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Critical review

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Abstract: The Mesoproterozoic Ikpiarjuk Formation (Borden Basin, Nunavut) consists of isolated dolostone mounds (>200 m thick, kilometres in diameter) centred on basin-scale faults. Mounds accumulated in deep water during deposition of Arctic Bay Formation black shale. Mounds consist of massive, featureless dolostone with locally mottled or clotted fabric. Clotted fabric is most common in mound centres, whereas massive and recrystallized fabrics are common throughout mounds. The terminal growth history of each mound is unique. Some mounds are flanked by intraclast debrites, and intraclast-filled vertical crack networks are present near mounds' tops. One mound is capped by shallow-water facies and tufa crusts, whereas another was karsted and then overlain by deep-water strata. Ikpiarjuk Formation mounds are interpreted as fossilized cold-seep mounds that accumulated near seafloor fissures associated with active faults. Clotted texture resembling thrombolites suggests that carbonate precipitation was influenced by chemosynthetic benthic microbial communities that are hitherto unknown in Mesoproterozoic rocks.

Résumé : La Formation d'Ikpiarjuk du Mésoprotérozoïque (bassin de Borden, au Nunavut) est constituée de monticules isolés de dolomie (>200 m d'épaisseur, diamètre de l'ordre de kilomètres) centrés sur des failles à l'échelle du bassin. Les monticules se sont accumulés en eau profonde pendant le dépôt du shale noir de la Formation d'Arctic Bay. Les monticules se composent de dolomie massive sans caractéristiques marquées avec, par endroits, une fabrique mouchetée ou grumeleuse. La fabrique grumeleuse est plus commune au centre des monticules, tandis que les fabriques massives et recristallisées sont répandues à la grandeur des monticules. L'évolution terminale de la croissance de chacun des monticules est unique. Certains monticules sont flanqués de coulées de débris à intraclastes, alors que des réseaux de fissures verticales remplies d'intraclastes sont présents près du sommet des monticules. L'un des monticules est coiffé d'un faciès d'eau peu profonde et de croûtes de tuf calcaire, tandis qu'un autre a été karstifié, puis recouvert de strates formées en eau profonde. Selon les interprétations, les monticules de la Formation d'Ikpiarjuk seraient des monticules fossilisés résultant de suintements froids, qui se sont accumulés près de fissures dans le plancher océanique associées à des failles actives. La texture grumeleuse, semblable à celle de thrombolites, laisse supposer que la précipitation des carbonates a été influencée par des communautés microbiennes benthiques chimiosynthétiques, jusqu'à maintenant inconnues dans les roches du Mésoprotérozoïque.

INTRODUCTION

The Mesoproterozoic Milne Inlet graben (Borden Basin; <1.2 Ga) was tectonically active throughout its depositional history, with episodes of rifting and subtle extension, and intervals of compression, that resulted in pronounced differential uplift and erosion. Much of the extensional adjustment in the Milne Inlet graben was accommodated on major northwest-trending faults, both at graben margins and inside the graben. The Ikpiarjuk Formation (Turner, 2009), consists of large, isolated, dolostone mounds that were deposited during deposition of deep-water black shale of the Arctic Bay Formation (Turner, 2009; Turner and Kamber, 2012). Mounds of the Ikpiarjuk Formation are unlike 'normal' Phanerozoic carbonate mounds, and are dissimilar to the stromatolite reefs that are characteristic of Precambrian shallow-marine carbonate rocks. The mounds are interpreted to have accumulated in deep water, below the photic zone, and are characterized by a subtly clotted fabric. They are centred along, and elongate parallel to, basin-scale faults that were periodically reactivated throughout the evolution of the basin (Turner, 2009). The mounds are kilometres in diameter and hundreds of metres thick. At least five isolated mounds have been identified in outcrops (Turner, 2009). This paper describes the mesoscopic composition of the mound lithofacies from two mounds studied in summer, 2011.

GEOLOGICAL SETTING

The Mesoproterozoic Borden Basin is exposed on northern Baffin Island and consists of three grabens, of which the largest is the Milne Inlet graben (Fig. 1). The Milne Inlet graben contains many longitudinal intragraben faults and is filled with strata of the Bylot Supergroup (Jackson and Iannelli, 1981; Scott and deKemp, 1998; Fig. 2). The Bylot Supergroup is crosscut by northwest-trending dykes associated with the Franklin igneous event (~723 Ma; Heaman et al., 1992; Pehrsson and Buchan, 1999). Several tectonic settings have been suggested for the origin of the Borden Basin. It was originally interpreted to have developed as a rift basin that experienced several intervals of downwarping followed by renewed rifting (Jackson and Iannelli, 1981; Knight and Jackson, 1994). Sherman et al. (2002) suggested that the basin originated as a rift that evolved into a foreland basin. The tectonic evolution of the basin has recently been re-evaluated (Turner, 2009, 2011; Long and Turner, in press; Fig. 3).

The Borden Basin formed during initial doming and splitting associated with the Mackenzie igneous event (Long and Turner, in press). Tholeiitic basalt of the Nauyat Formation is overlain by marine sandstone of the Adams Sound Formation, which was deposited during sag-phase sedimentation (Long and Turner, in press). Rift-like extension began during deposition of the Arctic Bay Formation (Turner and Kamber, 2012), which is dominated by sandstone-shale cycles. The upper Arctic Bay Formation in the northwestern part of the graben records deposition in a deep-water, euxinic shale basin (Turner, 2009; Turner and Kamber, 2012). During this time, a carbonate ramp (Iqqittuq Formation) developed in the southeast and deep-water, enigmatic dolostone mounds (Ikpiarjuk Formation; focus of this paper) developed throughout the basin along faults (Turner, 2004, 2009). After deposition of the Ikpiarjuk Formation mounds had ceased, the carbonate ramp developed into a rimmed platform in the southeast (Angmaat Formation) and deep-water laminated carbonate was deposited in the northwest (Nanisivik Formation; Turner, 2009). The basin was tectonically active during deposition of the Nanisivik and Angmaat formations (Turner 2009, 2011). Local subaqueous debris flows were shed off fault scarps in the basin and wedges of terrigenous clastic material were deposited along graben-bounding faults (Fabricius Fiord Formation; Jackson and Iannelli, 1981; Scott and deKemp, 1998). Following deposition of the Nanisivik and Angmaat formations, the basin was uplifted and tilted to the northeast, and underwent significant erosion (Turner, 2011). The basin was then re-submerged, and shale and limestone of the Victor Bay Formation was deposited throughout the basin as a northwest-deepening ramp during an interval of tectonic quiescence (Turner, 2011). The Victor Bay Formation was then uplifted and tilted, such that northwestern strata were karsted, but southeastern strata were drowned (Athole Point Formation; Sherman et al., 2002). The tectonic history of the upper part of the basin (Nunatsiaq Group) remains poorly known (Knight and Jackson, 1994).

METHODS

This study is based on field-based study of two Ikpiarjuk Formation mounds undertaken in 2011. The relationship between mound lithofacies and the surrounding strata was examined, stratigraphic sections were measured and described, and samples were collected. Lithofacies descriptions are based on field data and cut slabs augmented with petrographic descriptions for a few critical features. A detailed petrographic study will be presented in a future publication.

MOUND ARCHITECTURE

Red Rock mound

Mound geometry

Red Rock mound is a north-northwest-trending mound exposed on both walls of Red Rock valley (Fig. 1 and 4). The mound is approximately 20 km long and up to 5 km wide.

The thickest part of the mound is exposed in cliffs on both sides of Red Rock valley. In the centre of the valley, a small (<50 m thick) isolated moundlet is exposed below the base of the main mound and surrounded by Arctic Bay Formation

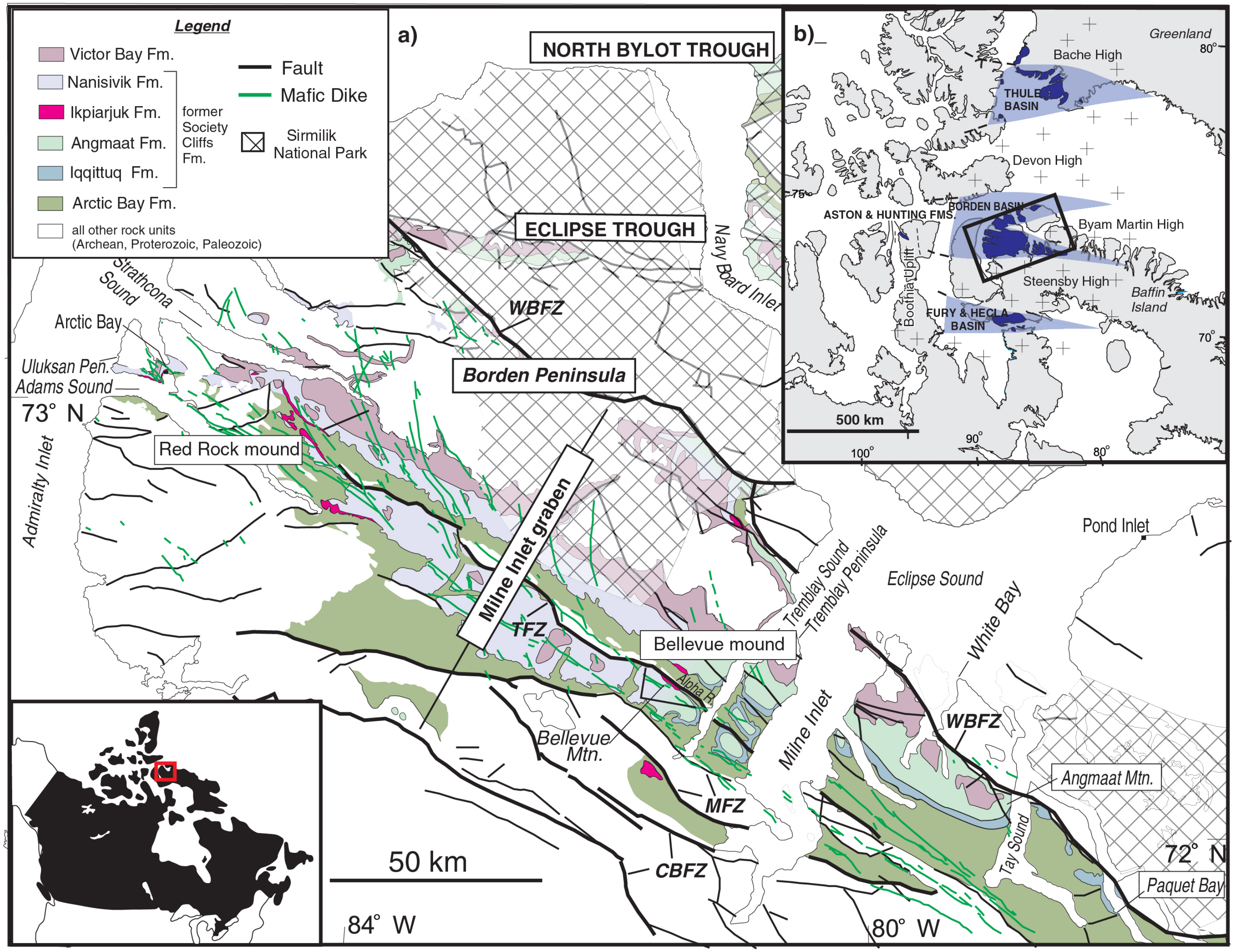

Figure 1. a) Map of northern Baffin Island illustrating the distribution of Ikpiarjuk Formation mounds and recently revised stratigraphy of the Milne Inlet graben (Turner, 2009). Locations of mounds described in text are marked. Abbreviations for structures are WBFZ, White Bay Fault Zone; TFZ, Tikirarjuaq Fault Zone; MFZ, Magda Fault Zone; CBFZ, Central Baffin Fault Zone. **b)** The location of the Borden Basin along with the Mesoproterozoic Bylot Basins (Jackson and Iannelli, 1981; LeCheminant and Heaman, 1989) with present day exposure in dark blue and the former extent of the basins (Jackson and Iannelli, 1981) in pale blue."

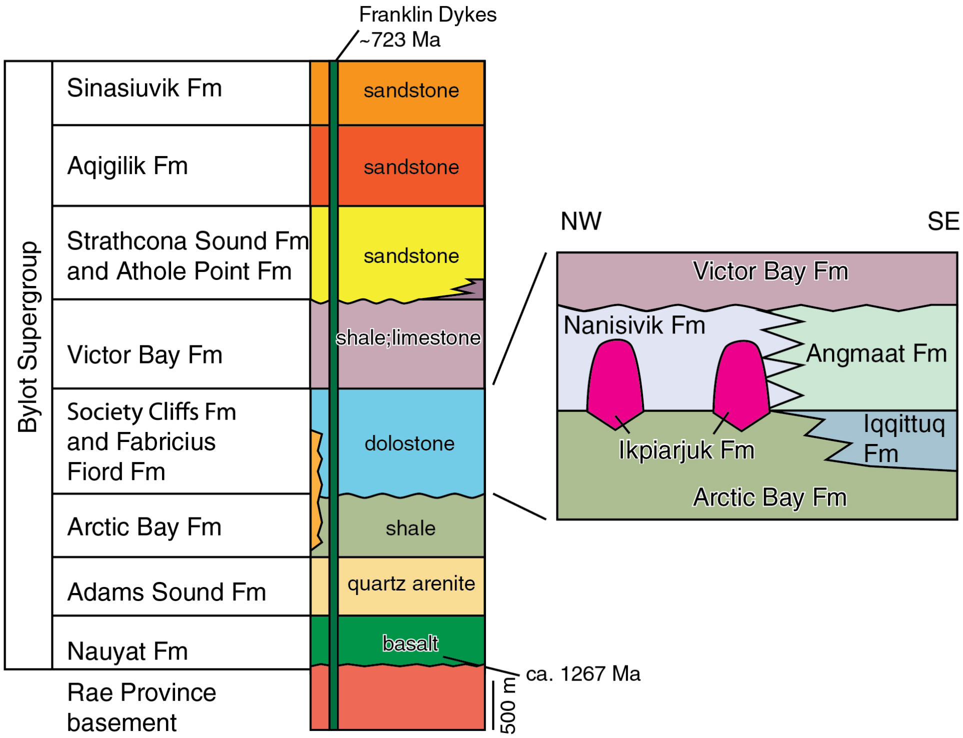

Figure 2. Original stratigraphy of the Milne Inlet graben from Jackson and Iannelli (1981) and Knight and Jackson (1994) with amendments by Turner (2009).

	Formation	Tectonic History	Environment of deposition	Reference
Bylot Supergroup	Sinasiuvik Fm	Unknown	Locally derived material and fluvial quartz sandstone Complex paleotopography	Jackson and Iannelli, 1981 Iannelli, 1992 Knight and Jackson, 1994
	Aqigilik Fm			
	Strathcona Sound Fm and Athole Point Fm			
		Uplift	Uplift and karst in west end Drowning and deepening in east (Athole Point Fm.)	
	Victor Bay Fm	Quiescence	Re-submersion, northwest, deepening ramp	Turner, 2009 Turner, 2011 Turner and Kamber, 2012
		Uplift/tilting	Dramatic uplift and tilting to the northwest	
	Nanisivik Fm; Angmaat Fm; Fabricus Fiord Fm; Ikpiarjuk Fm (Mounds); Iqqituq Fm; Arctic Bay Fm	Extension	Northwest deepening Alluvial fans (Fabricus Fjord Fm) at graben margins Active faults, local debris flows, soft sediment deformation Prograding carbonate ramp to platform in southeast Fault-related carbonate mounds through basin	
	Adams Sound Fm	Sag basin	Marine sandstone	Long and Turner, in press
	Nauyat Fm	Thermal doming	Basalt	
	Rae Province basement			

Figure 3. Revised stratigraphy of the Bylot Supergroup and associated tectonic and depositional environments during the different stages of development in the Milne Inlet Graben after Turner and others (Turner, 2009; 2011; Long and Turner, in press; Turner and Kamber, 2012). The former group names (Fig. 2) have been omitted because they are not relevant to new tectonic interpretations.

shale. Stylolites at a high angle to present-day horizontal (which are otherwise unknown in the basin) indicate that the moundlet was rotated after burial and chemical compaction. The Milne Inlet graben shows evidence of postdepositional deformation only in the vicinity of the major graben-bounding and intra-graben faults, generally in the form of subtle drag-folding. Post-burial rotation of the mound within its shale host supports the interpretation that a major intragraben fault (the Tikirarjuaq fault zone) continues along Red Rock valley from its mapped terminus to the southeast (Scott and deKemp, 1998; Turner, 2009, 2011). The moundlet is dominated by a conspicuously clotted lithofacies, which is described in detail below.

The lower contact of Red Rock mound is at least 100 m above the present-day top of the moundlet. The contact with underlying shale of the Arctic Bay Formation is sharp and appears to climb upwards stratigraphically to the south (Fig. 4b). The mound core is dominated by a clotted lithofacies (described in detail below) which varies in its characteristics with stratigraphic height (Fig. 5 and 6). The top of the mound is characterized by clotted fabric that has been modified extensively by dissolution. An intraclast debrite facies is exposed to the north and overlies a now-buried mound flank (Turner, 2004).

Lithofacies

Meso-clotted lithofacies: The meso-clotted lithofacies (Fig. 7a and 7b) is characterized by narrow, wispy, beige-grey clots surrounded by several generations of bladed isopachous cement. The clots form a network that is highly irregular in its configuration. Clots are generally bush-shaped, and up to 5 mm thick. Among the network of clots are irregularly shaped voids that range in size from 2 to 15 mm. The voids are filled with varying amounts of several generations of isopachous cement and locally contain internal sediment that

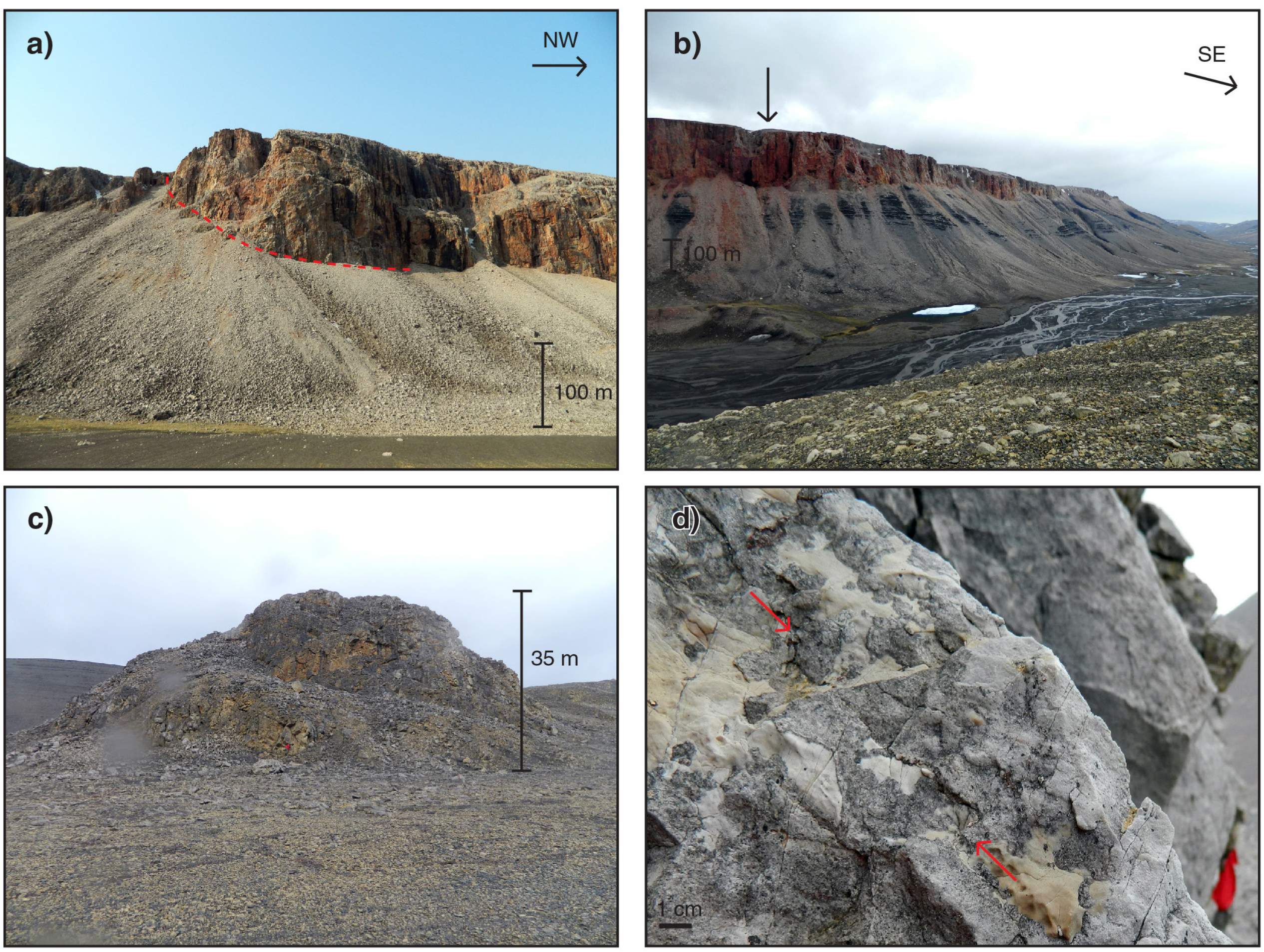

Figure 4. Exposures of Red Rock mound. **a)** Main measured section (~150 m) at Red Rock mound. 2013-053. **b)** Eastern exposure of Red Rock mound (arrow) extending southeast. The lower contact of the mound gradually climbs as the mound thins toward the south. Cliffs are approximately ~150 m high. 2013-037. **c)** Exposure of the Red Rock moundlet. Moundlet is isolated in black shale of the Arctic Bay Formation. 2013-055. **d)** Stylolite at 45° to present-day horizontal at Red Rock moundlet. 2013-040. All photographs by K. Hahn.

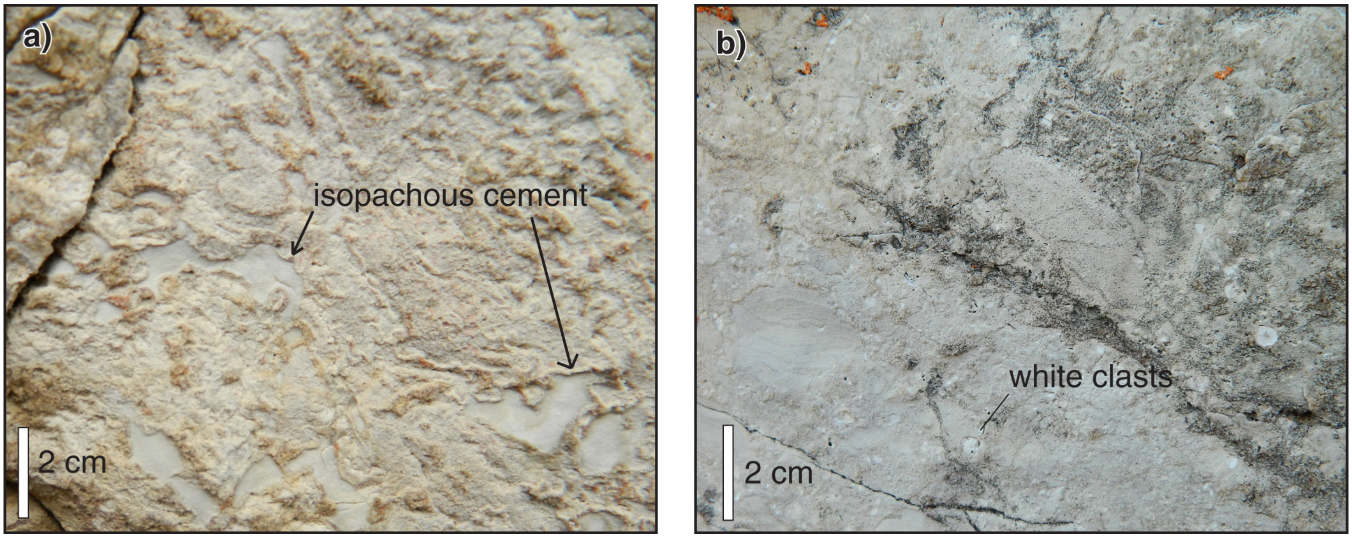

Figure 5. Exposure of Red Rock mound lithofacies. **a)** Clotted fabric exposed in the Red Rock moundlet. Note resistantly weathering rinds of isopachous cement and dolomudstone fill in voids. 2013-049. **b)** Intraclast wackestone to packstone with characteristic white clasts. Photographs by K. Hahn. 2013-036

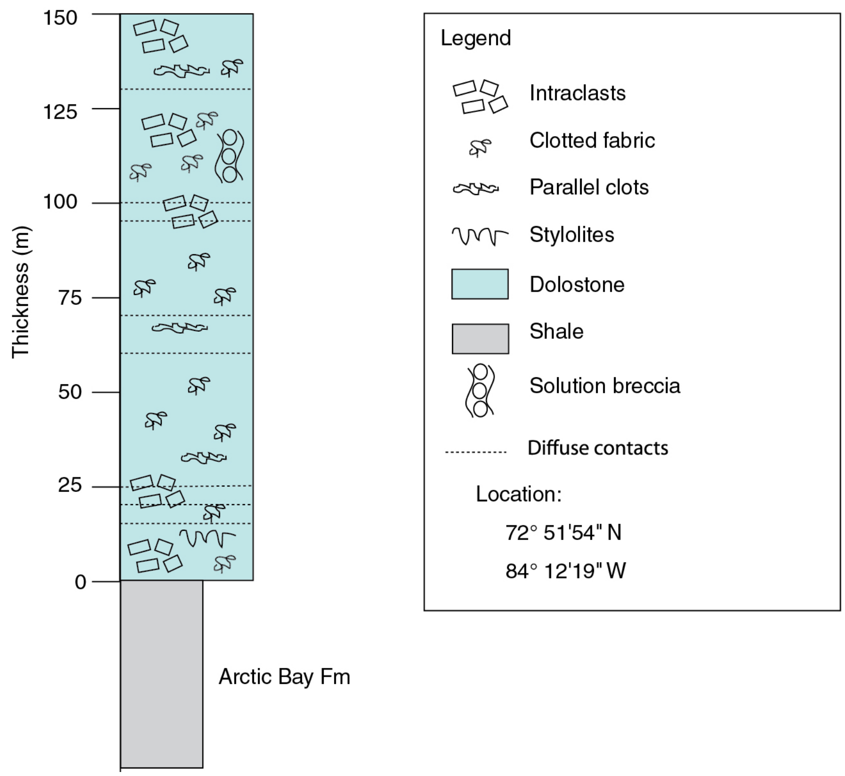

Figure 6. Stratigraphic section measured at Red Rock mound (Fig. 4). There are no sharp contacts between lithofacies; stratigraphic section is subdivided into crude zones of dominant lithofacies.

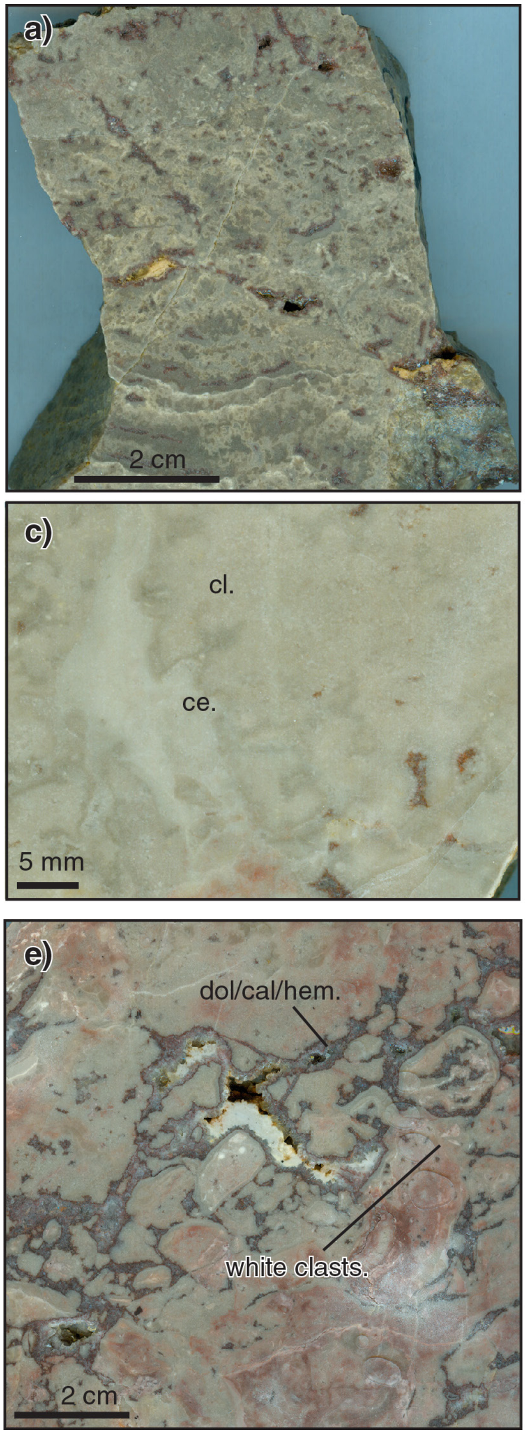

Figure 7. Dominant lithofacies in Red Rock mound. All photos are scans of wet cut slabs with stratigraphic 'way up' oriented toward top of page. **a)** Parallel clotted lithofacies. Note beige to pale grey clotted framework (dolomite), medium grey isopachous cement (dolomite), and late-stage purple dolomitic cement. 2013-054. **b)** Meso-clotted facies (cl). Note geopetal structure (GP), beige to pale grey clotted framework, medium grey isopachous cement (ic), and late-stage purple cement. 2013-044. **c)** Subtly clotted facies. Note subtle clots (cl.) and cement (ce) of similar colours. 2013-052. **d)** Massive dolostone facies. 2013-039. **e)** Solution breccia facies. Note late-stage dolomite/calcite/hematite cement fill of solution breccia. In this example the solution-brecciated rock was originally an intraclast wackestone to packstone. 2013-057. **f)** Intraclast wackestone to packstone. Note rare laminae of packstone and 'white clasts' with composition that contrasts with that of other mound lithofacies. 2013-056

postdates the isopachous cement. Geopetal structures are present but not common. Coarse, purple dolospar commonly fills the centres of voids (Fig. 7b) and lines healed fractures. This lithofacies is common in Red Rock moundlet and also throughout the main section at Red Rock mound. Toward the top of Red Rock mound, peloids and sand-grade intraclasts of massive dolomite in a dolomudstone matrix occupy the voids. Rarely intraclasts and peloids are trapped within individual clots.

Subtly clotted lithofacies: The subtly clotted lithofacies (Fig. 7c) is composed of relatively homogeneous, grey dolomudstone with poorly defined, randomly distributed clots. The clots are bush-shaped, are composed of grey dolomudstone, and are approximately 5 mm wide and 5 mm thick. The clots are variably connected and form larger clusters up to several centimetres in scale. Voids among clots are lined with isopachous dark grey cement and filled with light grey dolomudstone. Dark purple, coarsely crystalline dolospar is present in healed fractures and some voids (Fig. 7c). This facies is present throughout the main section at Red Rock mound.

Massive dolostone: The massive dolostone lithofacies is defined by massive mud-grade dolostone that is locally recrystallized. Rare, irregular spaces less than 2 mm in diameter are filled with purple cement resembles the clotted fabric. The massive facies is otherwise featureless.

Solution breccia lithofacies: The solution breccia lithofacies is present at the top of Red Rock mound. It is defined by an originally clotted fabric that is crosscut by zones of rounded, fitted, locally derived clasts of clotted fabric, which are cemented by late-stage coarse purple dolomite (Fig. 7e).

Intraclast wackestone/packstone/floatstone facies: The intraclast wackestone to packstone lithofacies consists of subangular clasts of massive, white dolostone in a dolostone matrix. The clasts are poorly sorted and range from <1 cm to >5 cm in diameter (Fig. 7f). This lithofacies is most common near the top of Red Rock mound north of the cliff-forming exposure. It is interstratified with laminated dolostone of the Nanisivik Formation.

Bellevue mound

Mound geometry

Bellevue Mound is exposed for approximately 5 km along the south side of a southeast- trending valley (Fig. 1 and 8). The thickest exposure of the mound is >200 m thick, and a nearly continuous vertical section can be accessed along a gully that runs through the centre of the mound exposure. Approximately 1 km east of the eastern margin of the mound, two smaller moundlets are exposed lower in the stratigraphy. The lower contacts of the moundlets are in sharp contact with Arctic Bay Formation shale, and their upper contacts appear to be in sharp to gradational contact with the overlying Iqqittuq Formation (outermost carbonate ramp). The moundlets are dominated by a clotted fabric with local intraformational conglomerates. The lowermost contact of the main part of Bellevue Mound is in gradational contact with both the Iqqittuq Formation (east) and the Arctic Bay Formation (west) (Fig. 9). The vertical and lateral transitions between shale of the Arctic Bay Formation and carbonate-dominated strata of the Iqqittuq Formation is also gradational. The upper contact of Bellevue Mound is overlain by shallow-water dolostone of the Angmaat Formation toward the east. The western flank of the mound is characterized by intraclast debrites interstratified with basinal laminite of the Nanisivik Formation.

<u>*Lithofacies*</u>

Mottled lithofacies: The mottled lithofacies is characterized by a rounded and irregular framework composed of coarsely crystalline spar. Among the framework components is dolo-microspar that contains 'floating' intraclasts and peloids of micritic dolomite. Fractures are common in the mottled facies and dolomite or calcite cement fills the fractures. Small (<1 mm) patches of hematite alteration are locally abundant. The mottled facies is common throughout the centre of the Bellevue Mound exposure. Recrystallization in the mottled facies resembles a subtle clotted fabric (Fig. 10a and b).

Purple-cemented breccia lithofacies: The purple cemented breccia lithofacies consists of angular clasts of massive dolomite, <5 mm to >3 cm in size. The clasts are poorly sorted and chaotically distributed, and are cemented by coarse, purple dolomite cement and locally by clear calcite cement (Fig. 10c). The lithofacies is present at the top of Bellevue Mound in irregular subvertical crack-like structures approximately 1 to 50 cm wide. In structures that are around 1 cm wide, the clasts exhibit moderate sorting and all clasts are <5 mm in size. The subvertical breccia structures are in sharp contact with surrounding, intact wall rock. The wall rock adjacent to the breccia is composed of massive dolomite with zones of very subtle mottling.

Clotted lithofacies: The clotted lithofacies consists of an irregular network of subtle, bush-shaped clots (typically 1 by 1 cm), surrounded by cement, with mud-grade sediment in voids in the clot framework. This lithofacies is not as well defined as the clotted lithofacies at Red Rock mound (Fig. 11a). Multiple generations of isopachous cement are not obvious, but at least one generation of void-lining cement is conspicuous as more resistantly weathering material in outcrop. The clotted lithofacies is common in both of the Bellevue moundlets and along the eastern flank of the main mound, where it is commonly interstratified with wedges of intraclast wackestone to packstone. The clotted facies is locally partly silicified. Clots are locally aligned in a subparallel fabric.

Stylolitic dolostone: This rock consists of massive dolostone with local lithoclasts. Massive dolostone is variably recrystallized from microspar to coarse spar.

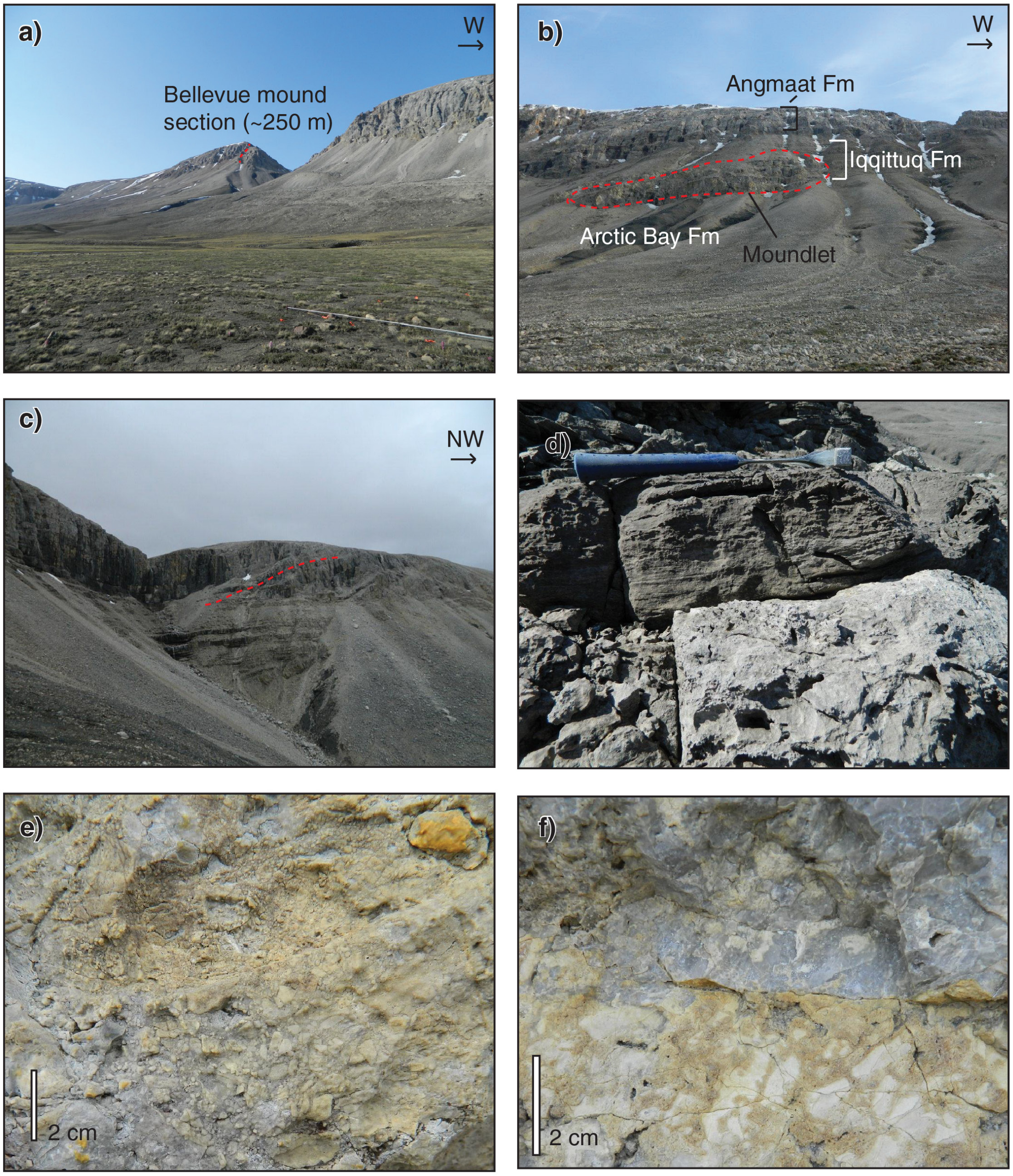

Figure 8. Exposure of Bellevue mound. **a)** Main measured section (~250 m) at Bellevue mound. 2013-051. **b)** One of the Bellevue moundlets, in black shale of the Arctic Bay Fm. and carbonate ramp strata of the Iqqittuq Fm. 2013-047. **c)** Eastern exposure of Bellevue mound. Note 'clinoform'-like inclined layers exposed on western side of stream cut (dashed line). Cliffs are ~100 m high. 2013-042. **d)** Interstratified intraclast wackestone to packstone (pale grey) and laminite of the Nanisivik Fm. (brown) exposed on the western flank of Bellevue mound. 2013-041. **e)** Intramound wackestone to packstone in the moundlets and along the eastern flank near Bellevue mound. 2013-045. **f)** Clotted fabric within the moundlets of Bellevue mound. Clots are more resistant-weathering and voids are filled with dolomudstone. 2013-035. All photographs by K. Hahn.

There is no preferred distribution of the recrystallized material. Stylolites are common parallel to bedding and are also present along sutured grain contacts of coarsely crystalline spar. Subrounded lithoclasts range in size from a few millimetres to 2 cm. Lithoclasts are composed of alternating laminae of fine-grained siliciclastic mud and concentrations of individual, euhedral, coarse dolomite crystals floating in an opaque matrix of iron oxides. This facies is present only at the base of Bellevue Mound (Fig. 9 and 11b).

Irregularly laminated lithofacies: In rare zones in the moundlets, an irregularly laminated lithofacies is present. This lithofacies is characterized by crinkly lamination with common stylolites. The irregularly laminated lithofacies is present as layers several tens of centimetres thick separating intervals of clotted moundlet material.

Massive lithofacies: The massive dolostone facies consists of relatively uniform dolostone with local zones of variable recrystallization. In thin section, medium-crystalline dolospar contains local concentrations of finer and coarser dolomite. Silica replacement of crystalline dolospar is present throughout the facies. Hematite alteration is common in this facies, which is present through the entire mound.

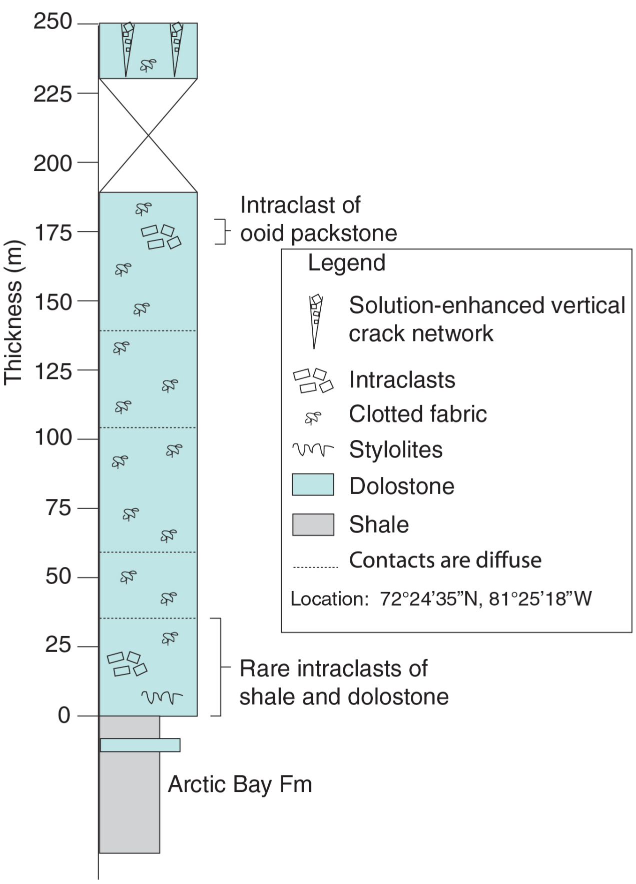

Figure 9. Stratigraphic section measured at Bellevue mound (Fig. 8). There are no sharp contacts between facies; stratigraphic section is subdivided into zones of dominant lithofacies.

Intraclast wackestone to packstone lithofacies: The intraclast wackestone to packstone facies is composed of subangular clasts of dolostone in a dolomudstone matrix (Fig. 11c). This facies is commonly associated with the mesoclotted facies along the eastern flank of Bellevue Mound and in the moundlets. This lithofacies is present as wedges tens of centimetres thick that pinch out laterally. This facies is interstratified with and in sharp contact with the mesoclotted facies.

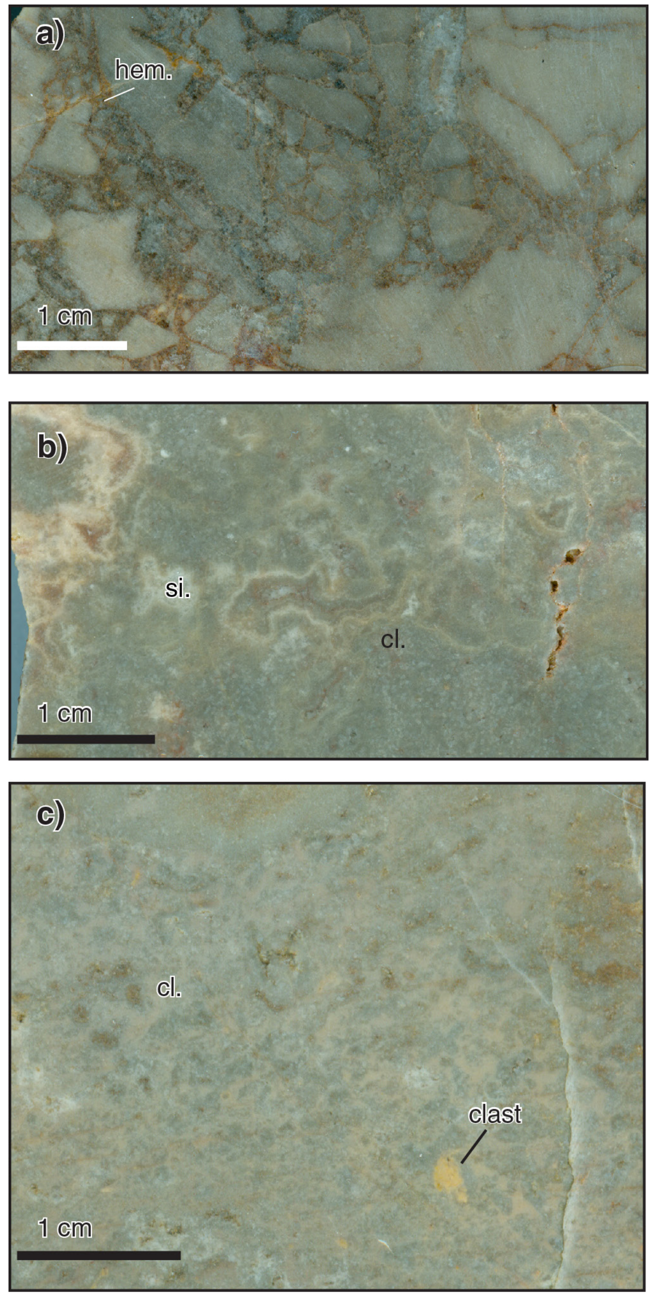

Figure 10. Major lithofacies of Bellevue mound. All photos are scans of wet cut slabs with depositional 'way up' oriented toward top of page. **a)** Purple-cemented breccia facies. Note angular clasts and hematite-rich cement. 2013-038. **b)** and **c)** Examples of the mottled facies. Clots (cl) are subtle and are rarely enhanced by silicification (si). 2013-048, 2013-058

Intraclast floatstone lithofacies: The intraclast floatstone lithofacies is common in the mound top and the western flank of Bellevue mound. It is characterized by poorly sorted, subrounded to subangular clasts of massive white dolostone floating in a dolostone matrix. This lithofacies is commonly interstratified with laminated dolostone of the Nanisivik Formation.

INTERPRETATION OF MOUND FACIES

Benthic precipitates: The clotted lithofacies documented in both mounds is interpreted as benthic precipitates. Precipitation of several generations of isopachous cement was nucleated on clots of carbonate mud of unknown origin. The presence of internal sediment in geopetal structures

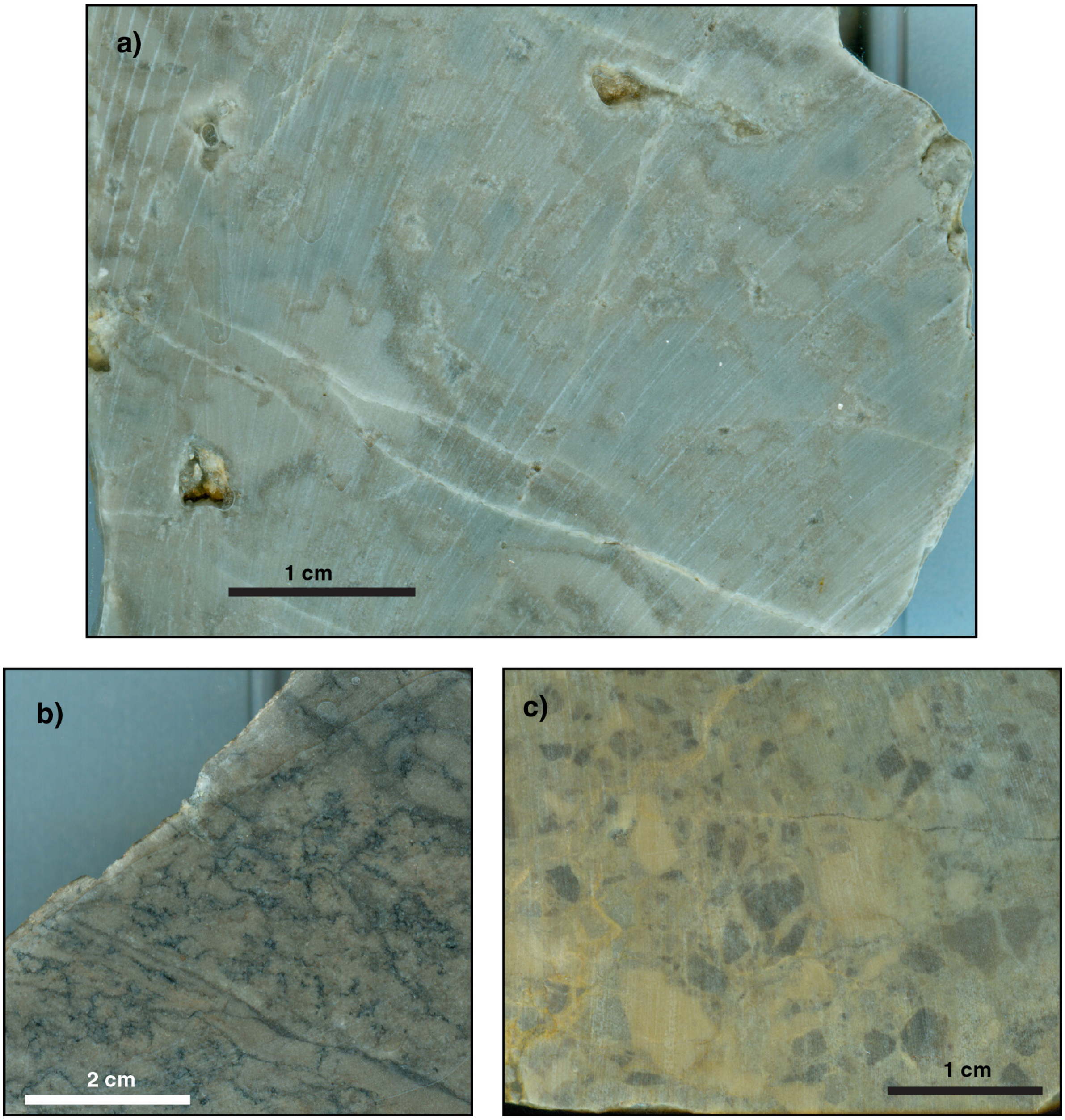

Figure 11. Major lithofacies of Bellevue mound. All photos are scans of wet cut slabs with 'way up' oriented toward top of page. **a)** Clotted facies from the Bellevue moundlets. Clots are more subtle than the clotted facies at Red Rock mound. 2013-050. **b)** Stylolitic lithofacies with stylolites parallel to bedding and sutured grain contacts along coarse crystalline spar. 2013-046. **c)** Intraclast packstone from Figure 8e. Note variable composition of clasts. 2013-043

in the void spaces among clots indicates that particulate carbonate was present in the water column and infiltrated through the clot framework's porosity.

Water-column precipitates: The massive lithofacies is interpreted as an accumulation of mud-grade particulate carbonate that precipitated in the water column and then settled to the seafloor. Local zones where the massive facies is more prevalent than the clotted facies suggest that at times during accumulation of the mounds or in particular areas of mounds, water-column precipitation was a more important driving factor than benthic precipitation (Fig. 12). This lithofacies zonation was controlled by variations in water chemistry, which may have at times become supersaturated with respect to carbonate and caused spontaneous mass precipitation of carbonate (similar to whitings in modern carbonate environments).

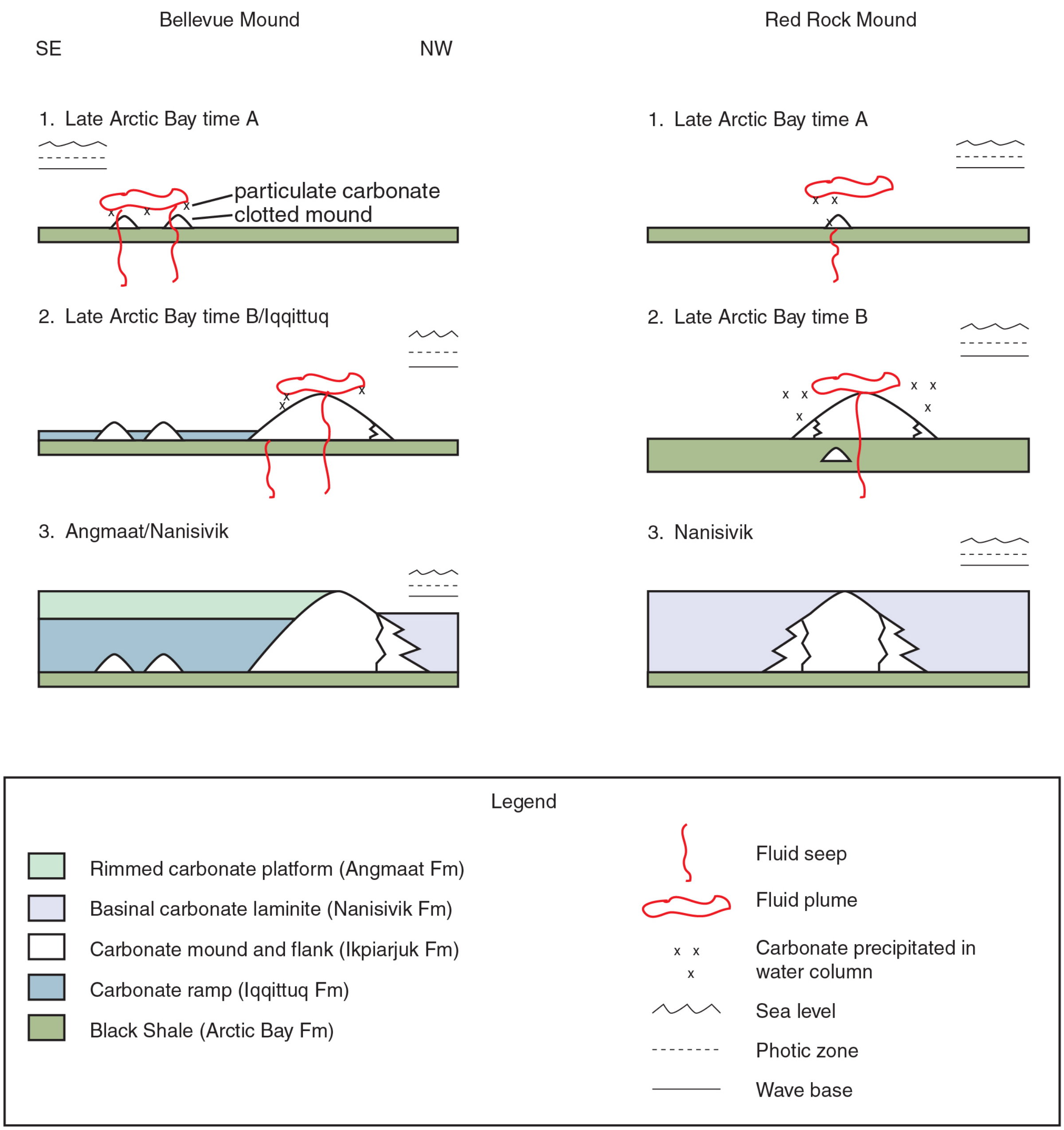

Figure 12. Interpreted evolution of Bellevue and Red Rock mounds. Both mounds formed late in deposition of the Arctic Bay Fm. Both mounds show benthic carbonate precipitates in the mound cores. Particulate carbonate was present in the water column, originated from fluids expulsed from the active seeps, and was deposited as massive carbonate mudstone facies. Both mounds show evidence of flanking facies of resedimented material shed from the mounds.

Mound-derived debrites: The thin beds of intraclast wackestone to packstone are interpreted as small debrites within mounds. The thick-bedded wackestone/packstone to floatstone lithofacies is present along the mound flanks is interpreted as a product of erosion from the topographic highs of the mounds. Material continued to shed off the mounds well after vertical accumulation (by benthic and water-column processes) of the mounds ceased as indicated by the interstratification of mound-derived breccia with laminite of the Nanisivik Formation.

The origin of the purple-cemented breccia facies at the top of Bellevue Mound is unclear.

DISCUSSION OF POSSIBLE ORIGIN OF MOUNDS

The mounds are elongate and centred along regional faults, indicating that proximity to faults was the single most important control on mound growth. The lack of any shallow-water lithofacies throughout the mounds indicates that these carbonate masses did not nucleate or accumulate in normal Proterozoic shallow-water carbonate depositional environments. Faults that intersected the seafloor and were undergoing displacement acted as porous zones where an inferred fluid was expelled through fissures, probably as cold seeps (Fig. 12). Syndepositional tectonic activity is conspicuous in the stratigraphy and sedimentology of contemporaneous black shale deposits of the Arctic Bay Formation, which surrounds and underlies the mounds (Turner and Kamber, 2012). The fluid composition is the focus of current study.

Modern cold seeps that produce particulate carbonate from solutes include methane- and alkali-rich waters. In both cases, where carbonate is accumulating, complex microbial communities of chemosynthetic bacteria are known to catalyze the precipitation of carbonate material. The relationship between bacteria and carbonate precipitation in these environments is complex and difficult to document. Modern locations of active methane seeps include the Hikurangi Margin of New Zealand (Liebetrau et al., 2010), the Congo Fan (Feng et al., 2010), and the Eel River Basin of California (Orphan et al., 2004). In each of these locations, in situ carbonate crusts are common on the seafloor. The carbonate crusts in these study areas are characterized by benthic precipitates and an irregular network of pores. This texture is very similar to the clotted fabric observed in the Ikpiarjuk mounds. Diverse communities of chemosynthetic bacteria, documented at modern methane seeps, catalyze the precipitation of carbonate through anaerobic oxidation of methane (AOM). The Ikpiarjuk Formation mounds are interpreted having formed in deep water under the same anoxic conditions that characterized the Arctic Bay Formation's black shale (Turner and Kamber, 2012). The AOM reaction does not require the presence of oxygen, and so this is one possible origin of the clotted fabric documented in this study. One caveat to the suggestion of AOM as the origin of carbonate in the Ikpiarjuk mounds is that in the modern environment AOM requires the presence of sulphate-reducing (pyrite-producing) bacteria. No significant pyrite has been documented in mound facies.

Alkali-rich springs are also known to induce the precipitation of carbonate. Alkali-rich springs can produce carbonate in a variety of environments, including terrestrial travertine deposits, and subaqueous tufa deposits in lakes and marine water. Lithofacies documented in various types of spring deposits are remarkably similar to those documented at modern methane seeps, and to those in the Ikpiarjuk Formation mounds (e.g. Council and Bennett, 1993; Buchardt et al., 2001). All such lithofacies are dominated by benthic precipitates and abundant primary pore space.

The clotted fabric, common throughout the mounds, is also similar to fabrics observed in thrombolites (bacterial origin; Aitken, 1967). It has been demonstrated that in modern environments, microbial organisms almost always exert some control on the precipitation of carbonate (e.g. Chafetz and Buczynski, 1992; Turner and Jones, 2005). Microbes induce precipitation either directly or indirectly. It is difficult to demonstrate the influence of microbes in the precipitation of carbonate in these environments because microbial communities exist in all ecological niches in the modern environment and there are no environments that are barren of microbial communities (e.g. Council and Bennett, 1993; Buchardt et al., 2001; Feng et al., 2010).

Future work on the Ikpiarjuk Formation mounds will include detailed petrography to determine the paragenesis of mound phases, and geochemical analyses to define the geochemistry of basin water and fissure fluids at the time of mound deposition.

CONCLUSIONS

The Ikpiarjuk Formation mounds represent fossilized cold-seep deposits of as-yet unknown fluid composition.

The clotted fabric that characterizes the mounds is a benthic precipitate that formed throughout mound deposition. Particulate carbonate was also present in the water column, and accumulated in vast quantities in some places at certain times. The spatial and temporal distribution of benthic versus water-column carbonate precipitation was complex.

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