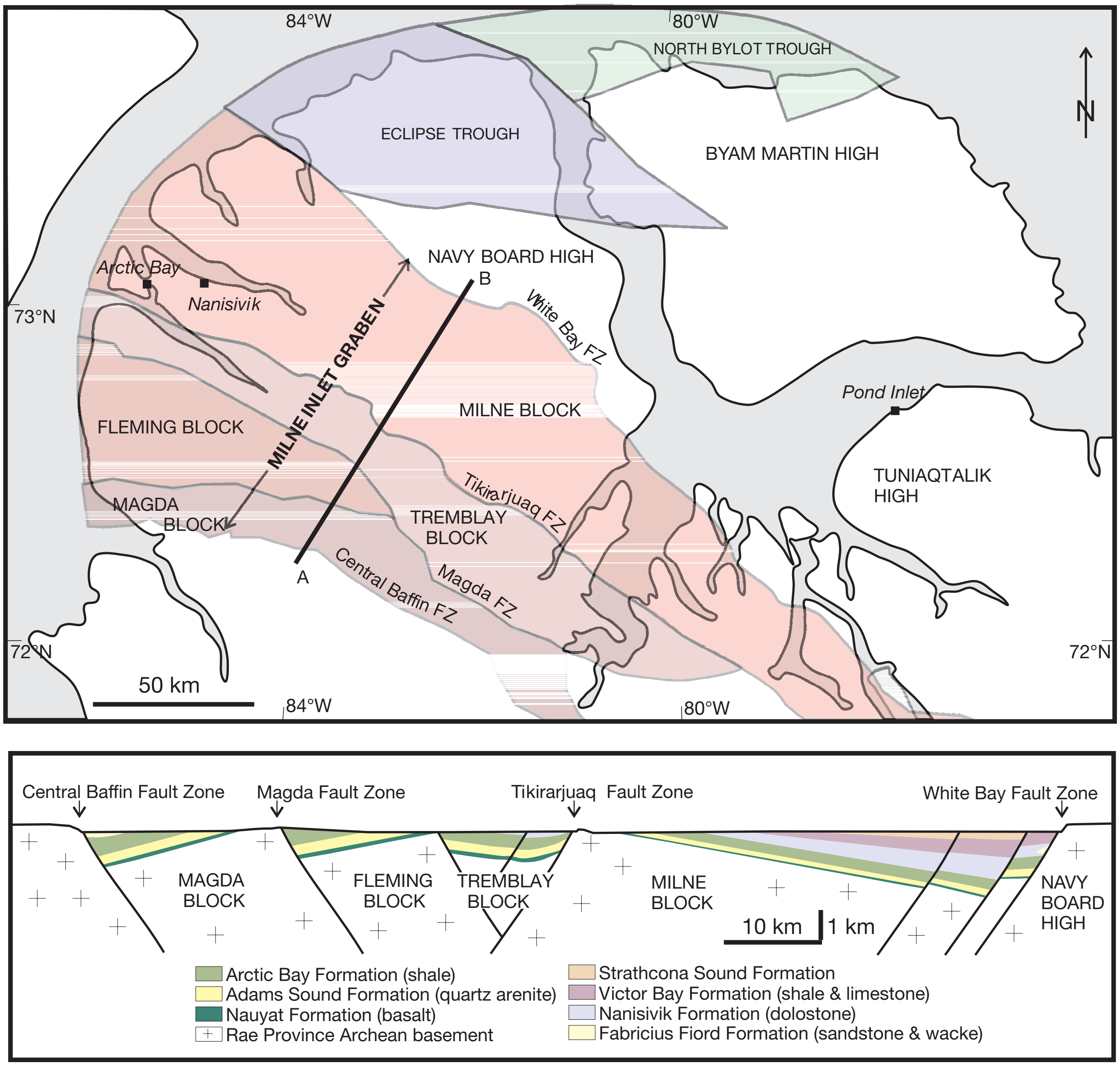

FIG. 5. Structural blocks of the Milne Inlet graben with diagrammatic present-day cross section (modified from Iannelli, 1992). Areas of inferred basement exposure in Mesoproterozoic are shown as gray in map and cross pattern in cross section.

Iqqittuq Formations. The Ikpiarjuk Formation hosts only one minor sulfide showing but locally contains fault-related specular hematite masses that weather to form pink cliff exposures. No showings are known from the Angmaat Formation.

Structure

The Milne Inlet graben is a gently west-plunging trough with an abrupt northern margin and a more gradual southern margin (Fig. 1). The regional structure of the Milne Inlet graben (Jackson and Iannelli, 1981; Scott and deKemp, 1998) is dominated by northwest-trending normal fault systems both at the graben margins and within the graben. These faults accommodated initial rifting as well as continued tectonic activity, strongly affected sedimentary facies distribution throughout Milne Inlet graben history, and were intermittently reactivated during the Phanerozoic (Jackson and Iannelli, 1981). The most recent episode of normal faulting was during the Eurekan orogeny (a contractional event in the Canadian high Arctic but extensional in the southern islands). In view of the repeated reactivation of many of these faults since the Mesoproterozoic, their present-day offsets and kinematic indicators may not bear any relationship to the displacements that were in effect at earlier stages of the graben's history.

The Milne Inlet graben is bounded to the north by the White Bay fault zone, a >200-km-long normal fault that currently exhibits thousands of meters of apparent vertical offset (Figs. 1, 5). The southern margin of the Milne Inlet graben is defined by several long faults with less extreme displacement, of which the southernmost is the Central Borden fault zone. The Tikirarjuaq fault zone runs along the axis of the graben; on the Borden Peninsula, it is marked by a long valley that is occupied by the Alpha and Adams Rivers. Present-day offset of the Tikirarjuaq fault zone is less significant in its distal reaches than in the central and eastern Borden Peninsula, where the fault juxtaposes Nanisivik Formation strata with basement gneiss at several locations (Scott and deKemp, 1998; Fig. 1). Major fracture zones parallel to these faults (and some with more northerly trends) express little to no displacement; some were later filled with gabbro dikes belonging to the Franklin igneous event (ca. 720 Ma; Heaman et al., 1992; Pehrsson and Buchan, 1999; Denyszyn et al., 2009).

The Tikirarjuaq fault zone separates two structural blocks in the central Milne Inlet graben (Iannelli, 1992; Fig. 5). South of the Tikirarjuaq fault zone (Tremblay block) strata are roughly horizontal, whereas north of the Tikirarjuaq fault zone (Milne block), strata below the top of the Nanisivik Formation dip 10° to 15° to the northeast, or to the north in the vicinity of Nanisivik and Arctic Bay (Scott and deKemp, 1998; Fig. 5). This affects the stratigraphic level of rocks exposed at surface. Across most of the Tremblay block, flat-lying Arctic Bay and Nanisivik Formation rocks dominate present-day surface exposure. In the Milne block, strata of these two formations dip and young northeastward to a zone about one-third of the way across the width of the block. Northeast of this zone, exposed strata belong to the Victor Bay Formation and the Nunatsiaq Group and exhibit a roughly flat-lying orientation (Scott and deKemp, 1998; Figs. 1, 5). Along the northeastern margin of the Milne block, close to the White Bay fault zone, layering dips subtly southwestward owing to postdepositional drag-folding. Outliers of Victor Bay Formation shale are present across the Tremblay block and south of the main dolostone-shale contact in the Milne block. These mark areas where valleys in the post-Nanisivik Formation unconformity surface were later filled with Victor Bay Formation shale (Fig. 1).

Both the Central Borden and White Bay fault zones were active during deposition of the Arctic Bay and Iqqittuq Formations, shedding terrigenous material at the graben's margins (locally mapped as the Fabricius Fiord Formation; Scott and deKemp, 1998). The graben-bounding and main intragraben faults were the loci of deep-water mound development during deposition of shale of the upper Arctic Bay Formation (Turner, 2009a). The Tikirarjuaq and Magda fault zones appear to have been subtly active during deposition of the basal Nanisivik Formation in the central Borden Peninsula, as indicated by laterally restricted tongues (tens of meters to <1 km in fault-parallel lateral extent; centimeters to meters thick; Turner, 2003, 2009a) of coarse, angular siliciclastic debris interlayered with basinal dolostone (Fig. 4, panel 3). Wedges of such terrigenous material are present in laminite overlying a mound flank in at least one location (near the head of Adams Sound), suggesting that locally, the Tikirarjuaq fault zone was active both during deposition of upper Arctic Bay Formation shale (and contemporaneous Ikpiarjuk Formation mounds) and again later, during deposition of Nanisivik Formation dololaminite. Very localized shedding of angular, compositionally immature material implies nearby (probably subaqueous) exposure of basement, suggesting up to hundreds of meters of fault offset on intragraben structures at or near the beginning of Nanisivik Formation deposition (Fig. 4, panel 3). Terrigenous material has not been noted in the Nanisivik Formation in the Nanisivik area.

The general northwest trend of major structures in the Milne Inlet graben changes to west-trending in the extreme northwest. Maps show a greater density of faults in this area (e.g., Scott and deKemp, 1998; Patterson et al., 2003), although this may be in part because Nanisivik has received more mapping and exploration attention than other parts of the Milne Inlet graben. The present work shows that at least some of the inferred faults in previous maps of the Nanisivik area are unnecessary: they were interpretive structures that were invoked to explain irregularities in the level of the Nanisivik-Victor Bay contact. Such irregularities are now known to be a function of the undulatory shape of the unconformity surface between the two formations (Turner, 2009a).

Documenting the structural features that contribute to mineralization in the Milne Inlet graben is difficult. Although sea-cliffs expose in situ strata along coasts, and major faults are locally marked by cliffs, much of the inland area underlain by Nanisivik, Iqqittuq, and Angmaat Formation dolostone consists of boulder fields of frost-heaved, locally derived material with very sparse outcrop. Many faults and fractures are signalled only by a subtle lineament. Correlation within the Nanisivik Formation laminite is impossible owing to the complete lack of regional or even local marker units, or stratigraphic trends; the only distinctive, nonlaminite units interlayered with the basinal dolostone are fault-related terrigenous wedges and resedimented deep-water dolostone units of extremely restricted lateral extent, and thick, generally unbedded, laterally restricted homogeneous debrites of mound-derived material. Gathering reliable structural data from in situ exposures is complicated by the effects of primary and secondary modifications: syndepositional brecciation randomly tilted blocks of all sizes, and later dissolution by the migration of basinal fluids caused void formation and associated settling and adjustment of loosened blocks, particularly in the upper part of the formation in areas of known mineralization. These factors resulted in chaotic structural orientations in the Nanisivik Formation, even though the regional dip is clear from map patterns. Although property-scale mapping has suggested the presence of folds in areas some distance from major faults (e.g., Patterson et al., 2003, which proposed north-trending folds at Nanisivik), this interpretation is not supported by any of the original mapping of the basin (as depicted by Scott and deKemp, 1998), the purported folds lack systematic spacing (Patterson et al., 2003), and with the exception of fault-related folds (e.g., Jackson and Cumming, 1981) putative folds are not documented beyond the immediate vicinity of Nanisivik. Identification of proposed, subtle, north-trending structures at Nanisivik (Patterson et al., 2003) was based not on structural measurements of bedding, but primarily on the exposure pattern of the Nanisivik-Victor Bay contact.

Age of mineralization at Nanisivik

The age of the orebody at Nanisivik is controversial, with suggestions ranging from Mesoproterozoic to Ordovician.

Olson (1984) provided a Pb-Pb model age of 800 to 600 Ma for galena. Fluid inclusion leachates of sphalerite yielded apparent Rb-Sr isochrons indicating an age of ~1100 Ma (Christensen et al., 1993). A paleomagnetic study of inferred, mineralization-related recrystallization of host dolostone yielded an age of 1095±10 Ma (Symons et al., 2000).

In contrast to these Proterozoic ages, Sherlock et al. (2004) presented an Ar-Ar date of 461 ±2 Ma (Ordovician) for altered material at the contact of ore and dike rock at Nanisivik; the material dated was interpreted as dike rock that had been altered by emplacement of the orebody. Tectonic or thermal events significant enough to drive the movement of great volumes of fluid are not known to have affected the Milne Inlet graben since the Mesoproterozoic, and the area experienced no major tectonic activity in the Ordovician. Laurentia was, however, in a low-latitude, arid zone throughout the Ordovician, and two successive evaporite basins [Baumann Fiord Formation (Lower Ordovician) and Bay Fiord Formation (Middle Ordovician)] developed ~200 km north of Nanisivik and may have been associated with deep-crustal brine convection. The depositional age of the Bay Fiord Formation (e.g., Harrison, 1995; Mayr et al., 1998) may coincide with the Ordovician alteration age provided by Sherlock et al. (2004). The nature of the dated mid-Ordovician alteration event remains enigmatic.

In contradiction to the young mineralization interpretation of Sherlock et al. (2004), fluid inclusion work of McNaughton and Smith (1986) and Arne et al. (1991) indicated that temperatures increased markedly in the vicinity of the mine dike, thereby indicating that the fluid inclusions had been reset (i.e., stretched) during dike emplacement. Unpublished observations indicate that decrepitated and negative-shaped fluid inclusions are present near the contact with the mine dike, which is consistent with their reequilibration owing to contact metamorphism (Arne, pers. commun., 2010). Together, these fluid inclusion data present a compelling reason to reconsider the conclusions of Sherlock et al. (2004) regarding the timing of mineralization at Nanisivik. Field relationships described in the present work also argue for a mineralization age that predates emplacement of the mine dike and the regional dike swarm, which is presumed to be ~720 Ma based on regional correlation (Heaman et al. 1992; Pehrsson and Buchan 1999; Denyszyn et al. 2009). A Proterozoic age for the Zn-Pb mineralization at Nanisivik, and possibly throughout the Milne Inlet graben, would represent an unusual data point in the distribution of carbonate-hosted Zn-Pb deposits through geologic time (Leach et al., 2010).

In summary, although paleomagnetic and Rb-Sr data are in reasonable agreement for a Mesoproterozoic mineralization age, and field relationships presented in this paper argue strongly for basin-wide mineralization that predates emplacement of the Franklin dikes, numerous attempts to date the ore-forming event at Nanisivik have failed to yield an age that can be directly linked to the ore-forming event. The age of the ore at Nanisivik and throughout the Borden basin remains uncertain.

Methods

This field-based study is founded on detailed stratigraphic data (Turner, 2009a) that facilitated new property-scale mapping and reanalysis of previous results. All information for this study was gathered on foot-traverses from a two-person backpacking-type camp that was moved intermittently by helicopter. Selected locations of known mineralization in the Milne Inlet graben (Sangster, 1998) were documented and new occurrences discovered. To date, approximately 25 known showings or showing groups have been documented in the Milne Inlet graben and are incorporated into the models presented here.

Spatial Controls on Mineralization in the Milne Inlet Graben

A modern understanding of the stratigraphy and evolution of the Milne Inlet graben during deposition of the dolostone host rocks (Turner, 2009a) means that structural, stratigraphic, and lithologic controls on mineralization are now more readily identified. The geologic settings for base metal mineralization form four partly overlapping categories (Fig. 6; Table 1). The presence of a fault or fracture is essential; stratigraphic and lithofacies controls are also important. Massively replacive, fracture-hosted, and fabric-selective replacement sulfides are all represented somewhere in the graben (Table 1). The relative proportions of metal species present (Zn, Pb, Cu, Fe) vary with showing type.

Type 1—unconformity ± structural trap

The orebody at Nanisivik is a horizontally elongate mass approximately 3 km long, 130 to 200 m wide, and 10 to 20 m thick, underlain by a network of mineralized fractures. Classically replacive and compositionally banded textures resulting from progressive, cyclic dissolution and replacement are common (Arne and Kissin, 1989; Arne et al., 1991; Fig. 7A, B). Depositional temperature was <130°C (D. Kontak, pers. commun., 2011). Sulfur isotope data from ore sulfides ($\delta^{34}S$ = 27.4–28.2‰ CDT; Arne et al., 1991) suggest that sulfur was derived from bedded evaporites ($\delta^{34}S$ = 22–32‰ VCDT; Kah et al., 2001) elsewhere in the basin [e.g., locations in Jackson and Cumming (1981) and Kah et al. (2001)]. Evaporite minerals or evidence of their former presence are not present in the host-rock unit (Nanisivik Formation).

The main orebody at Nanisivik is in a west-trending horst of Nanisivik Formation dolostone flanked to the north and south by Victor Bay Formation shale (Clayton and Thorpe, 1982; Arne et al., 1991; Sutherland and Dumka, 1995; Figs. 8–10). The upper surface of the orebody is strikingly flat, deviating in present-day elevation by no more than 3 m over the ~3-km length of the orebody, and crosscutting the gently north-dipping layering of the host rock (Sutherland and Dumka, 1995); sulfides are absent above this level (Clayton and Thorpe, 1982; Sherlock et al., 2004). The top of the orebody is more than 100 m below the inferred position of the unconformable contact with overlying Victor Bay Formation shale (now eroded). This geometry has been taken as strong evidence that the orebody was emplaced (1) after tilting of the host rock to its present-day dip of 10° to 20°, and (2) in the presence of a fluctuating, horizontal interface between metalliferous brine and trapped hydrocarbon gas (presumably CH_4; Arne et al., 1991) that promoted precipitation of ore sulfides that progressively replaced carbonate rocks ("gas-cap model"; Ghazban et al., 1990; Arne et al., 1991; Sutherland and Dumka, 1995; Sherlock et al., 2004).

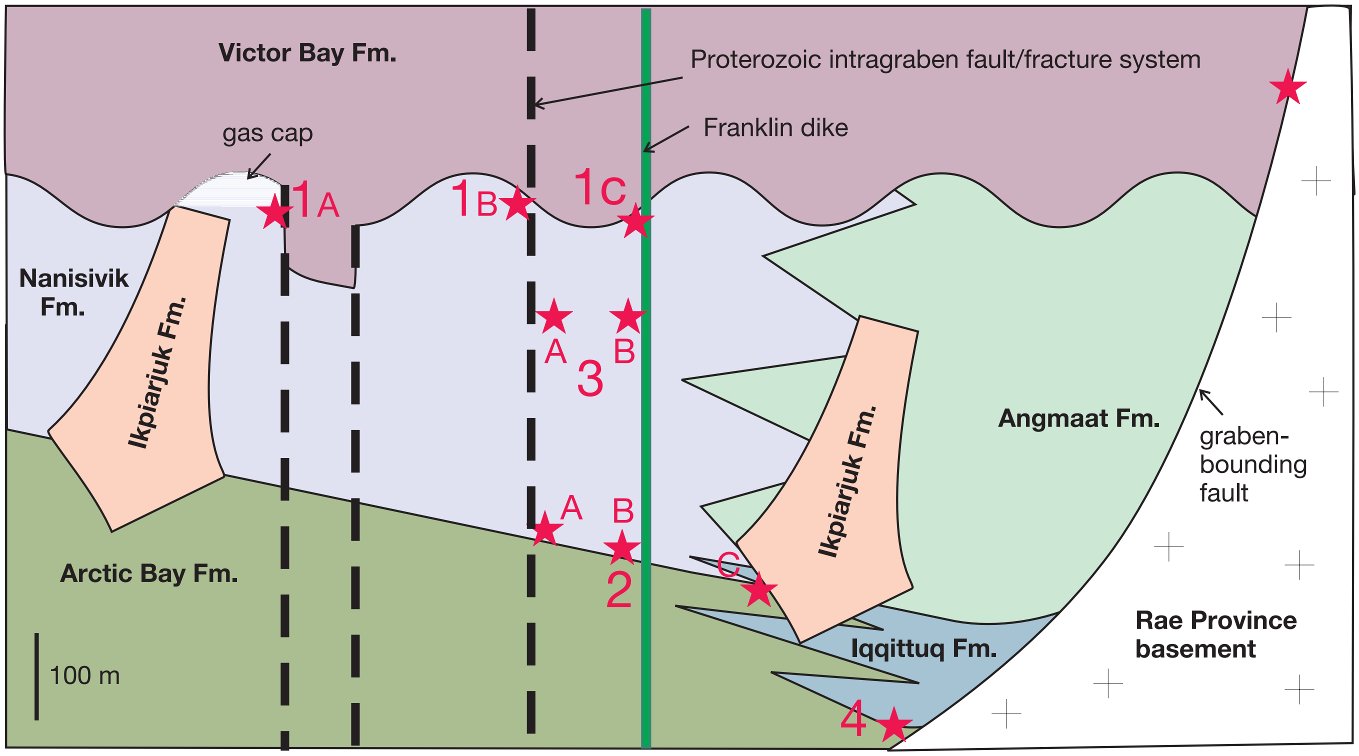

FIG. 6. Schematic summary of the four main structural-stratigraphic settings of known Zn-Pb ± Cu showings in the Milne Inlet graben, with extreme vertical exaggeration. Vertical scale bar is approximate; horizontal view spans length of Milne Inlet graben. For descriptions and examples of showing types, see text and Table 1.

Clayton and Thorpe (1982) noted that the position of the contact between the Nanisivik and Victor Bay Formations is highly variable in the Nanisivik area, and that the thickness of the Victor Bay Formation shale varies markedly (20–200 m; Sherman et al., 2002). This important phenomenon was attributed by Clayton and Thorpe (1982) to faulting that postdated Nanisivik Formation deposition but predated deposition of the Victor Bay Formation shale, but this important concept was not incorporated into the understanding of the ore deposit.

In the Nanisivik area, the Victor Bay Formation has been divided into lower (shale), middle [shale interlayered with carbonate slope deposits (intraclast rudstone)], and upper (intraclast rudstone) units (Patterson et al., 2003). Lower Victor Bay Formation shale overlies the unconformity with Nanisivik Formation dolostone at lower present-day topographic elevations, whereas middle Victor Bay Formation (shale with intercalated limestone layers) does so at higher topographic elevations (Figs. 8–10).

Conspicuous topographic lineaments are associated with the west-trending normal faults that characterize the Nanisivik area. Faults have commonly been invoked to explain the seemingly unpredictable distribution of the Nanisivik Formation-Victor Bay Formation contact at the present-day land surface (e.g., Clayton and Thorpe, 1982; Arne et al., 1991; Patterson and Powis, 2002; Patterson et al., 2003). Although most of the west-trending faults in previous maps are undeniably real, many of the faults with other orientations appear to be interpretive. Pronounced topographic lineaments are also associated with the northwest-trending dike system (Figs. 8–10).

Clayton and Thorpe (1982) proposed that the configuration of the Nanisivik Formation-Victor Bay Formation contact in the vicinity of Nanisivik depicts an "elongated dome tilted slightly to the north" over the Nanisivik property. This suggestion led to the assumption that areas where the Nanisivik Formation-Victor Bay Formation is north trending should be considered as the expression of north-trending folds (Patterson et al., 2003; Sherlock et al., 2004). Maps and cross sections through the area, however, show no hint of systematic folding in the undulations of the dolostone-shale contact, and structural measurements show no systematic patterns in the Nanisivik Formation either at Nanisivik or elsewhere across the Borden Peninsula. Folding is, in fact, entirely absent from the Milne Inlet graben except in the immediate vicinity of major faults (drag folds) and carbonate mounds (compactional folding). Because the Nanisivik Formation-Victor Bay Formation contact was widely assumed to be conformable, the possibility of significant irregularity along this interface was not contemplated, and the importance of the unconformity surface's shape on the distribution of sulfide bodies was not recognized. Although major west-trending faults in the immediate vicinity of the orebody are clearly present, many of the other interpretive faults that were based on surface exposure are not necessary if the contact can be conceptualized as a surface that was originally nonplanar.

Remapping and reinterpretation of the Nanisivik area based on a combination of field data, Landsat images, air photos, and previous maps yields an updated view of the geologic history of the area and of controls on the location of the Nanisivik orebody (Figs. 8–11). Dolostone-floored grabens north

TABLE 1. Locations, Controls, and Attributes of Known Mineralization in the Milne Inlet Graben

Showing name	Type	Host	Dike	Fault/fracture	Minerals	Style	UTM zone; x/y	Showing no. (Sangster, 1998)
Nanisivik	1A	Upper Nanisivik Fm.	x	Keystone fault	py, sph, gal	Replacive (non-fabric-selective)	16; 581500/8106500	1
Chris Creek	1A	Upper Nanisivik Fm.	-	(unnamed)	py, sph, gal	Replacive (non-fabric-selective); fracture-hosted	17; 403520/8100495	4
Hawker Creek	1	Upper Nanisivik Fm.	x	-	py, sph, gal	Replacive (non-fabric-selective); fracture-hosted	17; 418200/8088741	7
Adams Sound Zn	3A	Nanisivik Fm.	-	(lineament)	smithsonite	Fracture-hosted	17; 410990/8077180	–
Adams Sound Cu	3B	Nanisivik Fm.	x	-	mal, cpy	Fracture-hosted	17; 410750/8079070	–
Fleming River	2B	Nanisivik Fm.	x	-	sph, fluor	Fracture-hosted	17; 431690/8054670	14
Adams River C	2B	Lower Nanisivik Fm.	x	-	gal	Fracture-hosted	17; 432530/8075975	10
Adams River S	2B	Lower Nanisivik Fm.	x	TFZ	gal	Fracture-hosted	17; 430695/8073725	13
Adams River NW	3B	Nanisivik Fm.	x	-	sph, gal	Fracture-hosted	17; 430855/808175	9
Adams River NE	1C	Upper Nanisivik Fm.	x	-	sph, gal, fluor	Fracture-hosted	17; 444090/8075700	12
Bruno Creek	2B	Lower Nanisivik Fm.	x	-	sph, py, gal	Fracture-hosted	17; 461275/8057985	18
Surprise Creek N	3 or 1	Nanisivik Fm.	-	TFZ	gal, cpy, sph, ba	Fracture-hosted	17; 462705/8046525	20
Surprise Creek W	1B	Nanisivik Fm.	-	TFZ subsidiary	gal, ba, py, mal	Fracture-hosted	17; 462645/8046010	–
Surprise Creek C	1 or 3	Nanisivik Fm.	-	TFZ subsidiary	gal, mal, ba	Fracture-hosted	17; 463350/8044990	108
Surprise Creek E	1 or 3	Upper Nanisivik Fm.	x	TFZ subsidiary	gal, mal, ba	Fracture-hosted	17; 467945/8042340	21
Magda E	2B	Lower Nanisivik Fm.	x	MFZ	sph, py, gal	Fracture-hosted	17; 463040/8035255	24
Magda C	2B	Lower Nanisivik Fm.	x	MFZ	gal, fluor, sph	Fracture-hosted	17; 458895/8039117	23
Quiet River N	2A	Nanisivik Fm.	-	TFZ	gal, py, fluor	Fracture-hosted	17; 478190/8040215	27
Quiet River S	2B	Nanisivik Fm.	x	-	gal, fluor, sph	Fracture-hosted	17; 478945/8036914	26
K-Mesa 1	2C	Ikpiarjuk Fm.	-	MFZ	mal, gal	Fracture-hosted	17; 483175/8014890	50
K-Mesa 2	2C	Iqqittuq Fm.	-	MFZ	sph	Fracture-hosted	17; 479350/8016570	–
White Bay W		Upper Victor Bay Fm.	-	WBFZ	mc	Unknown	17; 545670/8031680	29
White Bay E	4	Iqqittuq Fm.	-	WBFZ	sph, gal	Replacive (fabric-selective)	17; 557840/8014000	32
Paquet Bay	4	Iqqittuq Fm.	-	WBFZ	sph, py, gal	Replacive (fabric-selective) and fracture-hosted	17; 593520/7983915	39

Abbreviations: MFZ = Magda fault zone, TFZ = Tikirarjuaq fault zone, WBFZ = White Bay fault zone; ba = barite, cpy = chalcopyrite, fluor = fluorite, gal = galena, mal = malachite, mc = microcline, py = pyrite, sph = sphalerite; - = not applicable

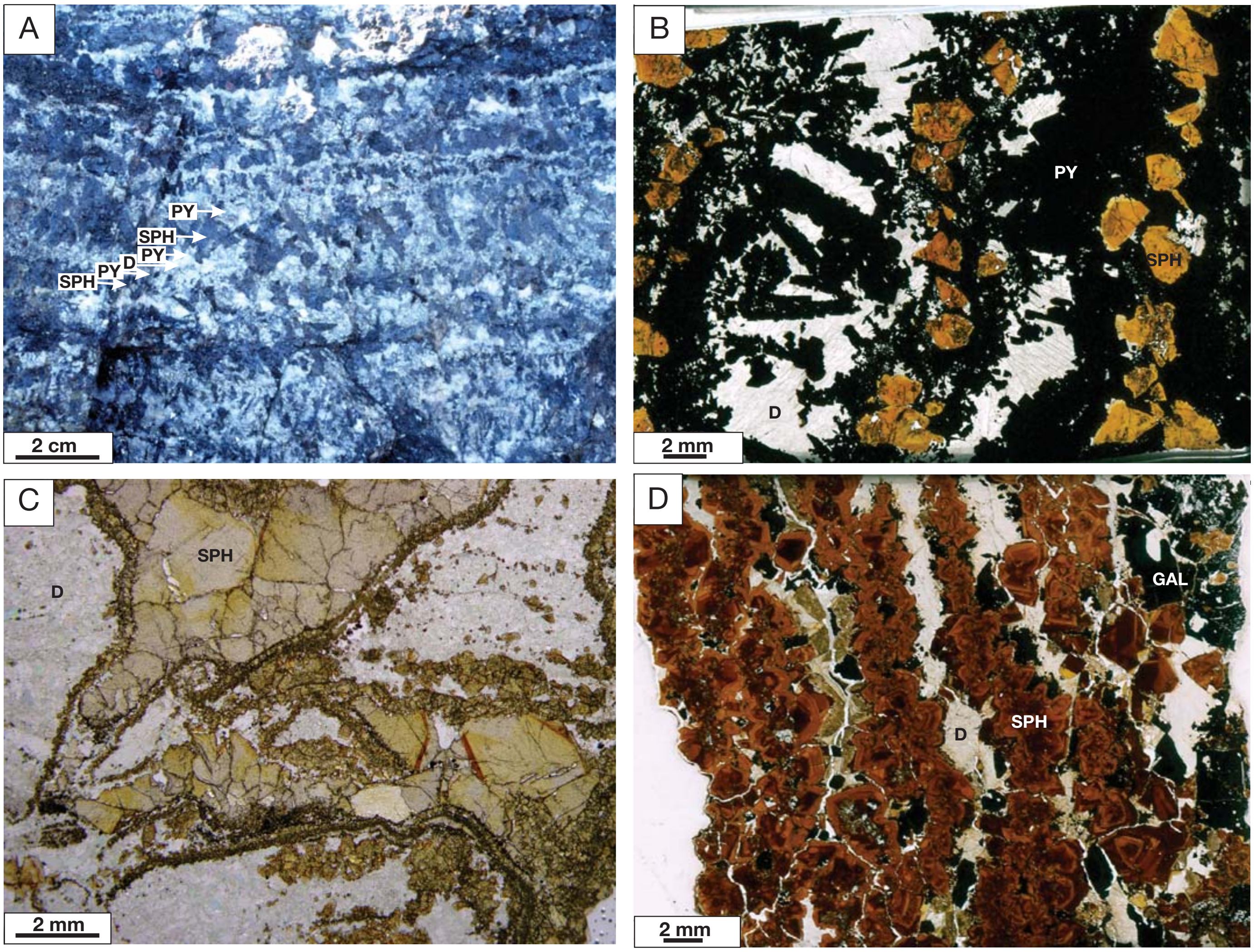

FIG. 7. Mineralization in type 1 settings. (A) Outcrop and (B) thin section (plane-polarized light) views of ore from Nanisivik (Ocean View pit) forming dissolution-replacement bands of dolomite, sphalerite, pyrite, and galena. (C). Void-filling and minor replacive sphalerite from fracture system in the Nanisivik Formation from hillside above pyrite body at Chris Creek (thin section in plane light). (D). Banded ore from Hawker Creek (thin section in plane light). D = dolomite, GAL = galena, PY = pyrite, SPH = sphalerite.

and south of the main horst formed late during the exposure interval that postdated Nanisivik Formation deposition, locally abruptly truncating and vertically offsetting hills and valleys that had developed on top of the Nanisivik Formation during subaerial exposure. The erosional and structural lows were later filled by lower Victor Bay Formation shale during rapid, regional marine inundation. By the time of deposition of the middle Victor Bay Formation, only paleotopographically high parts of the unconformity remained uncovered, and in such areas, the succession above the unconformity begins with middle Victor Bay strata. This sequence of events is the most parsimonious way to explain extreme local variability in the thickness of lower Victor Bay Formation shale (Clayton and Thorpe, 1982; Sherman et al., 2002), and the fact that the shale is entirely missing at contacts that would have been paleotopographically highest after the exposure interval (Figs. 8, 10).

The depositionally shale-flanked and -capped horst that now contains the orebody would have formed a combined structural and stratigraphic trap in north-south cross section (Fig. 10A); this configuration has long been known, although it was erroneously attributed to faulting that postdated shale deposition (e.g., Arne et al., 1991). Although the dolostone-shale contact has also been postdepositionally displaced by minor movement along some faults in the vicinity of the orebody (e.g., Fig. 10A), the sulfide bodies are not significantly displaced across faults (Clayton and Thorpe, 1982), indicating that their emplacement postdated most fault movement. The present work shows that most fault movement took place during the hiatus between deposition of the Nanisivik Formation and that of the Victor Bay Formation, although evidence of minor, later fault reactivation is indisputable.

The nature of the feature that trapped the inferred gas and mineralizing fluids in a west-east direction can now be addressed with a new understanding of the morphology of the Nanisivik Formation-Victor Bay Formation contact. In west-east, roughly strike-parallel cross section (Fig. 10B), the

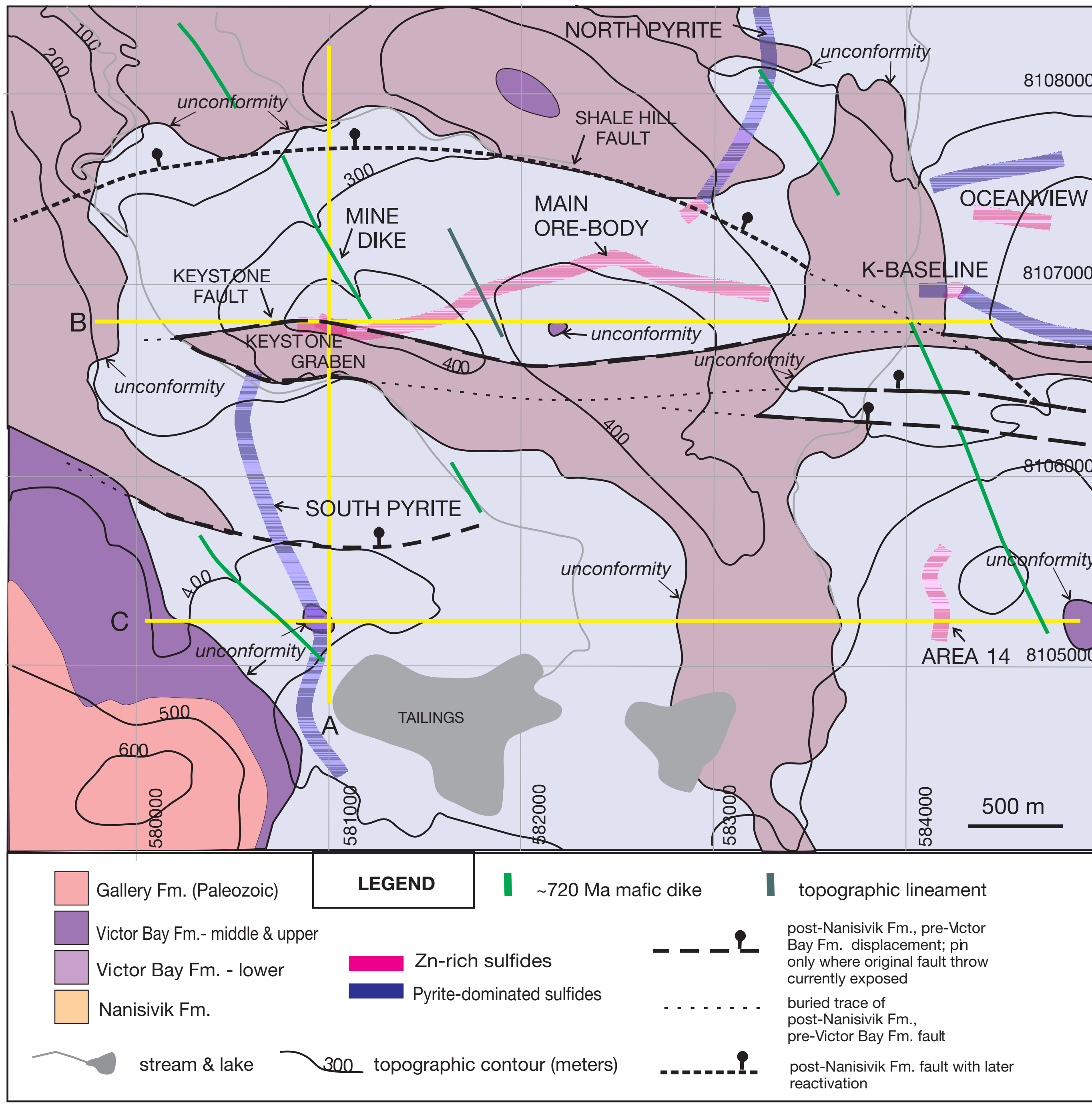

FIG. 8. Schematic map showing reinterpretation of the geology of part of the Nanisivik property (Milne block) shows that the irregularities of the contact between the Nanisivik and Victor Bay Formations are caused by erosional hills and valleys in the post-Nanisivik Formation landscape. Normal faults that crosscut the undulatory paleoland surface postdated most of the erosional hiatus but predated deposition of the Victor Bay Formation (some faults were also reactivated at a much later time). In this interpretation, most movement on the Keystone fault predated deposition of the Victor Bay Formation. Geology is based on field mapping, modification of previous work (Patterson et al., 2003), and interpretation of air photo and Landsat images. Small, inconspicuous exposures of Victor Bay Formation shale are critical to understanding the configuration of the unconformity. Grid at 1-km spacing is for UTM zone 16. Topographic contours were derived from a Landsat-based DEM. Yellow lines indicate location of interpretive cross sections shown in Figure 10. Color of rock units as in Figure 2, with the addition of the Paleozoic Gallery Formation (pink) and middle to upper Victor Bay Formation (dark purple).

dolostone-shale contact depicts a paleoerosional high along the upper surface of the Nanisivik Formation dolostone, descending both westward and eastward from the area over the orebody (paleotopographic differential of at least 250 m between hills and valleys). The orebody's shape and location conform to the flat base of a volume of gas that was trapped

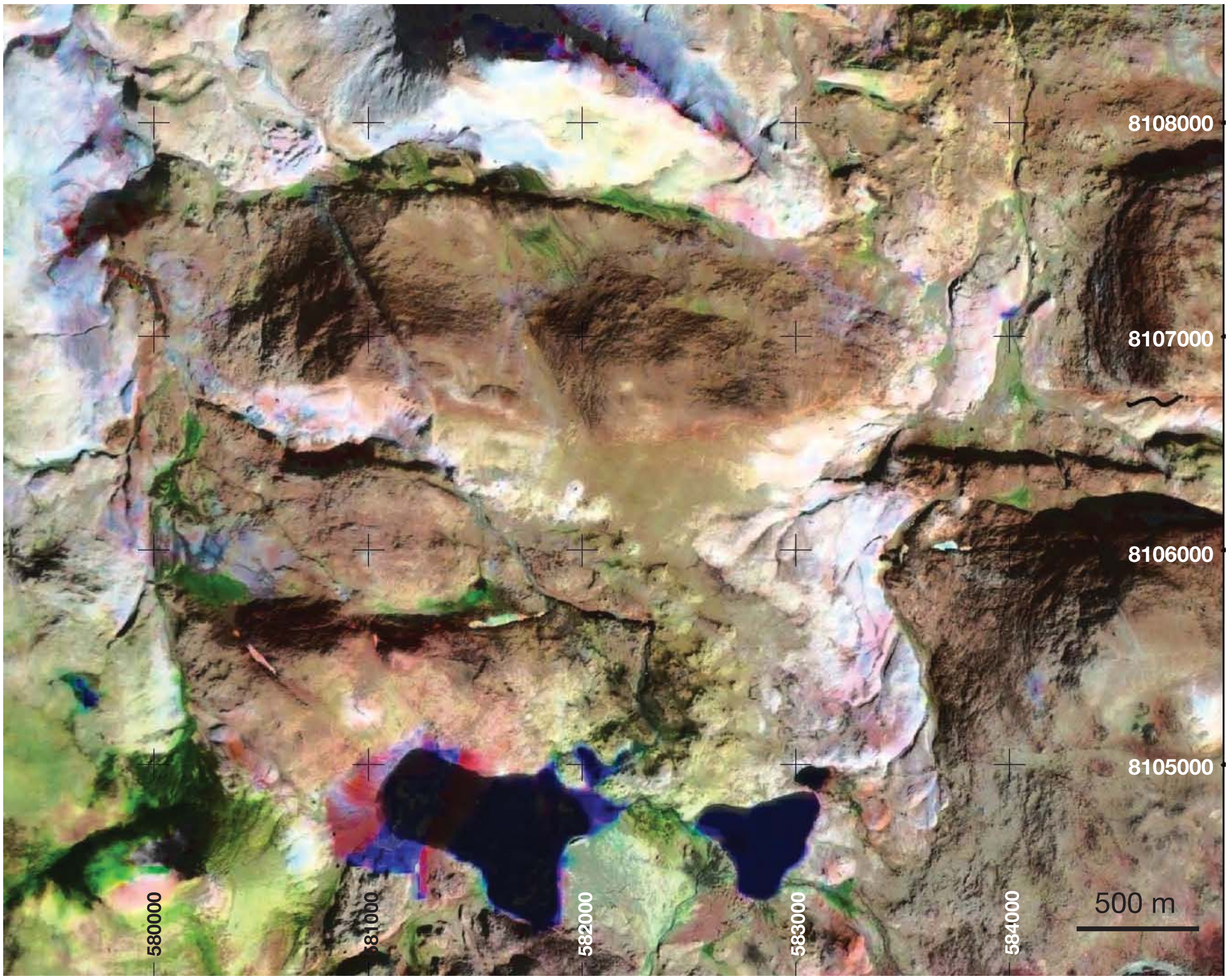

FIG. 9. Georeferenced digital combination of orthorectified air photo and Landsat 7 image (bands 7, 4, 2) for the same area as Figure 8. Even very small exposures of Victor Bay Formation felsenmeer are readily identified by their pale reflectivity in this image and are critical to reconstructing the shape and position of the unconformity. Grid at 1-km spacing is for UTM zone 16.

under the subtly convex-upward unconformity surface. A similar configuration is present in west-east cross section through the Area 14 deposit (Fig. 10C). An unconformity that is regionally characterized by pronounced erosional hills and valleys is also supported by map patterns across the Borden Peninsula; such hills and valleys are particularly clear in the present-day distribution of the Victor Bay Formation in the Tremblay block (Scott and deKemp, 1998; Fig. 1).

In strike-normal section (Figs. 8, 10A), the inferred gas cap associated with the Nanisivik orebody would have been trapped on the north and south sides by shale-filled grabens that formed lateral aquicludes. It must be emphasized that the graben-bounding faults did not displace shale; instead, the shale was deposited into grabens after faulting (Fig. 11). During initial shale deposition, the "keystone graben" would have been a steep-walled valley several hundred meters deep and wide and many kilometers long. In strike-parallel section, the inferred gas would have been trapped under a domical unconformity surface that descended both east and west (Fig. 10B). The trap for the ore-forming gas cap was, therefore, a combination of stratigraphic and structural features of which the configuration was complete by the time that middle Victor Bay Formation strata were being deposited.

It is unknown whether large orebodies like that at Nanisivik were emplaced elsewhere in the district, but the unconformity's shape controls the location of other showings across the Borden Peninsula. At Chris Creek (Fig. 12), a small massive pyrite body is present at surface, and features similar to those at Nanisivik, including a paleotopographic high on the unconformity surface, and lateral shale bodies (whether shale-filled graben or down-faulted shale is unclear). Fracture-related and disseminated sphalerite is also present (Fig. 7C). The similarity in structural and stratigraphic features suggests a similar mode of formation as that at Nanisivik.

The Hawker Creek area (Fig. 13) exhibits widespread mineralization at surface, including both fracture-hosted sulfides

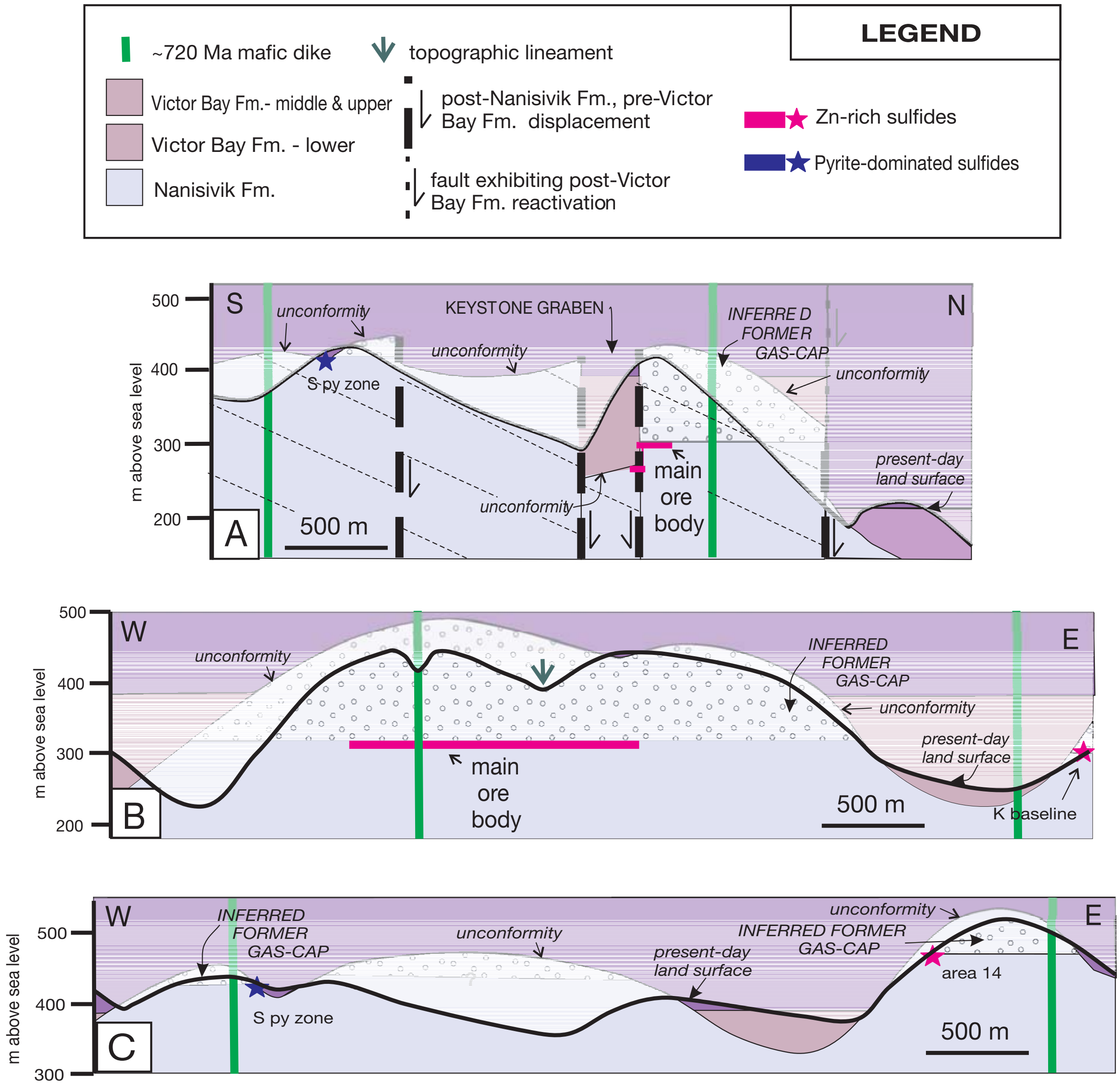

FIG. 10. Schematic cross sections through the Nanisivik property along yellow lines in Figure 8. A. South-north cross section through the west-trending horst- and -graben structures that define the structural limit for inferred gas caps in the south-north direction. Present-day land surface is depicted by a black line, and inferred configuration of erosionally removed, former rock masses are depicted in paler colors above the ground. Inferred gas cap (circle pattern) was trapped above the Nanisivik orebody by the basal Victor Bay Formation shale and to the north and south by downfaulted blocks of shale. Diagonal dashed lines in north-south section (A) show diagrammatically the dip of layering in the Nanisivik Formation (vertically exaggerated) relative to roughly flat-lying depositional units of the Victor Bay Formation and horizontal upper surface of the Nanisivik orebody. Sulfides are absent above the orebody. B. Schematic west-east cross section through the orebody with gas cap trapped under a paleohigh of the unconformity surface. Base of inferred gas cap trapped in the erosional high constrained the position of the top of the orebody. C. Schematic west-east cross section south of the Nanisivik orebody shows the same paleohill as in section (B), suggesting that long axes of hills and valleys trended roughly north. Area 14 orebody was also under a paleohigh in the unconformity.

and a banded, massive, sphalerite-pyrite-galena zone identical in texture to the banded Nanisivik ore (Fig. 7D). These attributes imply that the same types of conditions and events influenced their emplacement, including the former presence of a gas cap. A fault-related contribution to trap configuration is not obvious. Instead, the undulatory unconformity surface appears to be convex-upward in both strike-parallel and -normal orientations, with domical erosional highs and lows that may have constrained the accumulation of gas.

The aquiclude formed by the dolostone-shale contact also plays a role at showings where the former presence of a gas cap is not strongly implied. At Adams River (northeast

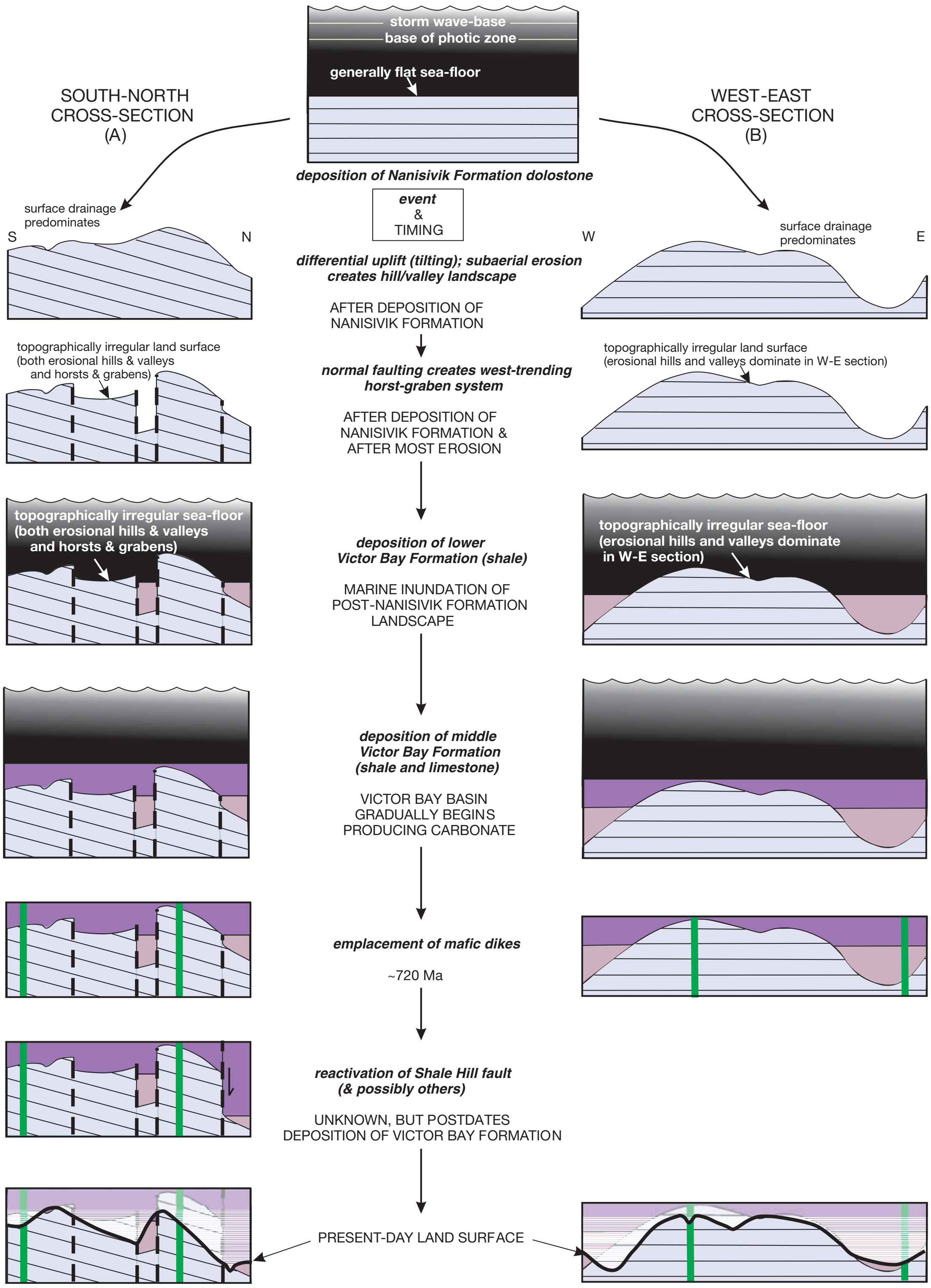

FIG. 11. Diagrammatic view of series of geologic events that resulted in present-day configuration along lines (A) and (B) in Figure 10. Prior to marine inundation and deposition of the Victor Bay Formation, the exposed dolostone bedrock (layering orientation indicated by parallel lines) had been tilted and had developed elongate erosional hills and valleys with ≥200 m of relief. Local normal faulting near the end of the exposure interval modified the irregular landscape such that north-trending hills and valleys were locally truncated by narrow, west-trending horst-graben systems. Lower Victor Bay Formation shale accumulated most thickly in the erosional and structural lows, whereas at some higher areas along the unconformity surface, the first unit to be deposited was shale and limestone of the middle Victor Bay Formation. The structural-stratigraphic trap that controlled the location of the Nanisivik orebody was complete by mid-Victor Bay time. Later geologic events included emplacement of Franklin dikes and minor reactivation of some faults.

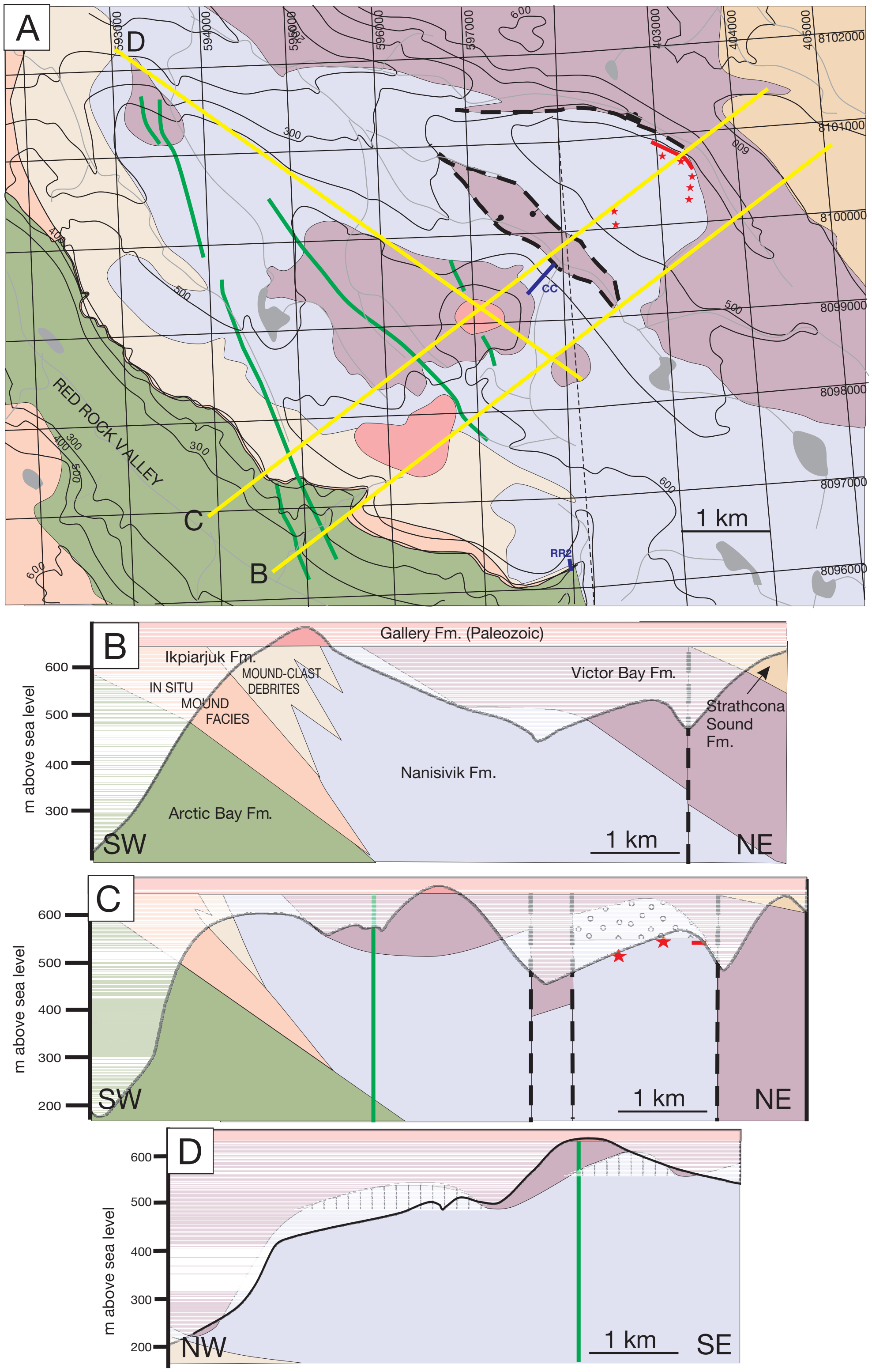

FIG. 12. A. Geologic map for the area of the Chris Creek showings (Milne block). All rock units dip gently northeast. Fracture-controlled sulfides at surface are shown by red stars, and massive pyrite-rich ore similar to that at Nanisivik is shown by the red line. Color of rock units and symbols as in Figures 2 and 8. Yellow lines show schematic cross sections (B), (C), and (D). Short blue lines with lettered labels indicate measured stratigraphic sections. Grid at 1-km spacing spans UTM zones 16 (left) and 17 (right). Topographic contours are from 1:50k NTS maps. B. Southeastern diagrammatic cross section exhibits no mineralization at surface and contains no possible stratigraphic or structural traps in strike-normal section. C. Northwestern diagrammatic cross section through the main area of sulfides at surface and configuration of inferred gas cap under a high in the unconformity between the Nanisivik and Victor Bay Formations (circle pattern). Although the shape and position of the unconformity's high is not known, dip is to the northeast and some form of trap would be unavoidable given the narrow shale-filled graben southwest of the showings. Fluid movement was probably focussed primarily through the fault northeast of the showings. Amount of vertical displacement on this fault would not necessarily have been as large as is shown. D. Strike-parallel schematic configuration of the unconformity; a valley in the northwest may have been over 300 m lower than an adjacent hill in the former land surface recorded by the unconformity's irregularities. A second hill farther southeast was relatively higher. These hills represent paleohighs in the post-Nanisivik Formation landscape and would have been stratigraphic traps once veneered by lower Victor Bay Formation shale. Locations of possible former gas caps are shown (vertical line pattern). No mineralization is known along this cross section, but fracture systems that were propagated throughout the development of the basin are commonly associated with sulfide mineralization, and some were later filled with gabbro during the Franklin intrusive event (~720 Ma). Neither of these hypothetical traps is complete in strike-normal view (e.g., cross section B).

showing), sulfides are present just below the unconformity, immediately beside a major dike. At the Surprise Creek North, Central and East showings (Fig. 14), motion along both the Tikirarjuaq fault zone and an associated, parallel fault displaced the Victor Bay shale downward to lie beside Nanisivik Formation dolostone, producing a drag-fold that tilted the unconformity on the downfaulted side of each fault. Mineralization is present between the two faults, where it appears to be elevation limited, possibly as though in the vicinity of a controlling, horizontal interface, and in the immediate footwall of the subsidiary fault, exactly at the unconformity.

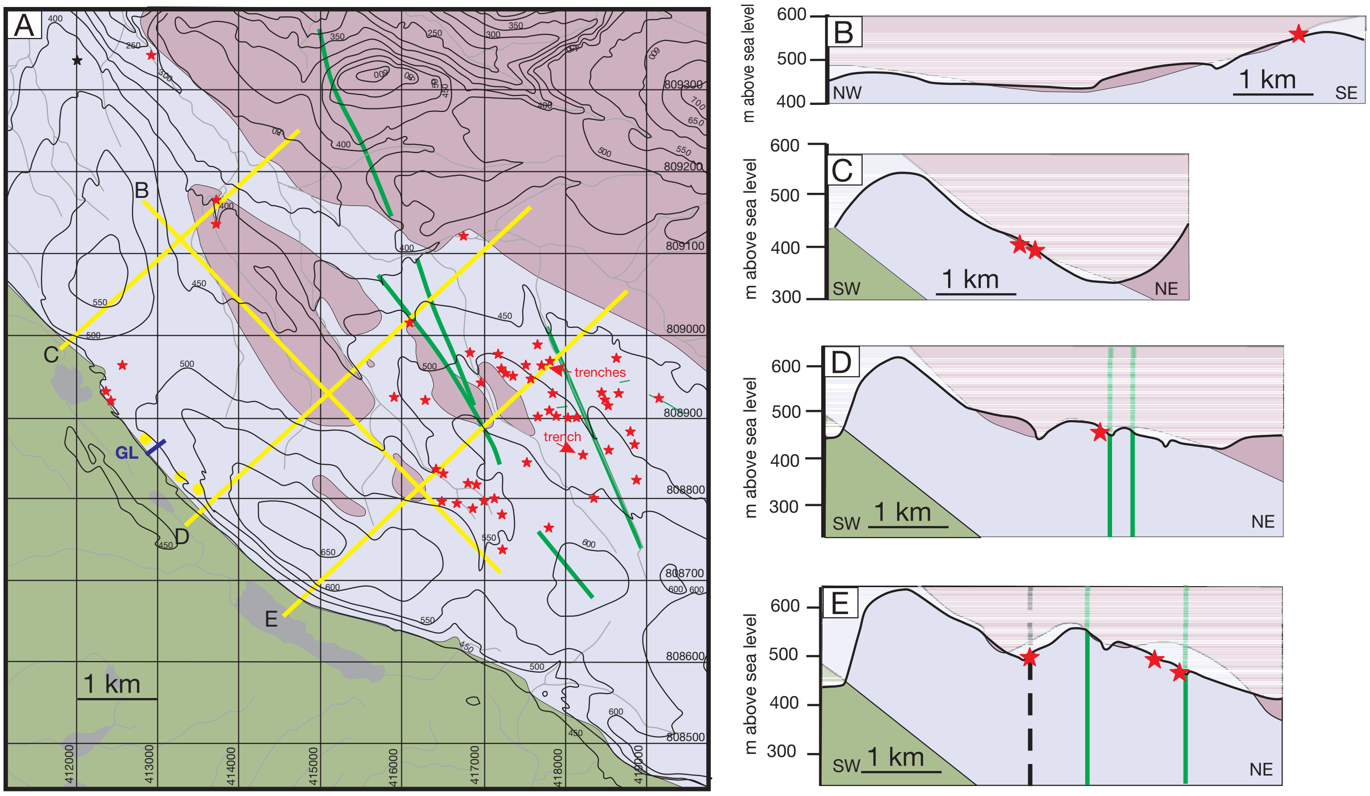

FIG. 13. Geologic map of the Hawker Creek showings (Milne block). Symbols and colors as in Figures 2 and 8. Topographic contours based on DEMs constructed from Landsat images. Short blue line with lettered label indicates measured stratigraphic section; yellow circles indicate terrigenous debrites in the lowermost Nanisivik Formation. Black star indicates galena-dominated showing; all other occurrences are sphalerite rich. The main trench contains banded, sphalerite- and pyrite-rich ore like that at Nanisivik; all other showings are fracture related. Strike-parallel (B) and strike-normal (C, D, E) schematic cross sections are shown by yellow lines. B. Strike-parallel diagrammatic cross section shows mineralization at present-day surface under topographic high in unconformity. C. Northwestern of three strike-normal diagrammatic cross sections, with sulfides at the unconformity. D. Central strike-normal schematic cross section with surface showing below a stratigraphic high in the unconformity and immediately adjacent to a dike that may represent occlusion of a feeder system that had existed prior to dike emplacement. Section (B) and the topographic contours in the map suggest that the high continues to the southeast, such that the trap may not have been complete in all directions. E. Southeastern strike-normal schematic cross section through an area of extensive surface showings. Many are under local stratigraphic highs and are spatially associated with a lineament (inferred fracture with no displacement; dashed black line) or dikes. Gas caps may have been present under the two unconformity highs shown, but trap completeness in all directions is uncertain. Lack of Victor Bay Formation shale outliers southeast of this area suggests that no local lows in the unconformity are present, but they may have been present at a small distance above the present-day land surface.

Type 2—lowest carbonate above shale

In numerous localities across the Borden Peninsula, sulfides are present in the lowermost dolostone, up to an estimated 10 m above the contact with underlying shale of the Arctic Bay Formation. The host is most commonly the Nanisivik Formation [e.g., at Fleming River, Bruno Creek, Magda East and Central (Fig. 14), Quiet River North and South; Table 1]. At K-Mesa, however, dolostones belonging to the Iqqittuq Formation (outermost ramp) and Ikpiarjuk Formation (mound) host sulfides immediately above Arctic Bay Formation shale. Although type 2 showings are invariably spatially associated with a dike, fracture, or fault, mineralizing fluids appear to have spread some distance laterally along stratigraphic surfaces, particularly where local paleoaquifer units are interlayered with dolostone. Sulfides at type 2 showings are typically fracture related (Fig. 15A).

At several localities in the central Borden Peninsula, unusual debrites and turbidites with a variety of clasts (quartz, feldspar, gneiss, shale, and dolostone) in a dolomitic matrix are present as spatially limited tongues of debris associated with major faults. The presence of clast-mouldic porosity and of sulfide mineralization in and immediately beside such layers (Fig. 15B) indicates that mineralizing fluids preferentially moved through them (e.g., Adams River south and southeast).

Type 3—stratigraphically random; major structural feature

Some fracture-hosted showings are of uncertain stratigraphic position within the Nanisivik Formation [e.g., Adams Sound Zn and Cu showings; Adams River northwest (Figs. 15C, D, 16)]. Most of these showings are in the immediate vicinity of major structures (faults or fractures, some occluded with gabbro), suggesting that the structures may have been feeders to higher structural or stratigraphic levels. The stockwork

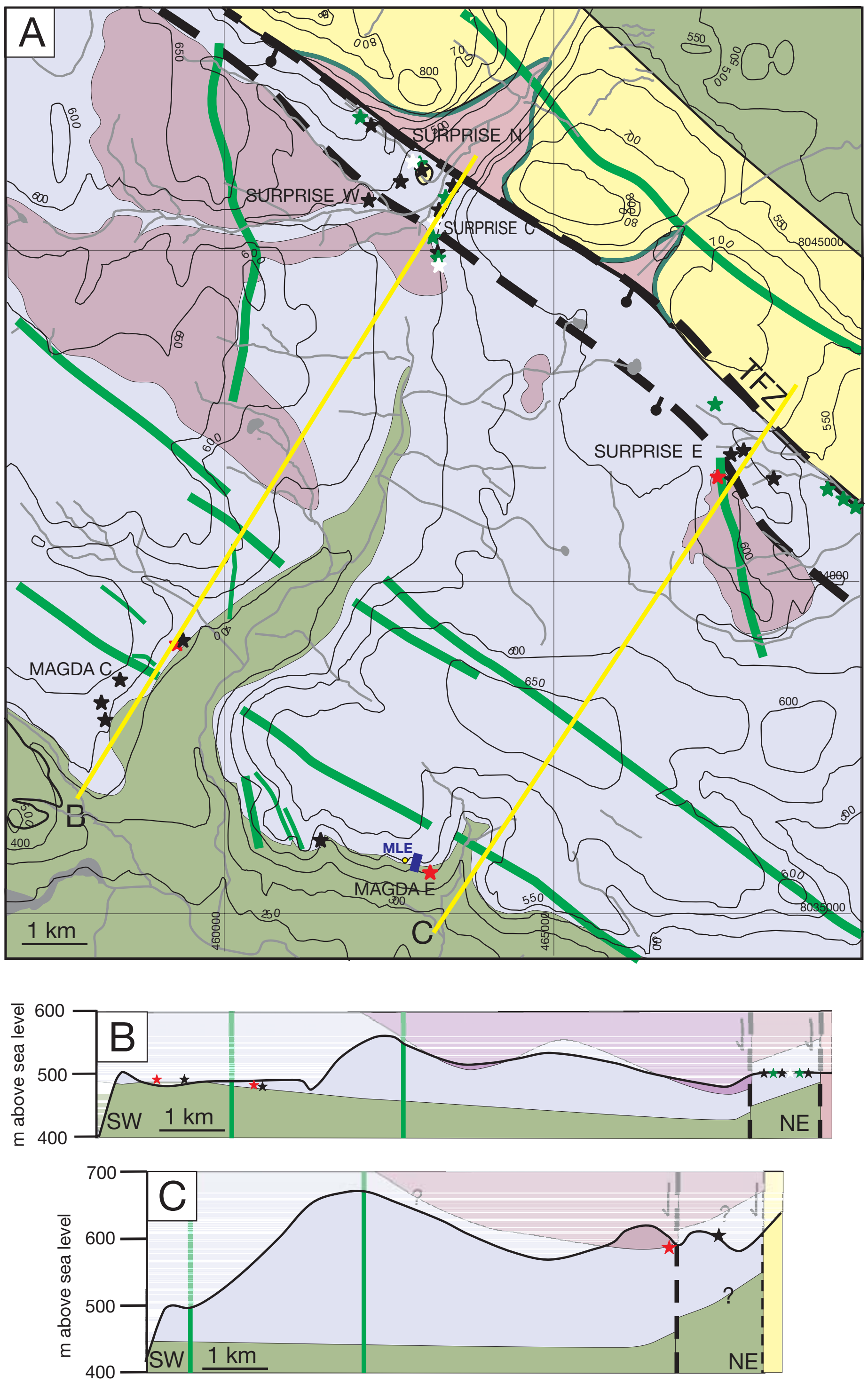

FIG. 14. Geologic map of the Surprise Creek and Magda Lakes showings (Tremblay block). Symbols and colors as in Figures 2 and 12. TFZ (Tikirarjuaq fault zone) separates the Tremblay block in the southwest from the Milne block in the northeast. The unconformity between the Nanisivik and Victor Bay Formations locally cuts almost as deep as the base of the Nanisivik Formation. Star color indicates dominant minerals: black (galena), red (sphalerite), green (Cu sulfides) and white (barite). All showings are fracture hosted, with the exception of Surprise West, which consists of a mass of large galena crystals at the contact of the Nanisivik and Victor Bay Formations. Blue line in the south-central part of the map indicates location of a measured stratigraphic section. Topographic contours were derived from a DEM based on Landsat data. Two strike-normal interpretive cross sections are indicated by yellow lines B and C. B. Strike-normal diagrammatic cross section through Magda Central and Surprise Central showings. Displacement on the Tikirarjuaq fault zone is large but probably not exactly as indicated. Magda Central sulfides are scattered over a surface area that is spatially associated both with dikes (former fractures now occupied by gabbro) and with the contact of the Arctic Bay Formation shale and overlying dolostone of the Nanisivik Formation. Surprise Central showing is associated with the Tikirarjuaq fault zone and may have had a structural trap in this southwest-northeast section. C. Strike-normal schematic cross section through Surprise East, showing sulfides at the unconformity surface as well as in a possible structural trap between faults. Exact position of the unconformity between the faults is unknown (erosionally removed).

system below the main lens at Nanisivik consists of fracture-controlled sulfides associated with a fault-related feeder system; this is probably a better developed version of the less concentrated type of mineralization comprising type-three showings.

The White Bay West showing appears to be randomly positioned in carbonate host rock of the upper Victor Bay Formation, directly on a graben-bounding fault; this is the only known showing not hosted by part of the former Society Cliffs Formation.

Type 4—lowest carbonate above shale; fabric-selective replacement

In the southeastern Milne Inlet graben, the White Bay East and Paquet Bay showings are very close to the graben-bounding White-Bay fault zone, a major structure that now

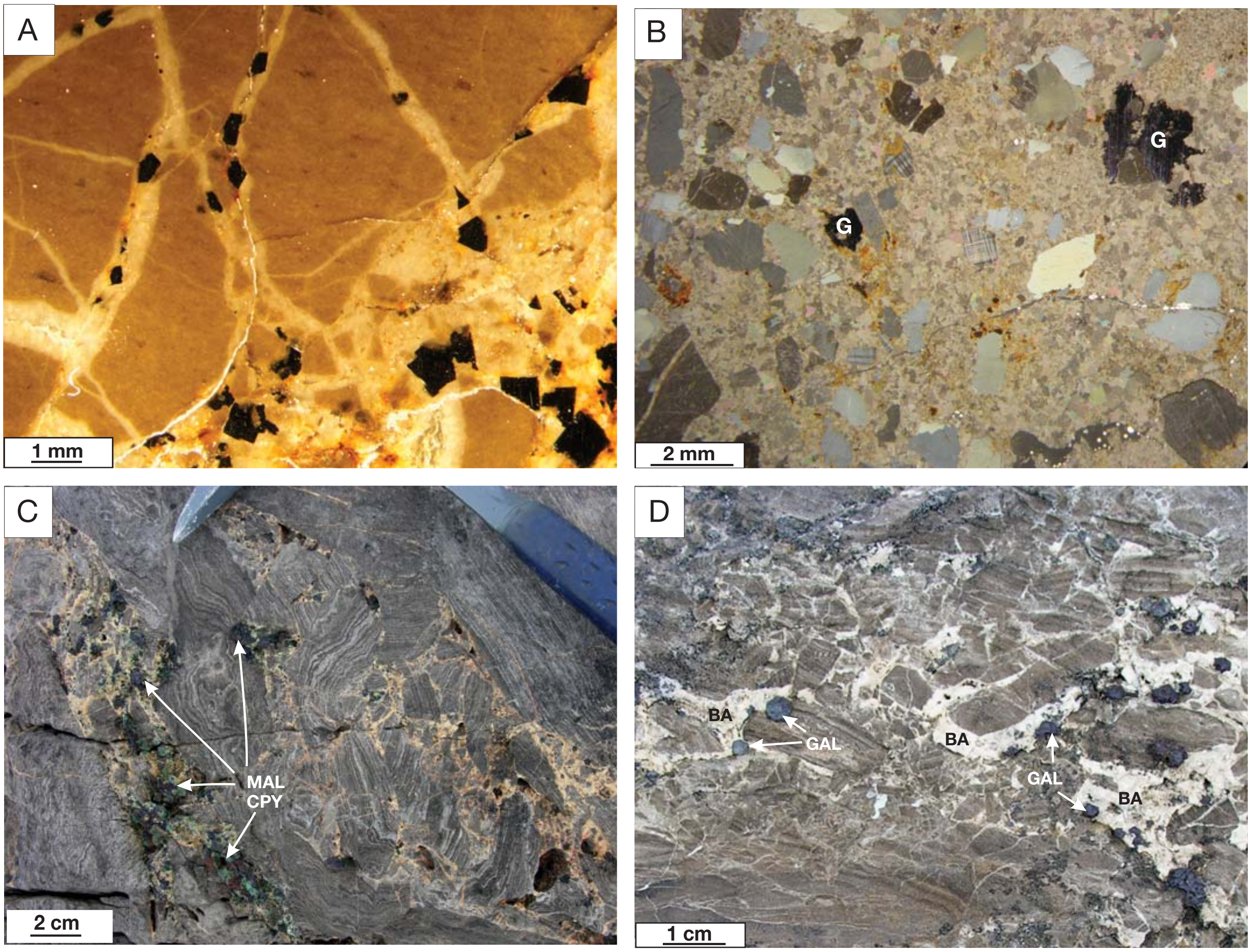

FIG. 15. Mineralization in types 2 and 3 settings. A. Fracture-hosted galena and dolomite in the Nanisivik Formation at Adams River South (thin section in oblique reflected light. B. Minor galena (G) in dolowacke with quartz, feldspar, and lithic clasts, associated with fracture-hosted sulfides in the Nanisivik Formation at Adams River Central (thin section in cross-polarized light). C. Outcrop view of fracture- and breccia-hosted copper [malachite [(MAL), chalcopyrite (CPY)] in the Nanisivik Formation at Adams Sound Cu. D. Outcrop view of fracture- and breccia-hosted galena (GAL) and barite (BA) in the Nanisivik Formation at Surprise West.

juxtaposes basement rocks with shallow-water dolostone lithofacies of the lower Iqqittuq Formation (Figs. 1, 6). These showings contain the only conspicuously fabric-selective, replacive mineralization in the Borden basin (Fig. 17). At White Bay, sphalerite and galena selectively replaced the formerly calcitic, crack-filling phase of molar-tooth structure (James et al., 1998; Fig. 17A-C) and are sparsely present in interlayered, locally derived terrigenous layers over an exposed stratigraphic interval of 10 m in exposures some 500 m from the White Bay fault zone.

At Paquet Bay, pale disseminated sphalerite pervades the groundmass of a highly altered, 17-m-thick stratigraphic interval of graded intraclast dolopackstone in Iqqittuq Formation dolostone approximately 250 m from the White Bay fault zone (Fig. 17D). Sphalerite and galena are also present in fractures. Although evidence for syndepositional fault activity (growth faulting) is present in the form of large, overturned blocks of stromatolitic dolostone enclosed by deeper water lithofacies, basement does not appear to have been exposed at this locality during carbonate deposition, because intercalated terrigenous material is absent.

Interpretation

Stratigraphic position

The unconformity at the top of the Nanisivik and laterally equivalent Angmaat Formations is critical to much of the Milne Inlet graben's base metal distribution. In contrast to earlier work that construed this importance as a function of karst-enhanced porosity associated with the contact, it is now clear that the unconformity's undulations functioned as stratigraphic traps for both gas and mineralizing fluids (Fig. 6).

Early work (Geldsetzer, 1973a, b) concluded that the conspicuous and ubiquitous breccias present throughout the

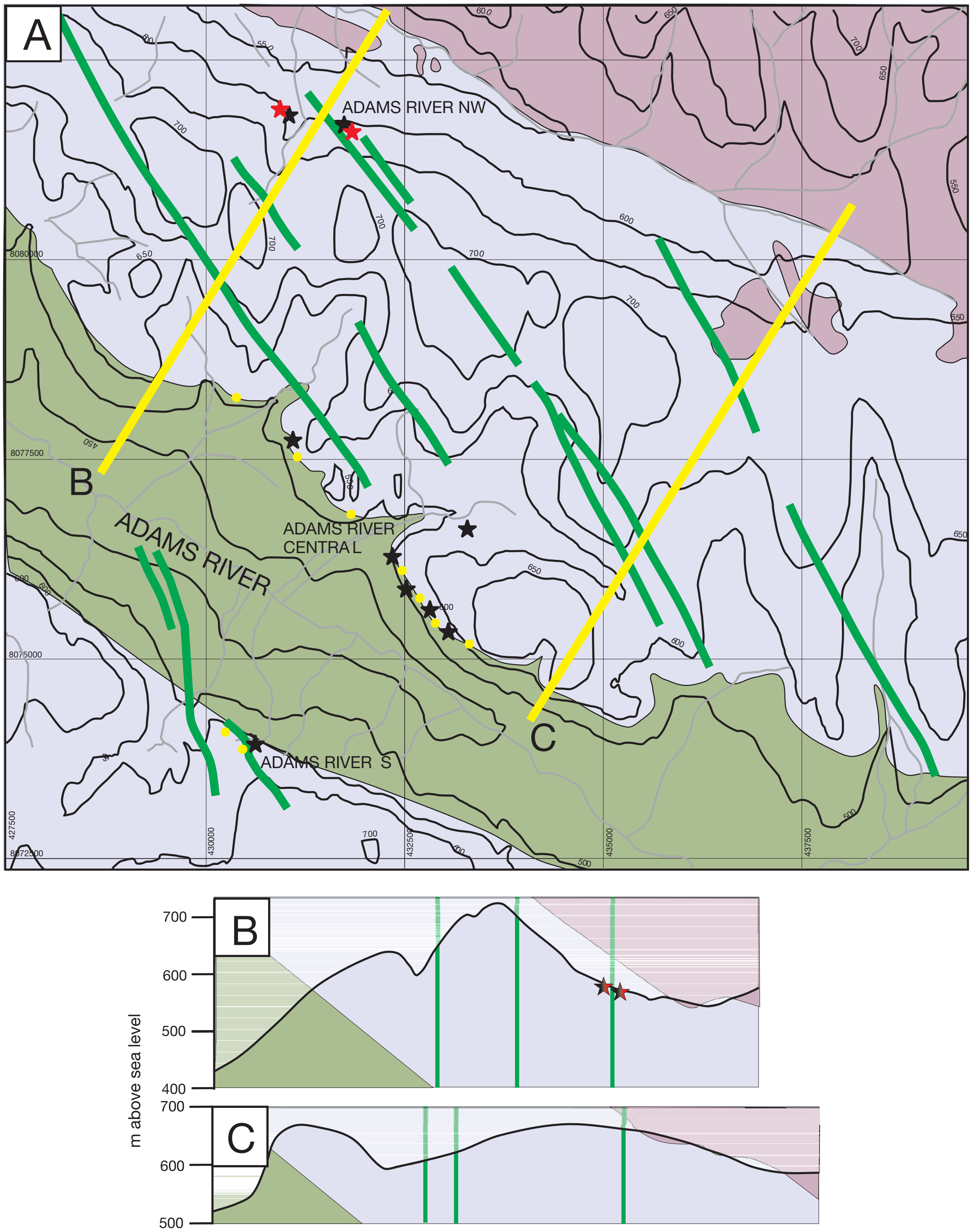

FIG. 16. A. Geologic map of the upper Adams River area (Milne block). Symbols and colors as in Figure 2. Stars indicate sphalerite- (red) and galena-dominated (black), fracture-hosted mineralization. Yellow circles indicate terrigenous debrite wedges in the basal Nanisivik Formation. Two strike-normal, schematic sections are shown (yellow lines). Topographic contours from DEMs based on Landsat images. B. Strike-normal schematic cross section through the Adams River Northwest occurrences, indicating that they are near the top of the Nanisivik Formation and spatially associated with former fracture systems now occluded by gabbro dikes. Unconformity shape is not well constrained in this area owing to lack of Victor Bay Formation outliers. C. Strike-normal schematic cross section showing lack of sulfides in vicinity of dikes. Paleotopographic variation is present at the top of the Nanisivik Formation in the northeast.

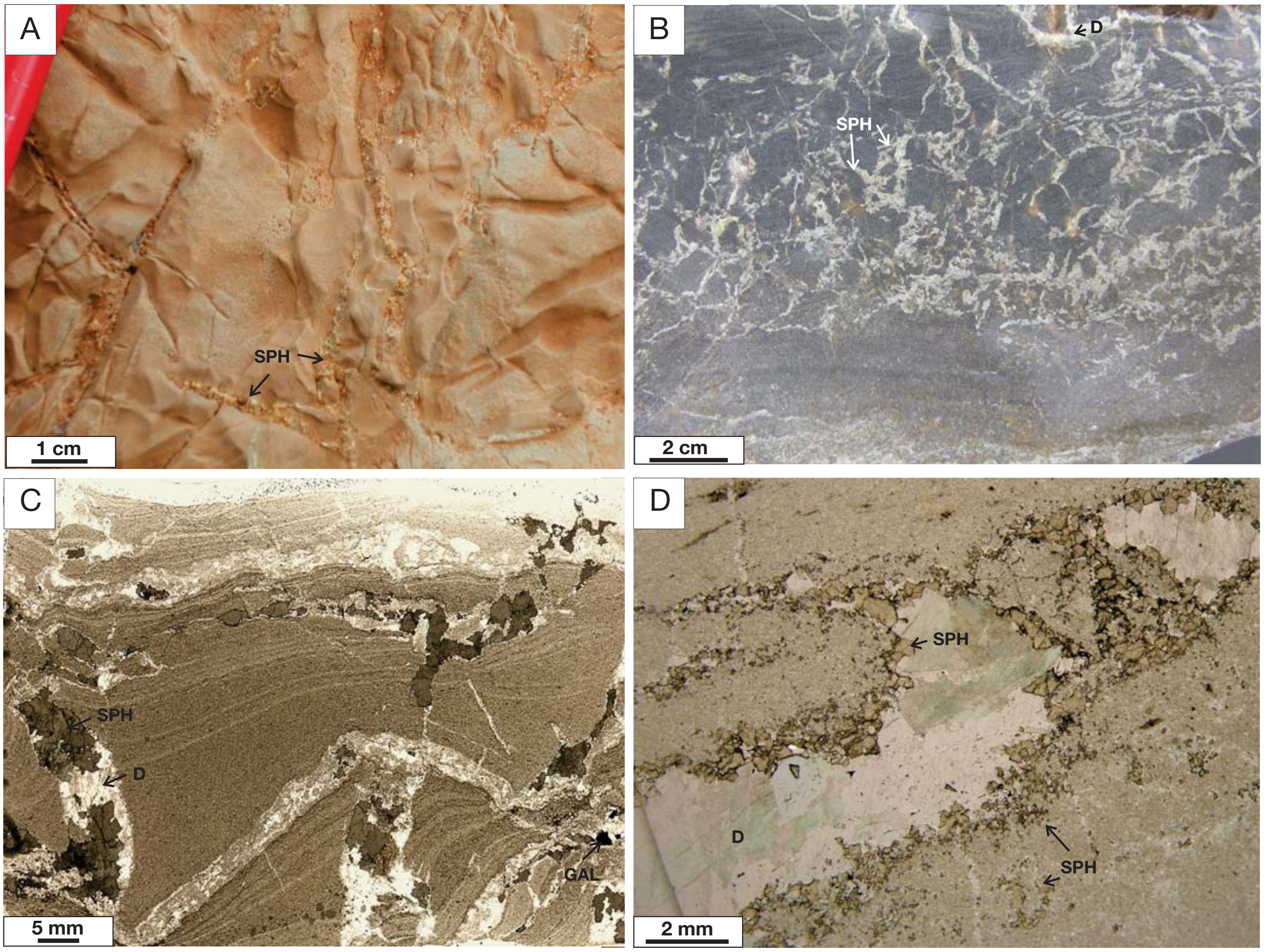

FIG. 17. Fabric-selective mineralization from type 4 settings. (A) Outcrop, (B) sawed slab, and (C) thin section (plane-polarized light) views of sulfides (sphalerite and minor galena) in the Iqqittuq Formation at White Bay East, replacing only the formerly calcitic fill of the primary sedimentary structure known as "molar-tooth structure." (D). Fracture-filling and replacive, pale sphalerite in the Iqqittuq Formation from Paquet Bay (thin section in plane-polarized light). D = dolomite, GAL = galena, SPH = sphalerite.

laminated basinal Nanisivik Formation were products of karstification. Jackson and Iannelli (1981) invoked karsting along the (undescribed) dolostone-shale contact but did not provide evidence. Olson (1984) and others argued that karstic caverns existed below the contact and that these caverns played a role in mineralization at Nanisivik, which was at that time, based on its morphology, was assumed to be a void-filling orebody. Still other workers have assumed or asserted that the contact is conformable (Iannelli, 1992; Kah, 1997). The Nanisivik orebody is no longer believed to have required significant preexisting open space (Arne and Kissin, 1989; Arne et al., 1991) and breccias in the Nanisivik Formation are no longer believed to be karstic in origin (Turner, 2004, 2009a). The influence of a gas cap is now accepted for Nanisivik, was probably important at Hawker Creek and Chris Creek, and was possibly present at Surprise Creek. The contribution of hydrocarbon gas to the development of mineralization at other showings is as yet unknown.

The dolostone-shale contact is critical to the spatial distribution of the dominant sulfide bodies in the Borden basin. The contact is sharp, undulatory, and unconformable but is not strongly karstified (dearth of meteoric solution-related voids, meteoric cements, or shale-filled grikes). Erosional downcutting of at least several hundred meters is evident from property-scale mapping and cross sections and may be in part responsible for the thickness differential between the Angmaat Formation in the eastern part of the Milne Inlet graben (~500 m and approx 11 stratigraphic cycles at Angmaat; ~600 m and approx 20 cycles at Tremblay Sound) and the equivalent, laminated, basinal Nanisivik Formation in the western part of the Milne Inlet graben (nowhere accurately measurable in outcrop, but possibly locally as thin as 225 m; Fig. 3). Dolostone highs were capable of acting as traps for hydrocarbons and metalliferous fluids, such as those known to have been important in showings in the westernmost part of the Milne Inlet graben. Shale is required to seal the stratigraphic and structural traps. The basal Victor Bay Formation shale is absent in the other two grabens of the Borden basin, where no base metal mineralization has been reported.

Regional thickness trends and property-scale geometries suggest the following history for the development of the unconformity surface between the Nanisivik and Angmaat Formations and the overlying basal shale of the Victor Bay Formation in the Milne Inlet graben (Figs. 4, 11). Uplift after deposition of the Nanisivik Formation and laterally equivalent Angmaat Formation was on the order of hundreds of meters. Differential uplift produced an inclined carbonate land surface across which northeast-trending hills and valleys developed (north trending near Nanisivik). Local faulting then produced elongate west-trending valleys, at least in the northwest. In view of the inferred development of a foreland basin after deposition of the Victor Bay Formation, the post-Nanisivik Formation combination of uplift, tilting, and normal faulting may be suggestive of forebulge migration, although other tectonic interpretations are possible. During subsequent marine inundation and deposition of the basal Victor Bay Formation, the thickest shale accumulated in structurally and erosionally low-lying areas in the northwest.

Many showings in the Milne Inlet graben are hosted by Nanisivik Formation dolostone immediately above the underlying Arctic Bay Formation shale (Fig. 6). This "lowest clean carbonate" setting is familiar from numerous carbonate-hosted Zn-Pb deposits. There is as yet no evidence of significant metal concentrations in this stratigraphic setting in the Milne Inlet graben, but nothing is known of the subsurface in these areas.

Faults

Mineralizing fluids clearly exploited faults in the carbonate host rock at Nanisivik. Geometric relationships between major or subsidiary faults or fractures and mineralization indicate that such structures were also vital to fluid-flow at all other showings in the Milne Inlet graben. The relationship between faults and rock permeability is complex. Faults in brittle rocks generally decrease long-term permeability in their immediate vicinity by destroying pore space but can be fluid conduits during intervals of ongoing displacement, when porosity is created on fault planes, or if they dilate during deformation. Any porosity created during movement along fault planes is generally occluded by later precipitation of minerals from pore fluid, and so some type of tectonism is generally required to maintain permeability of fault-related feeder systems, regardless of the general mineralization model invoked.

Given that faults, particularly those in carbonate rocks, gradually become occluded by precipitation of minerals from porewater fluids once fault activity ceases, it is probable that migration of mineralizing fluids took place while fault permeability was being maintained by ongoing displacement during some form of tectonism. The only known significant tectonic events to have affected the Milne Inlet graben after the post-Nanisivik-Formation uplift are basin inversion and differential uplift attributed to development of a foreland basin beginning during deposition of the uppermost Victor Bay Formation and extending at least until the end of Bylot Supergroup deposition (Sherman et al., 2002), and normal faulting associated with the Cenozoic Eurekan orogeny. Given the indisputable contribution of fault permeability to mineralization, and the presence of gabbro associated with the Franklin event (~720 Ma) in many of the fractures or faults that are associated with base metal showings in this district, it is difficult to envisage how mineralization could postdate dike emplacement.

The importance to mineralization of less conspicuous and less extensive faults is exemplified by the keystone graben at Nanisivik and by the small horst and graben mapped at Chris Creek. At these locations, shale-filled grabens acted as lateral barriers to gas and fluid, and faults provided conduits for metalliferous fluids. Detailed mapping of small or large structures that juxtapose dolostone and shale should be undertaken in order to identify other areas of similar configuration that could have been associated with mineralization. Both of these showings are located in the westernmost part of the Milne Inlet graben, where the present-day fault pattern appears to be most intense and deviates from the regional northwest trend. The westernmost area also exhibits more dense development of fault-related, deep-water mounds than elsewhere (Turner, 2009a). Together, these phenomena may reflect a significant role for faults, both syndepositionally and in focusing the later fluid flow that resulted in mineralization in this western area. It may be that densely spaced faults that developed in the time between deposition of the Nanisivik and Victor Bay Formations were limited to the area between Chris Creek and Nanisivik.

Lithofacies

Although the bulk of known mineralization is in Nanisivik Formation dololaminite, there is little evidence to suggest that primary lithofacies influenced the location of sulfide emplacement in this host facies. Instead, local configuration of the unconformity, stratigraphic level relative to the unconformity, stratigraphic proximity to underlying shale, interlayered allochthonous material, and structural factors are clearly dominant.

With one minor exception, sulfides are absent from deep-water mound dolostone of the Ikpiarjuk Formation, which suggests that the unlayered, compositionally homogeneous, hydrologically impermeable mounds may have been less susceptible to fracturing (types 2 and 3 mineralization) or to dissolution and replacement (types 1 and 4) than other carbonate lithofacies. Peritidal facies of the Angmaat Formation in the southeastern, shallow-water area lack known showings. The geographic area occupied by the Angmaat carbonate platform is roughly the same as the southeastern zone in which mineralization is present in Iqqittuq Formation carbonates near the White Bay fault zone, but the extent of mineralization in the subsurface near the White Bay fault zone is unknown, as is the possibility of unconformity-related mineralization in the Angmaat Formation beneath the Victor Bay Formation contact in this southeastern area.

Fabric-selective, replacive sulfides are conspicuous only in type 4 showings. Sphalerite and galena at White Bay East selectively replaced molar-tooth crack-fill, which implies that at the time of mineralization the carbonate mudstone matrix had been dolomitized, but that the crack-fill retained its primary calcite composition and its greater potential for diagenetic alteration. Disseminated sphalerite at the Paquet Bay showing appears to have selected certain strata, suggesting a fabric-specific replacement.

Terrigenous dolowackes in the Nanisivik Formation (Adams River central and south; Turner 2003) and quartzose sandstones interlayered with carbonate facies in the Iqqittuq Formation (White Bay East) contain sparsely disseminated, coarse sulfide crystals. Although some of these sulfides may have replaced intraclasts of diagenetically susceptible carbonate phases, it appears that this minor type of facies-specific mineralization is largely a product of the host rock's primary permeability.

Discussion

Spatial distribution of metals

Of the four new formations into which the former Society Cliffs Formation has been divided, only two are significant sulfide hosts in the Milne Inlet graben (Fig. 1; Table 1): the Nanisivik and the Iqqittuq Formations. Although lower Paleozoic carbonate rocks regionally overlie Mesoproterozoic strata, they are not known to host any significant sulfides. Sangster (1998) suggested metal zoning (Zn vs. Pb) across the Milne Inlet graben, with Zn-rich showings dominant in the northwest and Pb-dominated showings in the southeast, but the present work suggests otherwise: although there is a zone of Zn-poor showings in the central Borden Peninsula, Zn is generally present and is the dominant species in showings of types 1 and 4. Iron is common only in type 1 showings, and Cu and Ba are present only in type 2 and 3 showings. These regional variations suggest that there were geographic differences in the metals contributed by the locally dominant paleoaquifer, as well as a possibly protracted interval of mineralization during which fluid content may have changed significantly (Cu + Pb to Ba). Such geographic variability in metal distribution may have parallels in other districts (e.g., Sangster et al., 1998), suggesting that multiple fluid events or aquifers may be more important than is commonly recognized.

The gas-cap model for Nanisivik (Arne and Kissin, 1989; Arne et al., 1991) remains the most logical explanation for the stratigraphic distribution, morphology, and texture of ore at Nanisivik, Hawker Creek, and Chris Creek (type 1). Gas-cap–related Zn-Pb deposits are familiar from Phanerozoic deposits, generally in domal structures associated with evaporite diapirs (Leach et al., 2005). The Nanisivik deposit is located under a domal structure that was formed not by tectonic or density-driven deformation of a reservoir-cap rock interface but by depositional shale draping of erosional highs on an unconformity surface.

Timing and cause of mineralization

The timing of the regional mineralization event(s) remains unresolved, but geometric relationships among mineralized host rock and other rock bodies provides constraints on the timing of sulfide emplacement at some showings. Numerous showings are indisputably spatially associated with dikes of the Franklin event (Table 1), strongly suggesting that these were fracture systems that acted as fluid conduits prior to their occlusion with gabbro at ~720 Ma. Some showings (e.g., Chris Creek; Hawker Creek) can be assumed to be contemporaneous with emplacement of the Nanisivik orebody, on the basis of their shared compositional attributes (Fe and Zn rich) and distinctive textural characteristics (rhythmic banding of the ore). It remains unclear whether the entire district records only one mineralizing event or whether the metallogeny of the Borden basin is more complex.

The tectonic evolution of this part of the Canadian Arctic is not complicated. Proterozoic strata were subtly tilted in reactivated fault blocks, probably immediately after deposition of the carbonate successions that host the sulfides and before deposition of the Victor Bay Formation (Turner, 2009a). A second event during deposition of the Bylot Supergroup saw basin inversion that resulted from inferred, distant contractional deformation (Sherman et al., 2002). Caledonian and Ellesmerian compression (Paleozoic), and ensuing opening of the Sverdrup basin, may have had subtle far-field effects in this area, but no specific tectonic features have yet been identified. The only post-Mesoproterozoic tectonic event to have affected the area visibly is Eocene extension that reactivated normal faults during the Eurekan orogeny. If the mineralizing event(s) predated the Franklinian igneous event at ~720 Ma, the only viable candidate for a tectonic fluid-mobilizing event that postdated deposition of the Victor Bay Formation aquiclude is the event that began with differential uplift after deposition of the Victor Bay Formation. Terrigenous clastic rocks in the >2-km-thick succession that overlies the Victor Bay Formation carbonate rocks have complex facies variations (Jackson et al., 1978; Jackson and Iannelli, 1981) and paleocurrent directions (Knight and Jackson, 1994), suggesting that this was not a simple foreland basin, but that shallow-water sediment may have been deposited across a complex surface topography imposed by a complex stress field of the type associated with transtensional or oblique, rather than orthogonal, stress. If fluid movement took place during deposition of the uppermost preserved strata of the Nunatsiaq Group (of unknown original thickness), the host carbonate rocks would have been buried to approximately 2-km depth, the gas source rocks to 3 km, and the possible storage aquifer for mineralizing fluids (Adams Sound Formation) to approximately 4 km, based on a 2-km-minimum thickness of Nunatsiaq Group strata. These burial depths would be adequate to produce fluid temperatures equivalent to those of Nanisivik fluid inclusions (<130°C; D. Kontak pers. commun., 2011) under a normal geothermal gradient, preserve at least some volume of uncemented permeability in the Adams Sound Formation, and produce methane from black shale in the Arctic Bay Formation.

Metal prospectivity

The most impressive mineralization in the Borden basin is the Nanisivik orebody, and the setting of such type 1 mineralization may be the most prospective for further discoveries in this district. Areas near the dolostone-shale contact could be carefully mapped to determine the general shape of the unconformity and the location, plan dimensions, and paleotopographic relief of its paleohighs and -lows. This information could point to areas where prospective erosional highs are present in the shallow subsurface below Victor Bay Formation shale in the shallowly northeast-dipping Milne block, as well as where former highs may have existed in the almost flat-lying strata in the Tremblay block, where the present-day land surface is close to the now eroded dolostone-shale contact.

This assumes that gas caps could have formed beyond the northwesternmost part of the Milne Inlet graben. At present, the source and extent of gas formation and migration and its possible influence on mineralization in all areas southeast of Hawker Creek remain to be determined. Geometric relationships between the orebody and overlying, barren host rock at Nanisivik suggest that porosity of all dolostone overlying the orebody under the paleotopographic high in the unconformity was gas filled at the time of ore formation.

A mineralized fracture system is present beneath the main lens at Nanisivik (the "keel zone;" Clayton and Thorpe, 1982; Olson, 1984; Sutherland and Dumka, 1995), but sulfides are entirely absent above the main orebody, in the zone once occupied by the inferred gas cap. Some of the areas of known fracture-hosted mineralization at surface elsewhere may represent feeder systems beneath former orebodies that have been removed by recent erosion. The most prospective areas would, in theory, be characterized either by barren dolostone beneath a demonstrably convex unconformity or mineralized areas at surface that are laterally adjacent to present-day topographic highs that are coincident with paleotopographic highs in the unconformity surface. Along the Nanisivik-Victor Bay contact in the Milne block, on the Borden Peninsula alone, ~130 linear kilometers of unconformity are exposed; similarly, there are numerous areas in the Tremblay block where the Nanisivik Formation could once have exhibited an erosional high beneath shale. Simple mapping and cross sections like those performed in this study could help to identify some such areas, whereas others would have to be sought in the subsurface using geophysical methods.

The showings of fabric-specific, replacive sulfides associated with the White Bay fault zone in the southeasternmost part of the Milne Inlet graben suggest that there is potential for more concentrated sulfide volumes in stratigraphically low dolostone of the Iqqittuq Formation in the subsurface adjacent to and along the length of the fault. A more detailed understanding of the stratigraphic succession in the vicinity of the White Bay fault zone in the southeastern part of the Milne Inlet graben could help to identify those areas where the most prospective, stratigraphically low carbonates could be present in the shallow subsurface. Geophysical methods may be helpful in identifying blind sulfide bodies beneath the rise of land immediately adjacent to the fault.

Global context

Carbonate-hosted Zn-Pb deposits are widely viewed as sharing a general suite of host-rock characteristics (e.g., Leach et al., 2005; Paradis et al., 2007), but mineralization in the Borden basin deviates significantly from these generalizations. The carbonate unit that hosts much of the mineralization (Nanisivik Formation) in the Milne Inlet graben displays none of the hallmarks of "platformal" carbonate deposition and is not known to be spatially associated with a basin margin, a lateral transition to argillaceous facies, or a foreland thrust belt, as in generalized models for carbonate-hosted Zn-Pb deposits. Evaporites, or evidence of their former presence, are and were entirely absent from the main sulfide-hosting formation and from strata sub- and superjacent to it (Turner, 2009a) but were sparsely present in the southeastern part of the Milne Inlet graben (Kah et al., 2001). The distribution of shallow-water carbonate rocks (Iqqittuq and Angmaat Formations) that are in part laterally equivalent to the Nanisivik Formation was largely controlled by a tectonic hinge, and none of these carbonate strata can be considered to be passive-margin rocks. The basin had a history of protracted tectonism and was indeed never characterized by passive margin conditions (Turner, 2009a). Many of the showings (types 1 and 3) are neither strata bound nor stratiform at the scale of the stratigraphic formation that hosts them. Pre- or synore dissolutional collapse breccias do not seem to be important for any of the volumetrically significant mineralization in the district.

Most carbonate-hosted Zn-Pb deposits are associated with extensional domains within orogenic belts associated with major episodes of tectonic contraction (Leach et al., 2005). The tectonic regime under which Borden basin mineralization formed remains very poorly constrained, because the age of mineralization is at present assigned to either the Mesoproterozoic or the Ordovician. If mineralization in the Borden basin is considered to be late Mesoproterozoic (Christensen et al., 1993; Symons et al., 2000), it may be related to Grenvillian-aged tectonic events associated with the assembly of Rodinia. If mineralization is instead assigned an early Paleozoic age (Sherlock et al., 2004), its origin might be more enigmatic. Previous work (Knight and Jackson, 1994; Sherman et al., 2002) points to complex tectonic activity that accompanied deposition of the upper part of the Bylot Supergroup, which may represent an opportunity for the movement of mineralizing fluids.

Part of the reason why Zn-Pb mineralization in the Milne Inlet graben differs markedly from "typical" carbonate-hosted Zn-Pb deposits may be because its Mesoproterozoic host-rock age falls outside the general range (Phanerozoic) for such deposits (Leach et al., 2010). Zinc-lead deposits hosted by Precambrian carbonate rocks are not common but based on the few for which there are adequate published descriptions (discussed below), their attributes differ markedly from those hosted by Phanerozoic rocks, and so it is not surprising that many of the attributes of sulfide showings and deposits hosted by Mesoproterozoic carbonates of the Borden basin differ from those typical of the Phanerozoic.

The composition of Phanerozoic carbonate particles is controlled by the metabolisms of skeletal eukaryotes, whereas in the Proterozoic, no skeletal particles were present and primary carbonate sediment mineralogy was dominated by seawater composition. In the Phanerozoic, carbonate sediment with mixed mineralogy is, therefore, common and leads to mineral-driven, facies-controlled diagenesis that creates permeability pathways that can be exploited later by mineralizing fluids. This type of permeability-producing mineral-driven diagenesis would have been considerably less common in the Proterozoic. Furthermore, early dolomitization was quite common in Proterozoic rocks, which would have stabilized rock composition and diminished the potential for later permeability-forming diagenetic changes. Lastly, it has also been suggested that a higher proportion of coarse allochems in Phanerozoic sediment, associated with the development of skeletal eukaryotes, may have had a significant and positive effect on carbonate permeability in general (Leach et al., 2010).

Leach et al. (2010) suggested that Precambrian carbonate rocks are generally tighter than their Phanerozoic equivalents and so tended to develop permeability pathways that were predominantly vertical, rather than horizontal and lithofacies controlled. Permeability in Precambrian carbonate rocks that host Zn-Pb deposits developed in a variety of ways. In the case of Pering (Archean host; South Africa), vertical permeability was produced by hydrothermal brecciation associated with circulation of anomalously heated fluid (Duane et al., 2004; Gützmer, 2005). The Boquira deposit (Paleoproterozoic host; Brazil) appears to be stratiform and facies controlled, whereas the Canoas and Caboclo deposits (Mesoproterozoic host; Brazil) are closely related to growth faults (Misi et al., 1999). At Esker Lake (Paleoproterozoic host; Canada), mineralization is strata bound and entirely lithofacies controlled (Gummer et al., 1996). The Blende (late Paleoproterozoic host; Canada) is characterized by both structural and lithofacies controls (Robinson and Godwin, 1995), with the strongest spatial constraint being a fold axis (Moroskat, 2009). Gayna River (Neoproterozoic host; Canada) occupies vertical-dominant fracture networks formed owing to the differential rheologic responses of reef and surrounding layered carbonate rocks to tectonic stress (Hewton, 1982; Turner, 2005, 2009b; Wallace, 2009). Daliangzi and Tianbaoshan (Late Neoproterozoic hosts; China) are vein hosted (Zheng and Wang, 1991; Wang et al., 2000).

Nanisivik, the most significant among those Zn-Pb deposits that are hosted by Mesoproterozoic carbonates, has vertical permeability provided by the fault-related fracture network that served as its feeder zone, and lacks significant solution brecciation, which is very common in deposits hosted by Paleozoic carbonate rocks. This fracture network may have initially developed during extension caused by the tectonic events associated with differential uplift and erosion that developed atop host carbonates or during basin inversion at the end of Victor Bay Formation deposition. Although the evidence is equivocal, Nanisivik may also have had early horizontal permeability associated with a proposed horizontal karst system that may have contributed to the orebody's horizontal, highly elongated shape. Alternatively, this horizontal control on orebody morphology may have been configured by the intersection of an east-trending, discontinuous, fault-related fracture network (which later became the keel zone) with the base of the gas cap trapped under the domal unconformity.

Conclusions

This paper presents a first-order description of spatial controls on the distribution of known base metal mineralization in the hitherto undescribed Mesoproterozoic Milne Inlet graben of the Borden basin. The district's four showing types are generally compatible with most of the familiar aspects of carbonate-hosted Zn-Pb deposits. One salient distinction, however, is the unusual lithology and nonplatformal depositional setting of the main host rocks, which accumulated in a geologically ephemeral carbonate system controlled by local tectonics in an evolving rift system. Four structural-stratigraphic settings are identified. As in many carbonate-hosted Zn-Pb districts, the most important controls on the spatial distribution of base metal showings were faults and fractures. In addition to these requisite structural features, stratigraphic controls were also critical: the shape of a shale-covered unconformity surface dictated the disposition of gas caps that acted as the reductants for the most important mineralization (type 1: Nanisivik, Hawker Creek, and Chris Creek), whereas the lowest "clean" carbonate constrained the position of type 2 and 4 mineralization. Lithofacies was important at type 4 showings, which are associated with a deep-seated, syn- and postdepositionally active fault and are partly lithofacies controlled; these controls may represent an important and hitherto unappreciated aspect of the district's metal endowment. From this new understanding of the controls on mineralization in the Borden basin emerge the two most important factors that could be used to focus future exploration: the undulatory erosional shape of a shale-draped, buried unconformity, and proximity to major basement faults.

The timing of mineralization at Nanisivik and throughout the Milne Inlet graben remains contentious, and the degree of relationship (if any) among the disparate showing types and geographic zones in the graben remains unclear. Analytical components of the research program will address these concerns in the context of the regional controls established in this paper. Ongoing work on the tectonostratigraphic evolution of the Bylot basins may help to characterize the mechanism(s) that drove fluid flow in the Milne Inlet graben and to assess the metal prospectivity of other parts of the Bylot basins.

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