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Critical review

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Abstract: The Neoproterozoic Franklin magmatic event, related to the breakup of Laurentia, is predominantly characterized by intrusive sills and dykes that extend across Arctic Canada. Associated Natkusiak Formation flood basalts are exposed as erosional remnants within the core of a shallow syncline and cap sedimentary rocks of the Proterozoic Shaler Supergroup on Victoria Island in the western High Arctic, Northwest Territories. This study addresses the physical volcanology and stratigraphy of the southern lobe Natkusiak Formation flood basalts. The southern Natkusiak Formation is herein divided into four units. The basal unit consists of rare pillowed flows and common, laterally discontinuous, 1 to 10 m thick, basalt flows. These are overlain by a massive volcaniclastic conglomerate and quartz-rich volcaniclastic sandstone. Together these units are up to 100 m thick. The upper volcanic unit comprises 10 to 30 m thick, laterally continuous flows that are utilized as a stratigraphic datum. The four units are correlative to the previously established lower Natkusiak Formation stratigraphy of the northern lobe. Basal units of the volcanic pile show marked lateral thickness variations implying the existence of significant topography prior to onset of the main phase of Franklin volcanism associated with the breakup of Laurentia. Establishing such volcanostratigraphic relationships across the Minto Inlier will help to better understand and constrain the paleoenvironment of volcanism and provide a solid reference locality for comparisons with similar events during the break-up of Rodinia.

Résumé : L'événement magmatique de Franklin du Néoprotérozoïque, lié à la fragmentation de la Laurentie, se manifeste principalement par des filons-couches et des dykes intrusifs qui sont présents dans tout l'Arctique canadien. Les basaltes de plateau de la Formation de Natkusiak qui y sont associés affleurent sous forme de lambeaux d'érosion au cœur d'un synclinal de faible épaisseur et coiffent des roches sédimentaires du Supergroupe de Shaler du Protérozoïque dans l'île Victoria, dans l'ouest du Haut-Arctique (Territoires du Nord-Ouest). La présente étude porte sur la volcanologie physique et la stratigraphie des basaltes de plateau du lobe sud de la Formation de Natkusiak. Nous divisons la partie sud de la Formation de Natkusiak en quatre unités. L'unité basale se compose de rares coulées en coussins et, plus couramment, de coulées de basalte latéralement discontinues, d'une épaisseur de 1 à 10 m. Ces coulées sont surmontées d'un conglomérat volcanoclastique massif et d'un grès volcanoclastique riche en quartz. Ensemble, ces unités atteignent une épaisseur de 100 m. L'unité volcanique supérieure comporte des coulées latéralement continues d'une épaisseur de 10 à 30 m, qui sont utilisées comme niveau repère stratigraphique. Les quatre unités peuvent être corrélées à celles de la stratigraphie précédemment établie du lobe nord de la Formation de Natkusiak inférieure. Les unités basales de l'empilement volcanique montrent de fortes variations latérales de l'épaisseur, laissant supposer l'existence d'un relief important avant l'amorce de la phase principale du volcanisme de Franklin associé à la fragmentation de la Laurentie. L'établissement de telles relations volcanostratigraphiques dans l'enclave de Minto aidera à mieux comprendre et cerner le paléoenvironnement du volcanisme et à fournir une localité de référence solide permettant d'établir des comparaisons avec des événements similaires survenus lors de la fragmentation de la Rodinie.

INTRODUCTION

Detailed studies of volcanic stratigraphy, in conjunction with the traditional focus on geochemistry and large-scale structures has resulted in a more thorough understanding of flood basalt provinces (Jerram and Widdowson, 2005). The nature of the volcanic facies present at the base of a flood-basalt sequence provides valuable information about the onset of volcanism, including the environment and mechanism(s) of eruption. Neoproterozoic continental basalts of the Natkusiak Formation, Victoria Island, Northwest Territories, are the erosional remnants of the extrusive phase of the Franklin magmatic event and are related to the breakup of Laurentia (Rainbird, 1993). The exposures are preserved as two lobes trending east-west and southwest-northeast, herein referred to as the southern and northern lobes respectively (Fig. 1). Previous studies of the Natkusiak Formation have focused mainly on the northern lobe (Dostal et al., 1986; Jefferson et al., 1985), where approximately 1100 m of volcanic stratigraphy was documented. Existing age data imply that magmatism occurred at ca. 718 to 723 Ma (Heaman et al., 1992). Additional radiometric dating is currently underway to help provide better age constraints. This contribution presents the results and implications of detailed and regional-scale mapping of the southern lobe of the Natkusiak Formation, and tentatively correlates the stratigraphy between the northern and southern lobes.

In the southern lobe, up to 200 m of volcanic stratigraphy conformably overlies quartz arenite of the Kuujjua Formation, the uppermost unit of the Shaler Supergroup. Within this volcanic pile we emphasize the lower units that record the initial extrusive phases of the Franklin magmatic event, followed by a period of volcanic quiescence recorded by a package of volcaniclastic rocks. These basal units of the volcanic pile show marked lateral thickness variations that imply significant paleotopography, indicating emplacement within valleys and channels. The uppermost preserved unit is a package of thick sheet flows belonging to the main phase of flood volcanism. The stratigraphy in the southern lobe corresponds to the basal, pyroclastic and lower massive members of the Northern lobe as described by Jefferson et al. (1985); suggesting that the stratigraphy of the northern and southern lobes may be correlative.

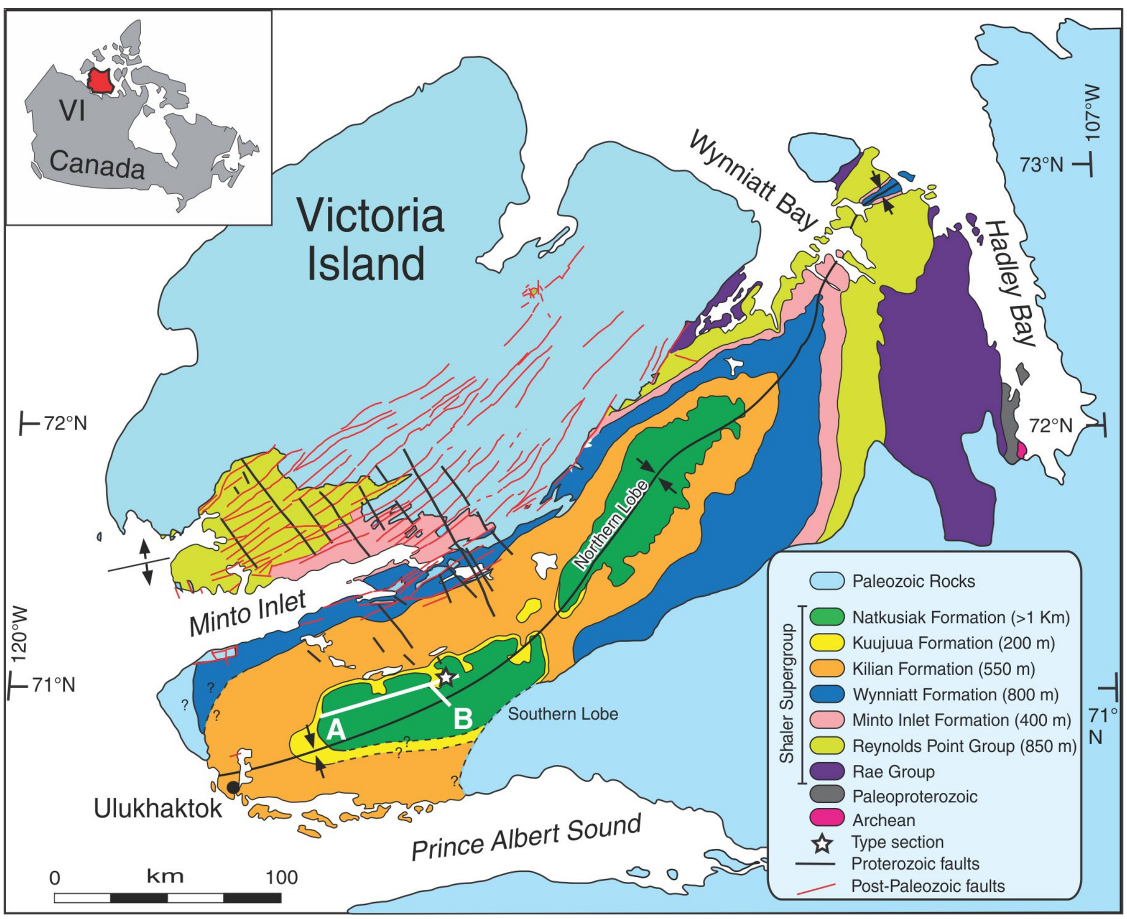

Figure 1. Regional geology of the Minto Inlier, Victoria Island (*modified from* Rainbird, 1993).

REGIONAL GEOLOGY

The Minto Inlier on northwestern Victoria Island preserves a thick package of sedimentary and igneous rocks gently folded along two northeast-trending axes. The Shaler Supergroup sedimentary rocks comprise a 4 km thick succession of shallow marine carbonate rocks, stromatolitic dolostones, shales, fluvial and deltaic sandstones, and evaporitic units that were deposited within the intracratonic Amundsen Basin during the Tonian-Cryogenian Neoproterozoic (Rainbird, 1993; Rainbird et al., 1996). Igneous rocks of the Minto Inlier consist of diabase sills and dykes, as well as the extrusive Natkusiak Formation flood basalts of the Franklin magmatic event. The sills and dykes intrude the sedimentary rocks of the Shaler Supergroup and represent the magmatic feeder system to the extrusive basaltic lavas that cap it, with north-northwest-trending faults guiding melt ascent in many cases (Bédard et al., 2012) (Fig. 2).

The Kilian and Kuujjua formations of the Shaler Supergroup directly underlie the Natkusiak Formation basalts. In the southern lobe the basalts conformably overlie sandstone of the Kuujjua Formation. Toward the northeast, however, the Kuujjua Formation pinches out so that the basalts unconformably overlie carbonate and evaporate units of the Kilian Formation (Rainbird, 1993). This, along with other evidence such as faulting and the discovery of rift-related conglomerates, led to the suggestion that these depositional relationships may be the result of domal uplift and extension caused by the impingement of a mantle plume on the base of the lithosphere (Rainbird, 1993).

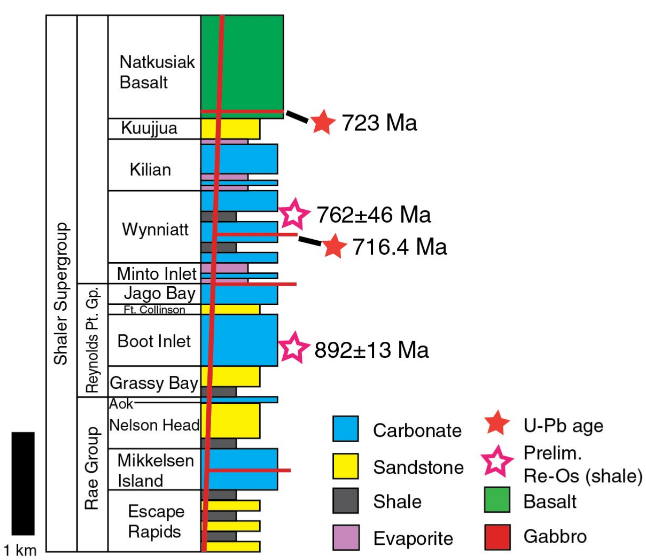

Figure 2. Stratigraphy of the Shaler Supergroup (Heaman et al., 1992; Macdonald et al., 2010; Rainbird, 1993; van Acken et al., 2013)

Southern lobe volcanostratigraphy

All descriptions in this section pertain to the southern lobe unless otherwise specified. The type section for this area is presented in Figures 3 and 4. Four main units have been recognized above the Kuujjua Formation: the basal V_0 volcanic unit, two clastic units, C_1 and C_2, and the V_1 basaltic sheet-flow unit. Other, stratigraphically higher, sheet flows are known to occur in the northern lobe, but these are not preserved in the south. The V_0 and V_1 units extend throughout the southern lobe, whereas the C_1 and C_2 clastic units pinch out toward the northwest and are absent in the western part of the area. The flow at the base of unit V_1 appears to be horizontal at all adequate exposures within the southern lobe, and thus we used its basal contact as a stratigraphic datum when measuring sections.

KUUJJUA FORMATION

The Kuujjua Formation is an alluvial-fluvial quartz arenite with well defined beds and large compound crossbeds. The paleoenvironment for the Kuujjua Formation is thought to have been a large river system with paleocurrents flowing toward the northwest (Rainbird, 1992). About 50 m below the Natkusiak Formation basalt, the Kuujjua sandstone locally contains basaltic clasts and interbedded volcanic material, suggesting that at least some volcanism was coeval with deposition of the sandstone (Rainbird, 1993). This is further supported by the presence of individual basaltic clasts that are indented by sand grains, suggesting deposition while the clasts were still malleable (Fig. 5a). The contact between the Kuujjua Formation and the Natkusiak basalts appears to be structurally conformable in many places, but is unconformable on a basin scale (Jefferson et al. (1985); Rainbird (1993)). Where it is exposed in the southern lobe, the contact is either sharp (Fig. 5b) or records the effects of interaction with water such as local pillowed basalt and hyaloclastic breccia within the basal 5 m of V_0 (Fig. 5c).

BASAL FLOWS (V_0)

The basal V_0 unit ranges in thickness from 30 m to over 100 m. It mostly consists of altered and crumbly basaltic lava flows traceable horizontally on a scale of about 500 to 1000 m that are, however, rarely traceable between stratigraphic sections. Individual flow units range in thickness from 1 to 5 m at the base of V_0 and gradually thicken toward the top of V_0 where they become as thick at 10 m. The flows generally have massive basal portions with vesicular, crumbly weathering flow tops. The flow tops weather recessively, highlighting individual V_0 flows on cliff exposures (visible in Fig. 4). It appears that architecturally simple, thin flows, displaying massive cores of varying degrees of vesicularity and crumbly vesicular flow tops, are the dominant flow morphology in most of unit V_0. In addition, what appear to be small (1 to 2 m) interweaving lobate-shaped flow lobes with chilled selvages (although the selvages are rarely well preserved) are present in outcrops at the base of V_0 in some locations. Two examples of ropy flow-top texture were found within talus proximal to an outcrop of the basal unit. In addition, many outcrops are flaggy in appearance, with distinct bedding-parallel partings, which might indicate an origin as amalgamated spatter (agglutinate). Pillow textures are preserved within the basal unit only in a few places, and are usually difficult to identify due to the weathered and crumbly nature of the section. However their glassy, hyaloclastite-textured rinds are well preserved, as are some examples of radial fracturing. A'a-type flows were not recognized.

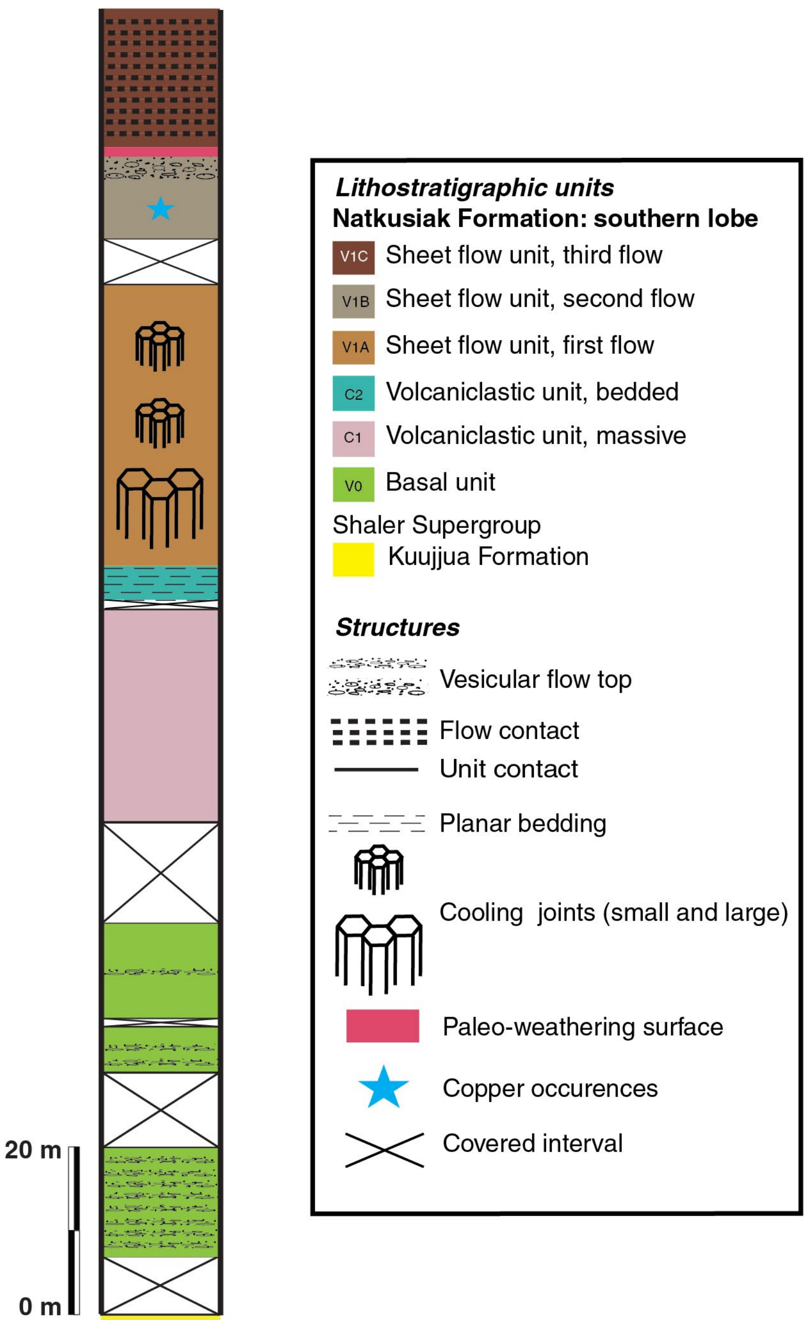

Figure 3. Type Section for the southern lobe Natkusiak Formation. Location of the section is indicated by the star in Figure 1 and is circled in yellow on the map of Figure 4.

Basal V_0 lavas are texturally diverse. Many samples are massive, fine-grained basalt with a groundmass of plagioclase laths, interstitial material with small intergranular crystals of pyroxene, and no significant phenocrysts. Other basalt samples are coarse and vesicular (10–20% vesicles), featuring ~1 mm sized clinopyroxene intergrown with plagioclase laths (~0.5 mm) (Fig. 6a). This subophitic texture occurs throughout V_0 but is most prominently developed in the lowermost flow units near the contact with underlying sandstone. Vesicles within V_0 are rounded to irregularly shaped and vary between 0.5 and 1 cm. Flow bases are commonly characterized by pipe-shaped or slightly flattened vesicles whereas flow tops typically contain rounded to subrounded vesicles (Fig. 6b). Vesicles are generally filled with quartz, calcite, prehnite, and pumpellyite, suggesting burial at greater than 2 km depth (Schiffman, 1995).

VOLCANICLASTIC UNITS C_1 AND C_2

Two distinct volcaniclastic units (C_1 and C_2) occur in the southern lobe (Fig. 7a). Regionally, stratigraphic sections of C_1 and C_2 clearly show a pattern of pinch and swell, and the units are absent from the western part of the southern lobe. The observed pattern suggests deposition in paleovalleys oriented approximately north-northeast to northeast with a maximum relief of 50 to 100 m.

The thickness of the C_1 volcaniclastic unit ranges from 0 to 50 m. The contact between the V_0 flows and the C_1 volcaniclastic unit is recessive, and was not observed. In outcrop, C_1 is dark maroon to brown in colour, massive, and structureless. C_1 typically displays a crumbly, flaky weathering pattern evocative of mudstone, but also weathers in a conchoidal pattern in some places. Unit C_1 is compositionally heterogeneous, and contains scoriaceous basalt clasts; rounded, slightly strained quartz grains; rectangular, elongate fine-grained mudstone clasts; and dark, small (0.25 to 2 mm), angular to subrounded clasts of unidentifiable composition. Clasts range in size from granule to fine cobble (~7 cm). In addition, the flat elongate clasts appear to be aligned along their long axes. The deposits are very poorly sorted, and appear to contain abundant mafic material, mainly present as groundmass (Fig. 7b). The C_1 unit also contains sandstone clasts up to 2 cm in size. Based on composition (dark colour, high abundance of basalt fragments, and mafic groundmass) we tentatively classify C_1 as a mafic volcaniclastic deposit, as described by Ross et al. (2005). Based on clast size and fabric (Wentworth, 1922) we would classify C_1 as a volcanic pebble conglomerate.

The C_2 volcaniclastic unit ranges in thickness from 0 to 30 m and has a much more restricted distribution than unit C_1. Where present in the southern lobe, it appears to conformably overlie C_1 even though the contact zone is recessive. In one river-cut, C_2 forms a lens within C_1. In outcrop, rocks of C_2 have a cream to green colour and generally display normally graded beds on the scale of a few centimetres. In at least two locations crossbeds are preserved. Similarly to C_1, C_2 contains quartz grains, with scoriaceous basalt and mudstone clasts; however, it has a higher percentage of quartz grains, more sand-sized to pebble-sized grains, and a more well sorted texture in a predominantly calcareous matrix (Fig. 7c). In addition, a few carbonate clasts were noted within C_2. In a few samples distributed from the middle to the top of the unit, it appears as though the amount of quartz grains and calcite cement increases, whereas the number of scoriaceous basalt clasts decreases. Based on composition as well as clast size, sorting, and fabric, we tentatively classify C_2 as a fine-pebble volcanic conglomerate.

FLOW UNIT V_1

Basalt flows of unit V_1 cap the volcanic succession in the southern lobe. This unit is a succession of thick, laterally continuous, sheet flows typical of flood basalt provinces (Bryan et al., 2010). Three flows are preserved within unit V_1: V_{1A}, V_{1B}, and V_{1C} (Fig. 8a). Where preserved, the

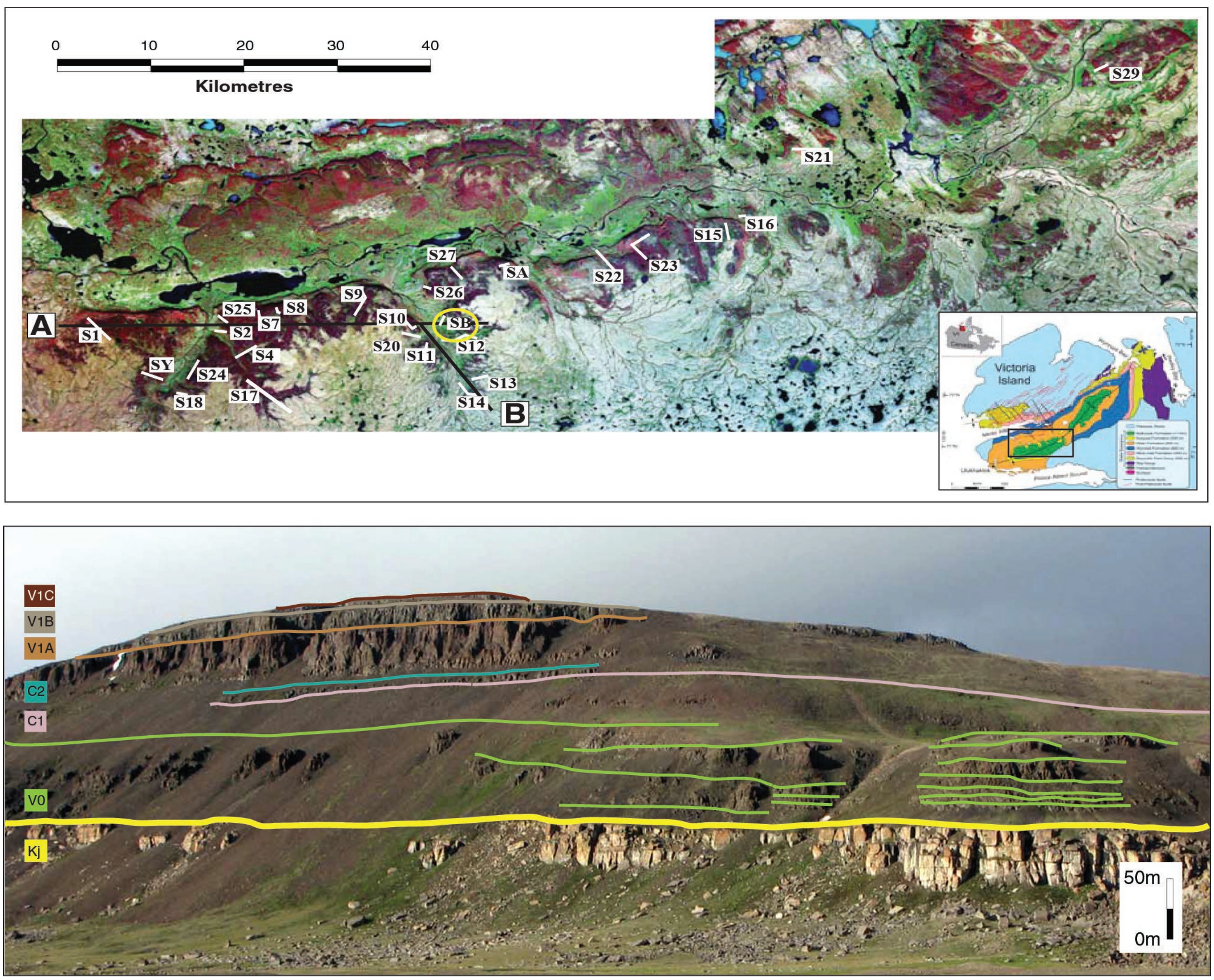

Figure 4. Type section for the southern lobe Natkusiak Formation. Location of the section is indicated on the inset map by the yellow circle. Line colours represent the top contacts of indicated units. Photograph by N. Williamson. 2013-248

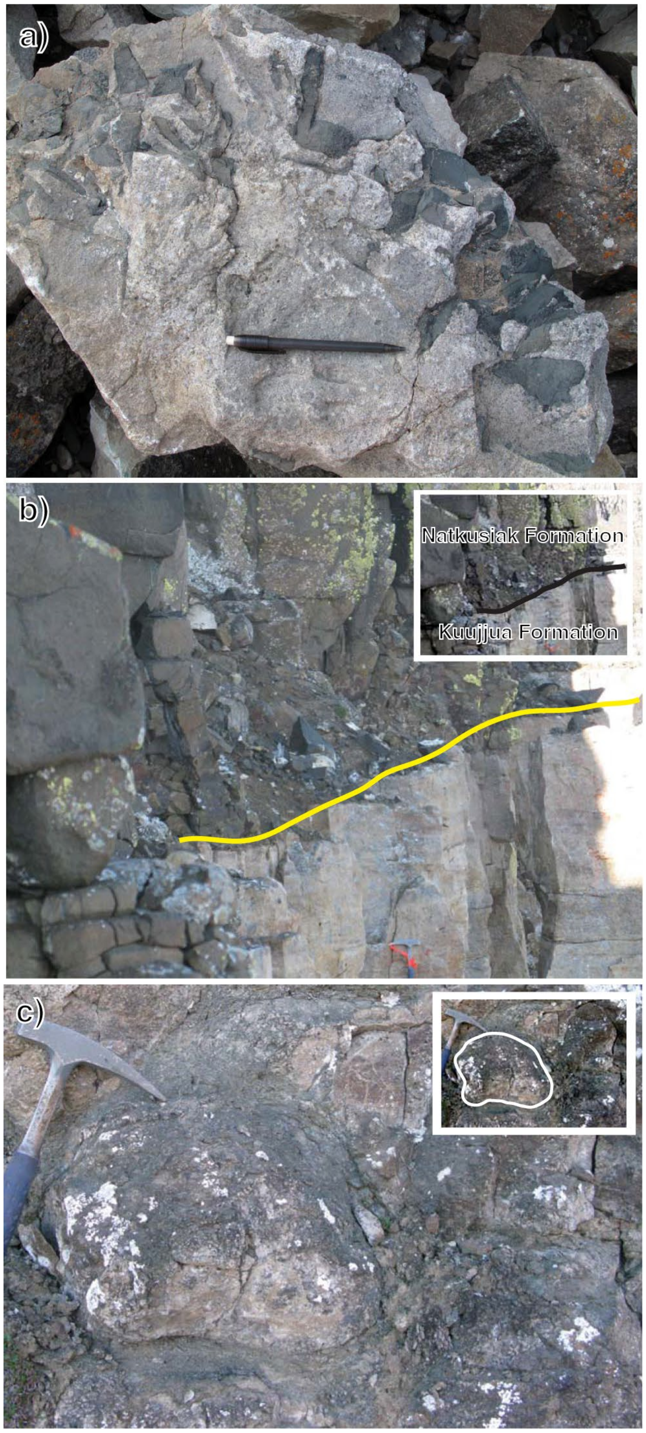

Figure 5. Photographs showing contact characteristics of the Kuujjua and Natkusiak Formations. **a)** Block of Kuujjua sandstone with imbedded basalt clasts, pen for scale. Photograph by R. Rainbird. 2013-246. **b)** Sharp contact between the Kuujjua and Natkusiak formations. Hammer for scale is at bottom of view. Photograph by N. Williamson. 2013-244. **c)** Pillowed basalt at the base of unit V_0. Photograph by N. Williamson. 2013-245

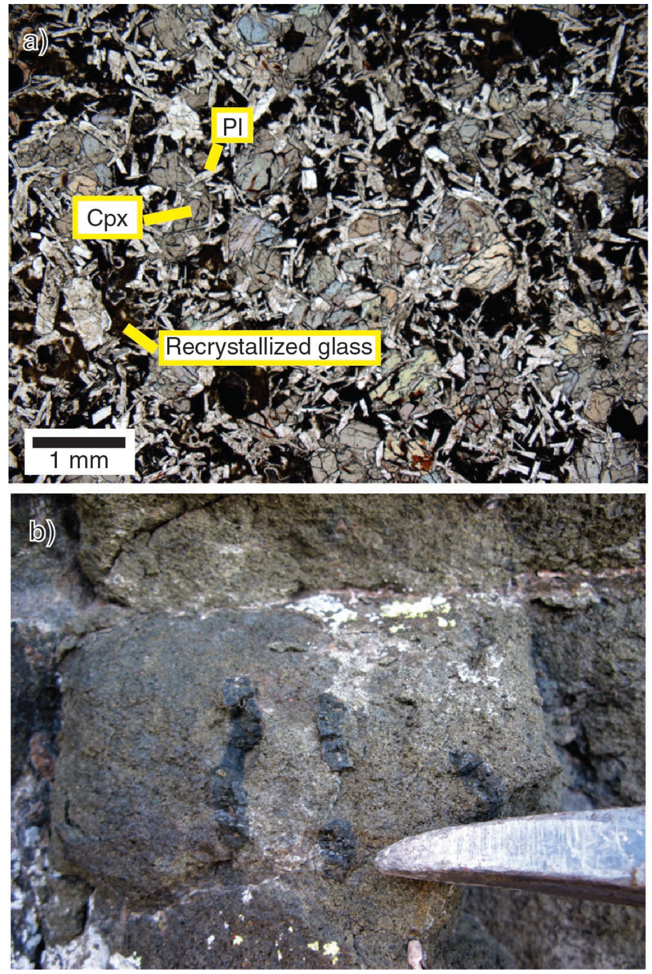

Figure 6. Photographs showing characteristics of the V_0 basal unit. **a)** Photomicrograph (2.5x magnification, plane-polarized light) showing subophitic texture of plagioclase (Pl) and clinopyroxene (Cpx) 2013-254. **b)** Pipe vesicles in a V_0 flow. Photo by N. Williamson. 2013-247

contact between the C_2 volcaniclastic unit and the overlying first flow of unit V_1 is sharp and follows the general attitude of the C_2 beds, with the base of the V_{1A} flow highly vesicular but largely unbrecciated (Fig. 8b). In one location, unit V_1 directly overlies volcaniclastic unit C_1. The contact between them appears to be rubbly and brecciated. In locations where units C_1 and C_2 are not present, i.e. the western southern lobe, unit V_1 is thought to conformably overlie unit V_0, even though the break between units has not been observed in the field, because the flow orientation is similar above and below the supposed contact.

Flow V_{1A} is close to 35 m thick, has a distinct orange to brownish-red weathering colour, and commonly displays lower colonnade and entablature columnar jointing, along with a highly vesicular and mildly brecciated flow base. These features, as well as its lateral continuity and presence throughout the southern lobe, make it a useful marker unit. Flow V_{1B} is approximately 15 m thick and weathers a

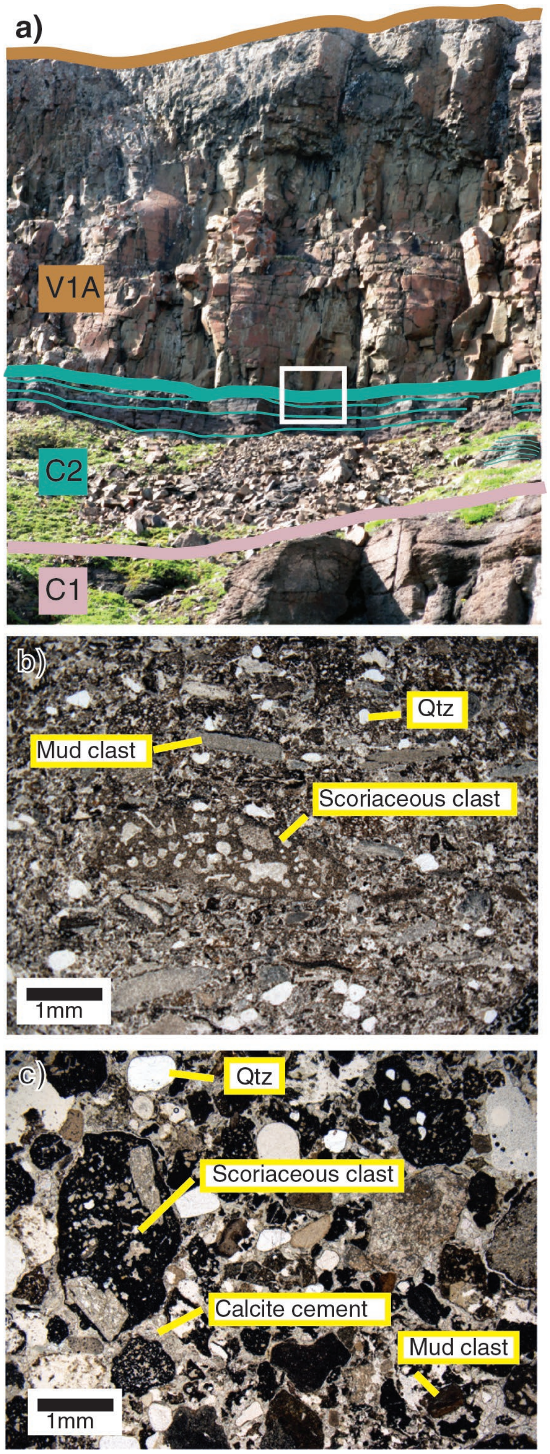

Figure 7. Photographs showing characteristics of the C_1 and C_2 volcaniclastic units. **a)** Section showing C_1, C_2 and bedding planes, and the relationship between C_2 and the overlying V_{1A} flow. Thick lines denote contacts, thin lines denote bedding in C_2. Box detail is Figure 8B. 2013-249. **b)** Photomicrograph (2.5x magnification, plane-polarized light) of C_1 texture showing mud clasts, scoriaceous clasts, and quartz grains (qtz). 2013-252. **c)** Photomicrograph (2.5x magnification, plane polarized light) of C_2 texture showing mud clasts, scoriaceous clasts, quartz grains (qtz), and calcite cement. 2013-253. All photographs by N. Williamson.

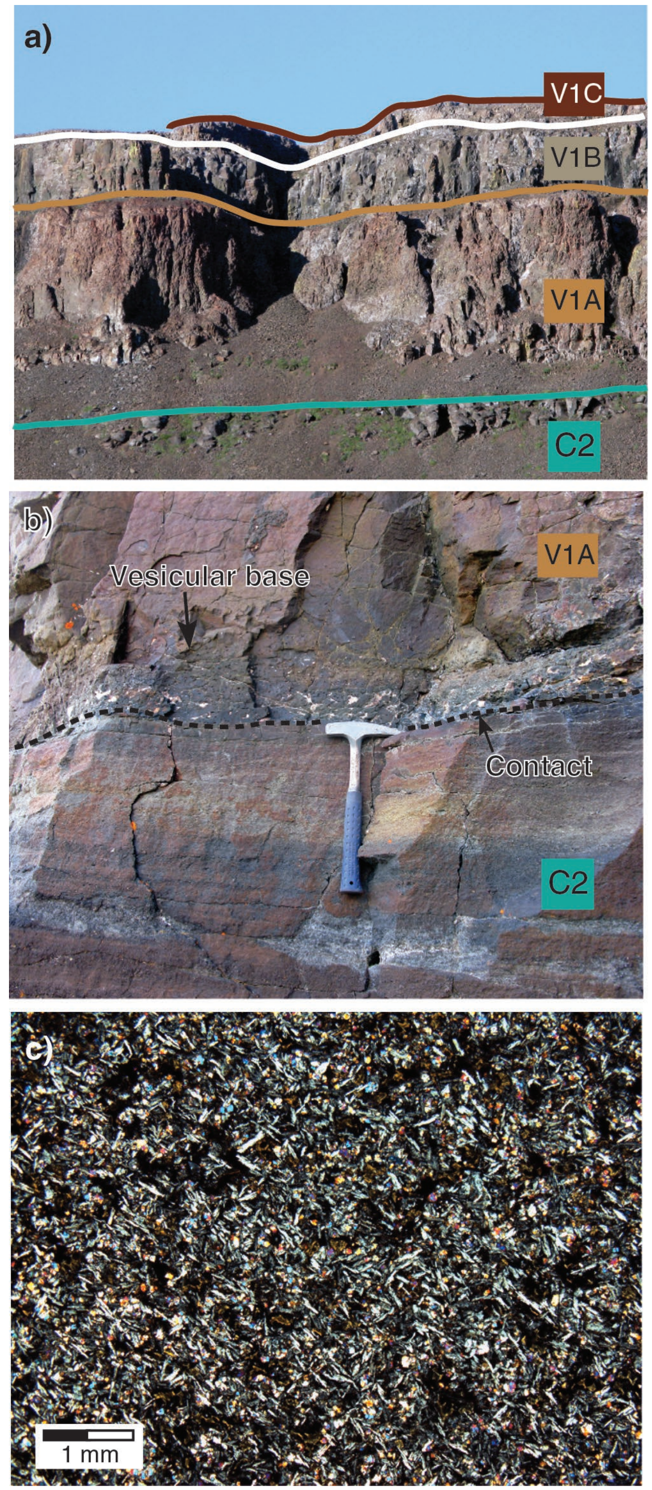

Figure 8. Photographs showing characteristics of V_1 sheet flows. **a)** Section of units C_2, V_{1A}, V_{1B}, and V_{1C}. From the top of unit C_2 section thickness is approximately 70m. 2013-250. **b)** Outcrop of the contact between units C_2 and V_{1A}. Both the contact and vesicular base are indicated. 2013-243. **c)** Photomicrograph (2.5x magnification, crossed-polarized light) of V_{1A} microtexture. 2013-251. All photographs by N. Williamson.

distinct blue-green colour. It has a massive flow base and vesicular flow top. This flow locally contains occurrences of native copper. The copper is present either as disseminated flecks within the basalt groundmass or as thin linings in calcite-, prehnite-, and quartz-filled amygdules. The top of flow V_{1B} is a 15 cm thick brick-red replacement zone, possibly representing a subaerial weathering surface. At the type section location, about 15 m of V_{1C} is preserved. The V_{1C} flow is weathered brown and appears to be a compound flow made up of a number of thinner flows about 0.5 to 1 m thick.

Microscopically, the textures of flows V_{1A} and V_{1C} are almost identical, while that of V_{1B} differs significantly. Samples of flow V_{1A} are fine-grained aphyric basalt, with a groundmass of plagioclase laths, and small, anhedral, clinopyroxene crystals (Fig. 8c). The abundance of vesicles is low (~2%), and secondary minerals mostly consist of chlorite and calcite present within these vesicles, as well as interstitial chlorite. The primary minerals themselves are not significantly altered, and there is little to no variability in microtexture from the bottom to the top of flow V_{1A}. In contrast to V_{1A}, samples from flow V_{1B} are coarser and display a subophitic texture. The clinopyroxene phenocrysts are sub- to anhedral, 0.5 to 1 mm in size, and either fully or partially enclose plagioclase laths 0.25 mm in length. Flow V_{1B} is heavily chloritized in thin section, and this might account for its blue-grey colour in outcrop. Similar to V_{1A}, chlorite is interstitial, as well as present in vesicles; the latter have a higher abundance than in flow V_{1A}, approximately 5%. In addition, clinopyroxene crystal size increases from bottom to top. Finally, although native copper was observed in outcrop, none has been observed in the two samples taken from the bottom and top of flow V_{1B}. Flow V_{1C} displays a microtexture very similar to V_{1A}, with the only significant difference being a slightly finer groundmass and fewer vesicles. Apart from these minor differences, V_{1C} shows the same mineralogy and degree of alteration as V_{1A}. In thin section, native copper is present as interstitial flecks, and as crusts within amygdules.

VOLCANOSTRATIGRAPHIC SECTIONS AND CORRELATIONS OF THE SOUTHERN LOBE

Correlations between sections measured in the southern lobe are based on the identification of distinctive contacts and marker units in measured stratigraphic sections. They provide insight into the environment of deposition that evolved over time, and they provide a basis for correlations with the volcanostratigraphy of the northern lobe. Unit V_{1A} is thick and has easily recognizable structures. Excellent exposures along extensive river valleys allow us to suggest that the base of unit V_{1A} was flat during its eruption. For these reasons the base of V_{1A} is used as a stratigraphic datum. In contrast, individual flows within the basal unit V_0 differ in thickness and are difficult to recognize from one location to another due to their highly weathered nature and lateral facies variability. For these reasons we have not attempted to correlate individual flows within the V_0 unit from one section to the next. The volcaniclastic units are easily recognizable, and although their contacts are commonly covered, they are easily correlated. Two composite sections are shown in Figure 9. Cross-section A is oriented parallel to the east-west axis of the southern lobe, whereas cross-section B is approximately orthogonal to it. The locations of both cross-sections are indicated on the maps of Figures 1 and 4.

The thickness variations of units V_0, C_1, and C_2 suggest that varying amounts of paleotopography existed when these units were deposited, and that the paleotopography changed over time due to active tectonism. The basal unit V_0 and the massive volcaniclastic unit C_1 both occupy paleotopographic lows. The C_2 lithofacies is present at one locality within, and caps C_1 in six of the measured sections. The paleotopographic lows might be products of the pre-existing physiographic environment at the time, prior to emplacement of V_0, and would represent valleys or channels carved by the major river system responsible for the deposition of the Kuujjua Formation sandstones. However, paleovalleys appear to trend to the northeast, almost normal to the estimated paleoflow of the river system according to Rainbird (1992). A second option is that the topographic lows were graben-like troughs resulting from extensional faulting related to the uplift that immediately preceded the Franklin magmatic event. A third option might be that the mass flows depositing the C_1 unit excavated channels in the underlying V_0 unit. Although we cannot exclude this third hypothesis, we do not favour it due to the lack of supporting field evidence and because in well documented situations of volcaniclastic sediment redistribution, material tends to follow pre-existing river valleys rather than carve them (Kataoka et al., 2008; Macías et al., 2004; Park and Schmincke, 1997; Reubi et al., 2005; Ross et al., 2005). Thus, although the evidence from fieldwork is largely inconclusive, we suggest that the topographic lows were developed by a combination of tectonic activity immediately before and during eruption, and previous fluvial erosion.

FRANKLIN VOLCANISM IN THE SOUTHERN LOBE

The first 200 m of volcanic stratigraphy within the Natkusiak Formation of the southern lobe records the initiation of volcanic activity (V_0), a hiatus involving active faulting and reworking (C_1-C_2), and the transition to the main phase of extrusive volcanism (V_1) of the Franklin magmatic event. Lava-sediment interaction below the contact between the Kuujjua and Natkusiak Formations is thought to represent one or more brief volcanic ‘precursor’ event(s) and indicates that some of the early magmatism was coeval with deposition of the fluvial sands (R. Rainbird, pers. comm., 2012).

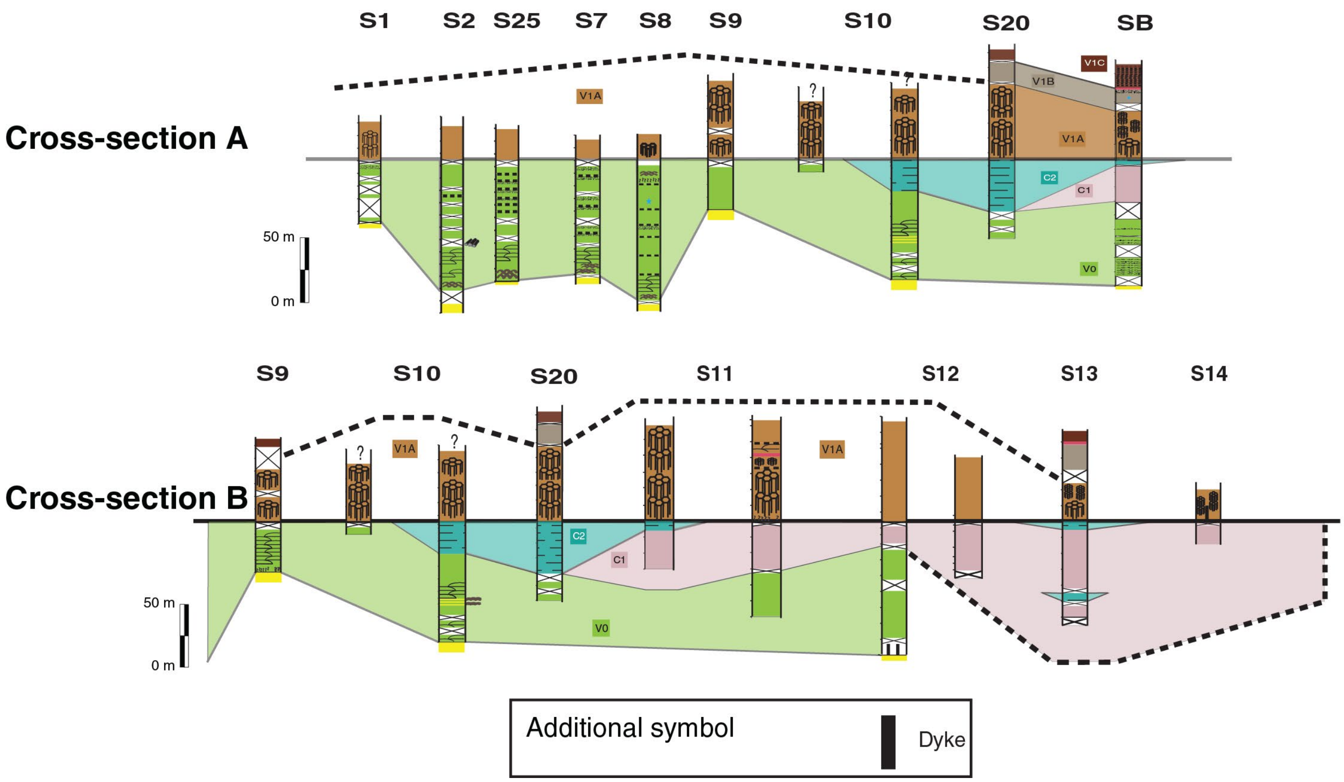

Figure 9. Simplified correlation panel of the western and central southern lobe Natkusiak Formation along a west-east and a northwest-southeast transect. *See* Figures 1 and 4 for transect locations. See Figure 3 for colour and symbol legend. Both cross-sections were drawn with a vertical exaggeration of 40x to emphasize relief.

The distribution of the V_0 flows was constrained by local paleotopographic effects resulting from erosion/deposition that was caused by extensional faulting, and re-orientation of river systems orthogonal to the previous Kuujjua deposystem. The locally pillowed and hyaloclastic nature of the V_0 unit indicates eruption onto wet, unlithified, sandy sediment of the Kuujjua Formation alluvial-fluvial system and into associated bodies of water. The interaction between basal volcanic facies and underlying sediments is a common phenomenon in other flood basalt provinces, such as the Etendeka Continental Flood Basalts, where basal flows intermingle with aeolian sediments of the Huab Basin, and the Deccan Traps in India where onset-phase fissure-fed tholeiitic flows interact and in some places are intercalated with sedimentary formations (Jerram and Widdowson, 2005). The basal V_0 lava flows have smaller volumes than the V_1 sheet flows, they are not laterally extensive, and the individual flows themselves are discontinuous in nature. These characteristics are typical of point-source volcanism with lower extrusion rates that often characterizes the onset phase of continental flood volcanism (Jerram and Widdowson, 2005). Based on the interpreted preservation of agglutinated spatter, the extensional regime known to have existed in the region, and the presence of fault-guided V_0-type magma in the underlying Shaler rocks, we suggest that the point-source volcanism was produced from volcanic fissures capable of producing both explosive (fire fountain) and effusive (lava flow) volcanism.

Due to the paucity of pyroclastic components in unit C_1, such as ash, lapilli, blocks, and bombs; the absence of obvious pyroclastic depositional structures; and the abundance of clastic components including rounded quartz grains; we propose that this unit is a reworked (epiclastic) mafic volcaniclastic rock. These deposits either filled existing topographic lows, excavated channels in the underlying V_0 unit, or both. Mafic volcaniclastic deposits intercalated with lavas are well documented in many flood basalt provinces such as the Yemen Province, the Deccan Plateau, parts of the North Atlantic Igneous Province, and the Siberian Platform (Ross et al., 2005). The volcaniclastic deposits vary in nature from structureless to layered to brecciated, and include a variety of materials including lapilli, altered glass, basaltic clasts, country-rock fragments, and quartz grains (Ross et al., 2005). Ross et al. (2005) also suggest that the presence of quartz grains within mafic volcaniclastic deposits indicates a clear interaction between the magma and the underlying consolidated or unconsolidated sediments, a feature predominant in unit C_1.

The actual mechanism of deposition for unit C_1 is still uncertain. Given the thick, massive nature of C_1, as well as the pebble-sized or smaller and compositionally heterogeneous clasts, the fine muddy groundmass, the very slight alignment of the elongate clasts, and the lack of obvious sedimentary structures such as planar or crossbedding, we suggest a mass flow mechanism of deposition such as a mudflow or lahar. A mass flow might have occurred as a gravity flow caused by slope instability and collapse on the flanks of paleovalleys initiated, for example, by seismicity. A mass flow would have reworked some of the V_0 flows as well as any pre-existing fallout or sedimentary deposits. The debris flows that carried unit C_1 material would have exploited any pre-existing topographic lows, and may also have further excavated channels. It is also possible that unit C_1 might represent a debris avalanche such as in the Mawson Formation of the Ferrar Large Igneous Province, central Allan Hills, Antarctica, where a 180 m thick debris avalanche deposit was identified despite a complete lack of steep volcanic edifice (Reubi et al., 2005). Reubi et al. (2005) argue that in large igneous province settings enough topography can exist from pre-eruptive uplift, faulting, and fluvial-valley incision to cause the formation of debris avalanches. Although unit C_1 lacks the large boulders, blocks, and megablocks typical of large debris avalanche deposits (Leyrit, 2000), its components could very well represent a mass or debris flow caused by seismic-activity-induced liquefaction or gravity instability.

The capping C_2 deposit is a more mature, fine volcanic-pebble conglomerate that contains an equal to high proportion of clastic to mafic components, as well as planar and cross-beds. In addition, easily weathered volcanic components such as scoriaceous basalt pieces are less well preserved in unit C_2 than in C_1. This, along with the higher proportion of clastic components and sedimentary structures of C_2, leads us to suggest that the transportation distance might have been greater for C_2 material than C_1 material, and that the former was deposited by moving water and might represent the temporary reactivation of small rivers associated with the Kuujjua regional river deposystem. One hypothesis is that the rivers that deposited the Kuujjua Formation were temporarily obstructed by the basal flows of unit V_0 and subsequently reactivated following a dam burst (Kataoka et al., 2008; Macías et al., 2004; Park and Schmincke, 1997). The dam burst may have generated the C_1 unit, but more certainly may have deposited the C_2 unit, given the latter's sedimentary structures. The reactivated rivers would have reworked volcanic material and incorporated quartz grains and carbonate clasts from the previously dammed river system. An alternative hypothesis is that fault tectonics generated an entirely new hydraulic network regionally orthogonal to the defunct Kuujjua system, accompanied by sufficient rainfall and earthquakes to accomplish the same result. In summary, C_1 and C_2 represent two units of reworked volcanic material likely deposited by gravity flows and small, reactivated or newly developed rivers. As such, both volcaniclastic units appear to record a pause and change in style of volcanism prior to the initiation of the main phase of flood volcanism. We are unable to exactly constrain the length of time corresponding to the C_{1}-$_{2}$ depositional events.

Following the volcaniclastic depositional events and peneplanation, the main phase of flood volcanism began. This produced the thick, regionally extensive, well preserved sheet flows of unit V_1. The internal architecture and structures of these flows (colonnade and entablature columnar jointing, compound pahoehoe flows) are typical of the main phase of volcanism in most other flood basalt provinces (Jerram and Widdowson, 2005). This leads to the interpretation that unit V_1 represents the beginning of large-volume flood volcanism.

COMPARISON OF SOUTHERN AND NORTHERN LOBES

In the northern lobe, a similar stratigraphic succession has been documented for the basal Natkusiak Formation (Dostal et al., 1986; Jefferson et al., 1985). Jefferson et al. (1985), describe a 'basal member' up to 70 m thick that pinches out locally. That study also notes the existence of pillowed lava and hyaloclastite, and they suggested that the basal member erupted into shallow water. Dostal et al. (1986) report basal flows of various thicknesses with massive bases and vesicular flow tops. However, within the northern basal member, Jefferson et al. (1985) observed massive columnar-jointed cliff-forming flows, which are not present in the south. Near the mouth of Trident Creek in the northern lobe, we observed a thin (1 m) basal hyaloclastite breccia, succeeded by massive 2 m thick flows. We believe that the V_0 unit in the Southern lobe correlates with the 'basal member' described by Jefferson et al. (Jefferson et al., 1985) in the northern lobe, although there are subtle differences.

With regards to the volcaniclastic units; in the Northern lobe Dostal et al. (1986) reports the presence of a unit of red volcanic sediments they call the 'red-bed member'. A sample from this unit examined in thin section contains an abundance of reworked volcanic material as well as rounded quartz grains, and so this unit likely correlates with the unit C_1 unit of the southern lobe. Jefferson et al. (1985) report a 'lithic pyroclastic member' composed of unsorted, unwelded material, with a large range in thickness (70–100 m), and a base composed of shallow-water turbidite sequences. The turbidite sequences are overlain by maroon and green volcanic reworked sedimentary units (Jefferson et al., 1985). Jefferson et al. (1985) suggested the presence of pyroclastic fallout deposits because of the presence of lapilli. However, Jefferson et al. (1985) interpreted the bulk of the massive, structureless, volcaniclastic material (facies that dominates C_1 in the southern lobe) as mass flow deposits.

We propose that unit V_1 in the south is equivalent to the 'Lower Massive Member' described by Jefferson et al. (1985). The flows of the 'Lower Massive Member' are 10 to 50 m thick, blue-grey-green weathering to orange-brown, massive, cliff-forming, and columnar jointed (Jefferson et al., 1985). Dostal et al. (1986) noted a distinctive flow ('Rosetta Flow'), above the red volcanic sedimentary unit, and traceable over 25 km. This may be the same flow as our V_{1A} unit, which we use as our stratigraphic base datum. Units above the first four sheet flows in the north do not have preserved equivalents in the south.

CONCLUSIONS

The southern lobe of the Natkusiak Formation preserves up to 200 m of volcanostratigraphy representing the early stages of volcanism related to the Franklin magmatic event. The volcanostratigraphy of the southern lobe resembles the pre, onset, and main phases of flood-basalt volcanism of other volcanic provinces in the style of lava-sediment interaction, laterally variable and discontinuous basal flows, as well as intercalated volcaniclastic units, and laterally continuous overlying sheet flows.

The onset of volcanism is represented by the laterally discontinuous V_0 unit basal flows erupted into topographic lows in relatively modest volumes, probably from volcanic fissures and vents. The topographic lows were locally occupied by water, evidence for which is provided by features such as pillows and hyaloclastite. Paleotopography might have been generated by pre- and syn-eruptive faulting, carved out by the rivers responsible for the deposition of the Kuujjua Formation sandstones, new rivers in a reorganized paleotopography, or all of these factors. The two volcaniclastic units follow the same paleotopographic lows and record a regional change and possible hiatus in volcanic activity. The mechanism for the deposition of unit C_1 is interpreted to be a mass flow produced from slope instability or a dam burst, whereas the quartz-rich volcanic fine-pebble conglomerate (unit C_2) that caps unit C_1 contains structures formed by traction currents and was probably deposited by small rivers. If this is the case, the C_2 unit could indicate the temporary reactivation of the local river system dammed by V_0 flows prior to the onset of the main phase of volcanism as represented by the sheet flows of unit V_1 above, or could record the development of entirely new fluvial drainage. The thick and laterally continuous nature of the V_1 flows is good evidence that they were vented over a relatively flat surface from a sustained volcanic plumbing system, thereby recording the beginning of the main phase of high-volume flood volcanism. Based on their physical characteristics, we have found that the four units identified within the volcanic pile of the southern lobe correlate with units described in the northern lobe by Dostal et al. (1986) and named by Jefferson et al. (1985). Our V_0 unit correlates well with Jefferson et al. (1985) 'Basal Member', C_1 and C_2 with the 'Pyroclastic Member', and V_1 with the 'Lower Massive Member'.

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