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A revised stratigraphic framework for Cretaceous sedimentary and igneous rocks at Mokka Fiord, Axel Heiberg Island, Nunavut, with implications for the Cretaceous Normal Superchron

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ABSTRACT

New data and interpretations on geological relationships of igneous rocks at Mokka Fiord, Axel Heiberg Island, Nunavut, provide insight into the timing and nature of magmatism associated with the Sverdrup Basin and High Arctic Large Igneous Province (HALIP). Field relationships indicate that the igneous rocks, previously interpreted to be volcanic flows, are most likely an intrusive unit discordant to regional bedding. An intrusive origin helps resolve chronostratigraphic inconsistencies in previous work. The host rocks are palynologically constrained to be late Barremian to late Aptian in age and are interpreted to be Paterson Island or Walker Island member of the Isachsen Formation. If the igneous body is intrusive, its previously reported Ar-Ar age (102.5 ± 2.6 Ma) is no longer in conflict with accepted stratigraphic interpretations and probably reflects the emplacement age of the intrusion. Lingering uncertainties in interpreting the normal and reverse magnetic polarities determined in the previous work remain, and both are considered viable. Although this uncertainty precludes definitive conclusions on the significance of paleomagnetic data at Mokka Fiord, examination of the stratigraphic, paleomagnetic, and geochronologic relationships there highlight potential for the study of excursions, or reversed magnetic polarity subchrons, in the Cretaceous Normal Superchron elsewhere in the HALIP.

Keywords: Sverdrup Basin, HALIP, paleomagnetism, stratigraphy, palynology
1. Introduction

Cretaceous siliciclastic and igneous rocks of the Sverdrup Basin near the mouth of Mokka Fiord, Axel Heiberg Island (Fig. 1), were examined to clarify conflicting and apparently irreconcilable published data and interpretations regarding their age. The issue is significant because stratigraphic and paleomagnetic work on Axel Heiberg Island was used to suggest that further analysis of volcanic flows and host strata in the upper Isachsen Formation has the potential to constrain the age of M0, the youngest of the M-sequence reversals prior to the Cretaceous Normal Superchron (Wynne et al. 1988). The base of M0 is defined as the base of the Aptian (Tarduno 1989; Erba 1996; Gradstein et al. 2012), but different methods of study have arrived at different absolute ages for this event. In some interpretations it occurs at 125/126 Ma (e.g. Ogg and Hinnov 2012; Cohen et al. 2013; Ogg et al. 2016), whereas alternative interpretations place this event at 121/122 Ma (e.g. Gilder et al. 2003; He et al. 2008; Malinverno et al. 2012; Midtkandal et al. 2016).

Mokka Fiord was considered to be one of the Sverdrup Basin localities that exhibits reversely magnetized volcanic flows which can be correlated to M0 (Embry and Osadetz 1988) and as such, held the potential to constrain the age of M0 if the flows yielded a precise age determination. However, more recent geochronological work by Estrada and Henjes-Kunst (2013) determined an Ar-Ar age of 102.5±2.6 Ma for one sample from the Mokka Fiord igneous body; this age is in stratigraphic conflict with previous interpretations, as well as being more than 20 million years younger than M0. The Ar-Ar age also complicates interpretation of the significance of the reversed polarity data attributed to the Mokka Fiord locality because 102 Ma is in the middle of the Cretaceous Normal Superchron. One possible explanation for this, not considered in previous work, is that the body cooled during a geomagnetic excursion, or a subchron, within the
superchron. Resolving the significance of the reversed data is further complicated by the fact that Wynne et al. (1988), the original authors of the paleomagnetic data, did not themselves interpret the Mokka Fiord dataset in their discussions of reversed magnetic polarity, calling into question how the data should be treated.

Fieldwork was undertaken with the goal of resolving the conflicts between previous interpretations by better characterizing the igneous body and its host rocks. Palynological analysis establishes that the host rocks are late Barremian to late Aptian in age, and are part of the Paterson Island Member or Walker Island Member of Isachsen Formation. No evidence for a volcanic origin was found in the igneous body, and megascopic relationships are more consistent with it being an igneous intrusion. The new interpretation reconciles conflicts between previous stratigraphic and radiometric work, but uncertainty in the significance of the reversed magnetic polarity data remains, and is discussed. The following methods were used to test previous interpretations and to provide evidence for new interpretations: new field observations; analysis of field and aerial photographs; palynology of stratified rocks; review of the paleomagnetic data; and, stratigraphic analysis that considers recent interpretations of the Early Cretaceous timescale and revisions to ages of stratigraphic units. New radiometric age dating of the igneous rock was attempted but ultimately did not yield an emplacement age; analytical procedures and data table are available for download from the online supplement1.

2. Regional Geological Setting

2.1. Sverdrup Basin

Sverdrup Basin is a 1300 km by 350 km paleo-depocentre in the Canadian Arctic Archipelago (Fig. 1). The basin contains up to 13 km of nearly continuous Carboniferous to Paleogene siliciclastic, evaporite, and carbonate strata (Balkwill 1978; Embry and Beauchamp
Rifting related to the opening of the proto-Arctic Ocean during Early Jurassic to earliest Cretaceous time progressed to sea-floor spreading by the Early Cretaceous (Embry and Beauchamp 2008; Hadlari et al. 2016), marking the opening of the proto-Arctic Ocean. Sedimentation in the Sverdrup Basin was then dominated by terrigenous clastic material that recorded basin-wide transgressive-regressive cycles driven by a combination of subsidence of the rifted margin, sediment supply, and eustatic sea level change (Embry 1991). This resulted in the accumulation of sandstone-dominated Isachsen Formation, shale-dominated Christopher Formation, sandstone-dominated Hassel Formation, and shale-dominated Kanguk Formation (Fig. 2). Episodic uplift of basin margins lasted into the Cretaceous, with a period of increased subsidence in the Early Cretaceous when basaltic volcanism and widespread emplacement of diabase dykes and sills of the High Arctic Large Igneous Province (HALIP) occurred (Balkwill 1978; Stephenson et al. 1987; Embry and Beauchamp 2008; Evenchick et al. 2015; Saumur et al. 2016). Deposition in the Sverdrup Basin ended by the Paleogene as a consequence of regional compression and widespread uplift during the Eurekan Orogeny (Embry and Beauchamp 2008). Sverdrup Basin strata were deformed during Mesozoic episodic flow of Carboniferous evaporites (e.g. Balkwill 1978; Boutelier et al. 2010; Galloway et al. 2013; Harrison et al. 2014), by Hauterivian to Cenomanian magmatism and faulting (e.g. Embry and Osadetz 1988; Embry 1991; Evenchick et al. 2015), and by the Eurekan Orogeny (Eocene), which produced tight folds and thrust faults in the northeast basin and more gentle folds to the west (e.g. Okulitch and Trettin 1991; Piepjohn et al. 2016).

2.2. High Arctic Large Igneous Province (HALIP)

The HALIP initiated near 130 Ma (Barremian) and resulted in episodic igneous activity until ca. 80 Ma (Campanian; Tarduno 1989; Estrada and Henjes-Kunst 2004, 2013; Tegner et al. 2016).
2011; Evenchick et al. 2015; Saumur et al. 2016; Dockman et al. 2018). In Canada’s High Arctic it occurs within the Cretaceous Sverdrup Basin. The Canadian HALIP is expressed by an early period of tholeiitic magmatism (~130-90 Ma) resulting in dykes, sills, and volcanic flows in the Isachsen and Strand Fiord formations, and a later period (~80 Ma) of alkaline magmatism occurring on northern Ellesmere Island as the Hansen Point Volcanics (e.g., Embry and Osadetz, 1988). This paper is concerned with the age and nature of igneous rock at the mouth of Mokka Fiord, for which Ar-Ar age analysis yielded a plateau age of 102.5 ± 2.6 Ma (Estrada and Henjes-Kunst 2013). This late Albian age is substantially younger than the lower Aptian (~121 or 125 Ma) paleomagnetic and stratigraphic interpretation of previous study (Embry and Osadetz 1988). Refinement of timing and nature of the HALIP has implications for understanding circum-Arctic plate reconstructions and Arctic basin evolution (Døssing et al. 2013; Saumur et al. 2016).

2.3. Isachsen Formation

Igneous rocks at Mokka Fiord are reported to occur within the Valanginian to late Aptian-aged Isachsen Formation (Embry and Osadetz 1988). Isachsen Formation sediments were deposited in marginal marine/deltaic and fluvial environments (Tullius et al. 2014), synchronous with volcanism (Embry and Osadetz 1988; Grantz et al. 2011). The formation ranges in thickness from ~120 m at basin margins to 1370 m on western Axel Heiberg Island (Hopkins 1971) and is divided into three members (Embry 1985). The lowermost Paterson Island Member overlies Deer Bay Formation or Mackenzie King Formation with unconformable contact at basin margins and conformable contact in basin centre. The member consists of fine to very coarse-grained sandstone with interbeds of carbonaceous siltstone, mudstone, coal, and volcanic and volcaniclastic/tuffaceous rocks, deposited in a marginal marine setting (Embry 1985; Embry and Osadetz 1988; Evenchick and Embry 2012a,b; Tullius et al. 2014; Evenchick et al. 2015; Galloway...
et al. 2015; Hadlari et al. 2016). Rondon Member mudstones conformably overlying Paterson Island Member were deposited in a marine shelf environment (Embry 1985). These are in turn conformably overlain by Walker Island Member, which is composed of interbedded fine to coarse-grained sandstone, siltstone, mudstone and minor coal (Embry 1985; Tullius et al. 2014; Galloway et al. 2015) with local volcanic flows, and is inferred to have been deposited in marginal marine delta front to delta plain and fluvial environments (Embry 1985; Embry and Osadetz 1988; Tullius et al. 2014; Galloway et al. 2015). Walker Island Member is conformably overlain by mudstone and fine-grained sandstone of Christopher Formation.

Age control for Isachsen Formation (Fig. 2) is based on limited paleontological evidence described in Galloway et al. (2015) and on carbon isotope stratigraphy (Herrle et al. 2015). In Galloway et al. (2015) the Paterson Island Member ranges in age from Valanginian to Barremian, whereas Herrle et al. (2015) extend the range of the member into early Aptian. This difference has implications for the ages of overlying members of the formation, and for interpretations presented herein. The Rondon Member ranges from Barremian to early Aptian (Galloway et al. 2015) or is entirely early Aptian in age if the early Aptian age for upper Paterson Island Member proposed by Herrle et al. (2015) is accepted. The Walker Island Member ranges in age from Barremian to late Aptian (Galloway et al. 2015) or from early Aptian to late Aptian (Herrle et al. 2015). The overlying Christopher Formation ranges in age from late Aptian to late Albian (Schröder-Adams et al. 2014).

2.4. Cretaceous Igneous Rocks

Isachsen Formation includes basaltic volcanic rocks and is intruded by diabase dykes and sills. Some of the intrusions were likely emplaced during deposition of the Isachsen Formation (e.g. Villeneuve and Williamson 2006; Evenchick et al. 2015; Dockman et al. 2018). Sills and
dykes also intrude the overlying Christopher and Hassel formations and these are probably related
to the more-voluminous Upper Cretaceous extrusive event represented by the Strand Fiord
Formation (Fig. 2; Ricketts et al. 1985).

Volcanic rocks in Isachsen Formation are generally local units of breccia and basaltic flows
near the base (Paterson Island Member) or top (Walker Island Member) of the formation. Notable
basaltic flows in Isachsen Formation are listed in Table 1. Lack of detailed stratigraphic context is
a barrier to constraining the ages of these igneous rocks. The subject of this paper is an occurrence
near the mouth of Mokka Fiord, Axel Heiberg Island, of massive ‘basalt’, originally interpreted to
be a volcanic flow about 30 m thick tentatively assigned to Christopher Formation (Thorsteinsson
1971), and later as three volcanic flows totalling 28 m thickness within the Walker Island Member
of the Isachsen Formation (Embry and Osadetz 1988). Below we argue that this igneous unit is
best interpreted as an intrusion.

Volcanic rocks are sparse in the Christopher Formation. They include breccia more than
100 m thick at Ellef Ringnes Island, and several horizons of more widespread, finer grained,
volcanogenic sedimentary rocks (e.g. Schröder-Adams et al. 2014; Evenchick et al. 2015).

Strand Fiord Formation volcanic rocks are up to 1 km thick, limited to west Axel Heiberg
Island, and are Cenomanian in age, consistent with the ages of diabase and gabbro intrusions on
Axel Heiberg Island, and gabbroic intrusions on Ellesmere Island (Fig. 2; Ricketts et al. 1985;
Dockman et al. 2018).

3. Geological Setting at Mokka Fiord

Stream-cuts between the Mokka Fiord evaporite diapir and the western shore of Mokka
Fiord (Fig. 3) provide limited bedrock exposure. Strata are Triassic to Upper Cretaceous
siliciclastic rocks of the Sverdrup Basin; the study area is near the shore of Mokka Fiord, on the southeast limb of a northeast-trending syncline with sub-horizontal plunge (Thorsteinsson 1971; Fig. 3).

3.1. Previous Data and Interpretations

The initial interpretation of strata at Mokka Fiord assigned a volcanic flow tentatively to the top of Christopher Formation, with the flow overlain by Eureka Sound Formation, now Eureka Sound Group (Thorsteinsson 1971; stratigraphic nomenclature after Miall 1986). The history of interpretation of strata at this locality is shown in Fig. 4 and outlined in Table 2, with quotes from the relevant papers. Osadetz and Moore (1988) reinterpreted the section and reassigned the flow to Isachsen Formation, with the overlying strata reassigned to Christopher Formation (Fig. 4). This stratigraphic interpretation was based on correlation of the Mokka Fiord flow with volcanic flows within the Walker Island Member at central Axel Heiberg Island (Geodetic Hills), and northwest Ellesmere Island (Blue Mountains); the latter are now considered to be sills (Bédard et al. 2016). Wynne et al. (1988) focussed on paleomagnetism of Cretaceous volcanic rocks in the Sverdrup Basin and concluded that there are two intervals of reversely magnetized volcanic flows in the Isachsen Formation, one in the lower part (Paterson Island Member) and one in the upper part (Walker Island Member), but that the uppermost flows of the Walker Island Member have normal magnetization (Fig. 4). Wynne et al. (1988) concluded that the change from reversely to normally magnetized horizons of the Walker Island Member may be used to bracket M0, and in doing so, refine the age of the base of the Cretaceous Normal Superchron. Data are reported from two sample sites at the Mokka Fiord locality: one site with exclusively normal magnetic polarity and the other with both normal and reversed data. However, the Mokka Fiord dataset was not interpreted or discussed by Wynne et al. (1988), and their text and figures dealing with magnetic reversals and
the age of M0 exclude the Mokka Fiord data without explanation. A third paper (Embry and Osadetz 1988) focussed on Sverdrup Basin volcanism. They assigned the volcanic rocks at Mokka Fiord, which they interpreted to comprise three flows, to Walker Island Member based on stratigraphic position below Christopher Formation and, citing Wynne et al. (1988), because they are reversely magnetized (Fig. 4). Embry and Osadetz (1988) did not comment on the difference between their assignment of reversed magnetic polarity to the rocks and the results reported by Wynne et al. (1988), nor the conflict between their interpretation that the reversely magnetized flow is overlain by Christopher Formation with the interpretation of Wynne et al. (1988) that the highest flows in the Isachsen Formation are normally magnetized at all sites.

Estrada and Henjes-Kunst (2004, 2013) and Estrada (2015) conducted geochemical and geochronological studies on aliquots of the same Mokka Fiord samples used in the paleomagnetic study. With only hand samples to examine, Estrada and Henjes-Kunst (2004) accepted the stratigraphic and other field interpretations of the 1988 papers, but when their Ar-Ar analyses indicated a younger age (102.5 ± 2.6 Ma), Estrada and Henjes-Kunst (2013) reinterpreted the flows to be Strand Fiord Formation (Fig. 4). The Ar-Ar age (late Albian) is older than biostratigraphic and radiometric ages for the Strand Fiord Formation or associated volcaniclastic strata (Cenomanian; e.g. Tarduno et al. 1998; Davis et al. 2016; Kingsbury et al. 2017; Dostal and MacRae 2018). Estrada and Henjes-Kunst (2004) commented that mafic units of Mokka Fiord and Blue Mountains contain low Cu, which is more akin to Strand Fiord Formation volcanic rocks than those that occur within the Isachsen Formation. This conclusion was supported by Saumur and Williamson (2016) for the Mokka Fiord mafic unit, based on major oxide and trace element compositions that overlap with compositional arrays of Strand Fiord Formation basalts but are distinct from those that occur within Isachsen Formation. Evenchick et al. (2015), in a summary
of Sverdrup Basin HALIP ages, noted the conflict between the Ar-Ar geochronological result of Estrada and Henjes-Kunst (2013) and the stratigraphic / paleomagnetic interpretation of Embry and Osadetz (1988). They questioned the reliability of the Ar-Ar age based on the stratigraphic conflict between the two studies and on the observation that Ar-Ar ages have been shown to be unreliable in some cases elsewhere within the HALIP (e.g. Corfu et al. 2013).

3.2. Implications of the Magnetic Polarity Time Scale for Previous Interpretations

Figure 4 shows the interpretations of Embry and Osadetz (1988) in the context of regional stratigraphy and the magnetic polarity timescale. The beginning of M0 is at the base of the Aptian (Erba 1996), and is considered to be either 125/126 Ma (Fig 4A; e.g. Gradstein et al. 2012; Cohen et al. 2013), or 121/122 Ma (Fig. 4B; e.g. He et al. 2008; Midtkandal et al. 2016). If the flows, as interpreted by Embry and Osadetz (1988), were extruded during M0, they must have been extruded during deposition of the uppermost Paterson Island Member (Fig. 4B), or lower Walker Island Member (Fig. 4A), depending on the accepted age of these units. The flows were interpreted to be immediately overlain by mudrock of the Christopher Formation. If the flows are at the top of Paterson Island Member or base of Walker Island, and overlain by Christopher Formation, then all or most of the Walker Island Member must be missing, with a disconformity between upper Barremian or lower Aptian rocks of Walker Island Member and upper Aptian Christopher Formation. This is in contrast with regional stratigraphic relationships which suggest the contact between the Christopher and Isachsen formations is conformable (e.g. Tullius et al. 2014; Schröder-Adams et al. 2014; Galloway et al. 2015; Herrle et al. 2015). An additional conflict between previous interpretations that is highlighted in Fig. 4 is that Wynne et al. (1988) state that the highest flows in Isachsen Formation have normal polarity, whereas Embry and Osadetz (1988) interpret the flows at Mokka Fiord to be at the top of Isachsen Formation but with reversed
magnetism, citing Wynne et al. (1988). However, Wynne et al. (1988) do not specifically include
the Mokka Fiord samples within their reversely magnetized units. Wynne et al. (1988) do not
explain why Mokka Fiord samples are excluded from discussion and are not interpreted as
reversely magnetized, nor do Embry and Osadetz (1988) explain why they include them as
reversely polarized.

4. New Observations, Analytical Work, and Interpretations

4.1. Locality Description

New fieldwork at Mokka Fiord was carried out in 2015. The banks of the creek at the
igneous locality are about 8 to 15 m high. The igneous rocks are resistant to erosion and result in
a short canyon with continuous exposure from creek-level to top of the cutbank (Fig. 5A). In
contrast, there is little exposure of siliciclastic bedrock within 500 m upstream of the igneous rocks,
or downstream 300 m to the shore of Mokka Fiord. Contact relationships are not exposed, and
away from the igneous rocks the valley has gentle slopes of slumped, barely consolidated medium-
grained sandstone, fine-grained sandstone, and siltstone (Fig. 5).

4.2. Sedimentary Rocks

4.2.1. Field Observations and Measurements

The best sedimentary rock exposure in the vicinity of the igneous body is about 200 m
away downstream (Fig. 5A). A steep cutbank provides 5 x 20 m of exposure; excavation with rock
hammers resulted in fresh outcrop (Figs. 6A, B). Several metres of laminated and cross-laminated
fine-grained quartz sandstone and siltstone (Fig. 6B) are capped by about 2 m of white quartz
sandstone; all are weakly consolidated. Bedding is gently dipping, and all measured dips are
subhorizontal. Dark weathered material at the top of the cutbank was not examined.
Five hundred metres upstream from the igneous rocks is a large exposure of sedimentary rock. It was not visited in the field, but from examination of photographs it appears to be at least 30 m of distinctly bedded dark weathering clastic rock, assumed to be sandstone and mudstone, overlain by about 100 m of light coloured rock assumed to be predominantly sandstone (Fig. 5C). The distinctly bedded dark weathering rocks are continuous with the only bedding traces that can be followed southwest of the creek (Figs. 5C, 7). Based on these relationships, sedimentary rocks at this exposure are interpreted to dip about 40° west northwest.

4.2.2. Palynology

One sample was collected for palynological analysis to constrain the age and stratigraphic position of the clastic rocks. Sample 15EP003A01 (C-602800) is from the exposure 200 m downstream from the igneous body (Fig. 5A). The sample consists of dark grey/brown mudstone and very fine-grained sandstone, and was collected from between thin beds and laminae of quartz sandstone. The sample contains numerous and well-preserved palynomorphs (Galloway 2017). The assemblage preserved in the examined unsieved preparation (P-5356-1B) includes pollen and spore taxa typical of the Early Cretaceous of Arctic Canada (Galloway et al. 2012, 2013, 2015). The sample contains the monocolpate angiosperm taxa *Liliacidites* Couper 1953 and *Monocolpites* Van der Hammen 1954, abundant pollen with coniferous affinities (undifferentiated bisaccates, *Cerebropollenites mesozoicus* (Couper 1958) Nilsson 1958 and Cupressaceae-Taxaceae pollen), and rare *Appendicispites* cf. *potomacensis* Brenner 1963 and *Klukisporites?* cf. *foveolatus* Pocock 1965 specimens. Abundant *Antulsporites clavus* (Balme 1957) Filatoff 1975 and *Stereisporites antiquasporites* (Wilson and Webster 1946) Dettmann 1963 in the sample indicate that bryophytes were a common element of the terrestrial vegetation. Other abundant spore taxa include *Deltoidospora hallei* Miner 1935 and *Gleicheniidites senonicus* Ross 1949. Dinocysts
(undiifferentiated) and acritarchs (*Micrhystridium*, Delfandre 1938; *Pterospermopsis* W. Wetzel 1952) are rare.

### 4.3. Igneous Rocks

#### 4.3.1. Field Relationships and Petrography

Igneous rocks exposed at Mokka Fiord weather to a dark rusty brown colour (Fig. 5A). They are strongly jointed, but otherwise massive and homogeneous (Figs. 5A, 6C). No indications of flow tops or contacts to distinguish the three flows noted by Embry and Osadetz (1988) were observed. The dense network of fractures has no regular pattern that could be considered columnar. Fresh rock is dark grey and fine-grained, with sparse plagioclase glomerocrysts up to 5 mm across. The southeast contact is covered by an apron of igneous rock talus (Fig. 5A). The northwestern contact is not exposed because there is no clastic bedrock present, but igneous bedrock in the creek is considered to be within a couple of metres of the contact, based on the limit of resistant rock, and continuity of that boundary up the dip-slope above the creek and to the northwest limit of resistant rock on the plateau above (Figs. 5A, 6D). Igneous bedrock within 1 m of the northwestern (upper) contact has similar character to that near the centre of the body. In thin section, the matrix appears as isotropic gabbro exhibiting a weakly developed subophitic texture defined by tabular plagioclase locally partly enclosed by anhedral clinopyroxene; accessory minerals include opaques (~5-7% modal, mostly magnetite), minor olivine (1-2%) and retrograde interstitial biotite (10-15%, after hornblende and/or pyroxenes).

#### 4.3.2. Megascopic Relationships

Examination of field photographs and aerial photographs facilitates interpretation of the extent and orientation of the igneous body based on the strong contrast in resistance to erosion between the igneous and sedimentary rocks (Fig. 5A). If the limit of resistant igneous outcrop
approximates its contact, the northwestern contact of the body dips about 30°-40° northwest (Figs. 5A, 7); deflection of the creek to a southwest direction at the upstream limit of igneous rock is interpreted to reflect the southwesterly strike of the body (Figs. 5A, 6D). The strike is also indicated by the extent of outcrop and frost heaved outcrop above the creek, continuous with the creek exposure (i1 in Fig. 5A). Our approximation of the dip value is consistent with Wynne et al. (1988), who report a dip of 38°. Their reported dip direction of 072°, however, is highly oblique to our interpretation of the southwesterly strike of the igneous body (Figs. 5A, 7), as well as the south southwesterly strike of bedding farther west as shown by Thorsteinsson (1971) and in Fig. 5C. Considering that the strike of the igneous body reported by Wynne et al. (1988) is highly oblique to the strike of sedimentary bedding, it is also in conflict with their interpretation that it is a volcanic flow.

Well-exposed sedimentary rocks 500 m upstream of the igneous rocks are continuous with bedding traces across about 1.5 kilometres of gently undulating topography south of the creek (Figs. 5C, 7). The bedding traces indicate a strike of about 205° (Fig. 7). Igneous bedrock at the creek is continuous with frost heaved igneous rocks on the plateau above the creek, coincident with a topographic feature elongate to the southwest for about 180 m, suggesting a southwesterly strike (i1 in Fig. 5A). Field and aerial photographs reveal that along trend there is another elongate ridge over 200 m long, and a third, smaller area (i2 and i3, respectively in Figs. 5A, B; Fig. 7). All areas have similar dark colour and resistance to weathering. They are interpreted to be igneous rock because of their contrast in colour and resistance to erosion with local sedimentary rocks. The three areas are coincident with a topographic ridge and define a strike of about 220° (Figs. 5A, 7). These relationships, as shown in plan on Fig. 7, and as viewed along i1, i2, and i3 in Fig. 5A, indicate that the trace of the igneous body is oblique to bedding, and suggest to us that continuation
of exposure of the igneous rocks a few hundred metres along trend would result in their intersection with the bedding traces.

5. Discussion - Reconciliation of New Observations and Interpretations with Previous Work

5.1. Age of Sedimentary Rocks

5.1.1. Palynology Interpretation

Monocolpate angiosperm taxa in the sample are of limited biostratigraphic value. Angiosperm pollen first appear on Ellef Ringnes and Amund Ringnes islands in the central Sverdrup Basin as two species of tricolpate pollen in the uppermost beds of the Christopher Formation (Hopkins 1974). Monocotyledonous angiosperms are considered to have evolved prior to dicotyledonous plants; in mid-latitudes, strata containing monocotyledonous angiosperm pollen are overlain by rocks containing dicotyledonous angiosperm pollen (Brenner 1967; Singh 1971; Leckie and Burden 2001). In Sverdrup Basin strata, monocotyledonous pollen are reported from the Cenomanian Bastion Ridge and Strand Fiord formations on Axel Heiberg Island but are absent from the underlying Albian Hassel Formation (Núñez-Betelu et al. 1992). It is therefore difficult to precisely constrain the age of the Mokka Fiord sample based on angiosperm pollen due to a lack of information on the latitudinally diachronous dispersal patterns and oldest occurrences of early angiosperms in high northern latitudes (Galloway et al. 2012).

Pollen with coniferous affinities are typical for samples of Isachsen Formation (cf. Galloway et al. 2015). *Cerebropollenites mesozoicus* pollen is a distinctive element in the Early Cretaceous *Cerebropollenites* Province of the northern hemisphere (Herngreen et al. 1996).

Rare *Appendicisporites* cf. *potomacensis* and *Klukisporites?* cf. *foveolatus* specimens may indicate that the Mokka Fiord sample is not older than late Barremian. The Cadomin and Dalhousie formations in the southern Rocky Mountains and Foothills of Alberta and British Columbia contain...
an older assemblage that contains neither angiosperm pollen nor *Appendicisporites* spores that
White and Leckie (1999) interpret to be of Berriasian to Valanginian age, and a younger
assemblage that lacks angiosperm pollen but contains *Appendicisporites* and *Klukisporites* spores
that they interpret to be of late Barremian to ?early Aptian age.

5.1.2. Interpretation of Age and Stratigraphic Position of Sedimentary Rocks

From the paleontology interpretation it can be concluded that the sample is no older than
late Barremian. If the age interpretations of Herrle et al. (2015) are accepted, the Mokka Fiord
sample could be from as low as the mid-Paterson Island Member (lower Barremian; Fig. 4B), or
from Rondon (lower Aptian) or Walker Island (lower to upper Aptian) members of the Isachsen
Formation. Alternatively, if previous age interpretations are retained (e.g., Galloway et al. 2015;
Fig. 4A) the sample could be from the Rondon (Barremian) or Walker Island Member (uppermost
Barremian to upper Aptian). The sample could also be from the lowermost Christopher Formation
(upper Aptian to Albian; Fig. 4) but the paucity of dinocysts suggest that the sample did not come
from marine sediments (i.e., Rondon Member, or Christopher, Bastion Ridge, or Strand Fiord
formations) and thus limits the sample to have come from the mid or upper Paterson Island or
Walker Island member of the Isachsen Formation. We reject that the Mokka sample can be
assigned to Hassel Formation or younger units based on the absence of tricolpate angiosperm

Osadetz and Moore (1988) and Embry and Osadetz (1988) assigned the clastic rocks to the
Walker Island Member, which is consistent with, but more limited than, the palynological analysis
presented herein. Their conclusion was based on the interpretations that the igneous body is a
volcanic flow correlative with others in the Isachsen Formation, that the flow has reversed
magnetic polarity, and that it underlies Christopher Formation. Their reasoning is challenged by
our interpretation, argued below, that the igneous rock is most likely intrusive. If valid, this re-interpretation negates stratigraphic correlations based on the presence of volcanic rock. Independent of re-interpretation of the igneous body, correlation of shale above it with Christopher Formation is weak because only two metres, at most, of non-diagnostic shale talus are present at the contact area (Fig. 6D), and intervals of shale this thick are common in Isachsen Formation.

5.2. Interpretation of Igneous Rocks

We question the interpretation that the igneous body is a volcanic flow based on: 1) the impressively homogeneous and massive nature of the rock in outcrop; 2) the lack of observed flow features; 3) moderate dip (30-40°) of the igneous body relative to subhorizontal bedding at outcrops 200 m downstream; and 4) the apparent cross-cutting relationship at a larger scale between the igneous rocks and bedding in sedimentary rock to the northwest. Although we find these relationships compelling, we concede that they are not absolutely conclusive in the absence of definitive contact relationships. For this reason, we discuss the larger scale implications of both extrusive and intrusive options for origin of the igneous body within the constraints of known regional Sverdrup Basin stratigraphy, and known relationships of the body. The latter are: 1) late Barremian to late Aptian age of the clastic rocks 200 m downstream, as determined from palynological analysis, which confirms that they are Isachsen Formation; 2) an Ar-Ar plateau age of 102.5 ± 2.6 Ma (Estrada and Henjes-Kunst 2013) for the igneous body; 3) geochemical similarities to mafic rocks within or associated with the Strand Fiord Formation (Saumur and Williamson 2016). The Ar-Ar age was rejected in previous work (Evenchick et al. 2015) based on its conflict with the stratigraphic / paleomagnetic interpretation of age of the body (Embry and Osadetz 1988). But, the stratigraphic / paleomagnetic argument is suspect because the magnetic polarity is in question, and, as discussed below, reverse polarity does not necessarily restrict age
of the body to prior to the Cretaceous Normal Superchron. There is no longer a reason to dismiss
the Ar-Ar age; it is considered to record emplacement age of the body.

5.2.1. Interpretation of the Igneous Body as Volcanic Rock

The igneous body cannot be Isachsen Formation volcanic rock because its Ar-Ar age, 102.5 ± 2.6 Ma (late Albian; Estrada and Henjes-Kunst 2013), is significantly younger than the late
Aptian upper age limit of Isachsen Formation. Reversed magnetic polarity was considered to
constrain the age of the body to prior to the Cretaceous Normal Superchron, and therefore Isachsen
Formation (Embry and Osadetz 1988), but that argument is rejected for reasons noted earlier.

The only other volcanic succession in the Sverdrup Basin that includes flows and is
compatible with geochemistry of the Mokka Fiord igneous body is the Strand Fiord Formation.
Although the Ar-Ar age of the igneous body is close to the age of the Strand Fiord Formation, its
error limits do not overlap with age determinations for volcanic rocks in the formation. As
discussed by Dostal and MacRae (2018), only two Ar-Ar age determinations on Strand Fiord strata
are within the biostratigraphic limits (Cenomanian) of the formation. These are 95.3 ± 0.2 Ma
(Tarduno et al. 1998) and 96.1 ± 1.6 Ma (Villeneuve and Williamson 2006). In addition, Strand
Fiord Formation is not known from eastern Axel Heiberg Island (Ricketts et al. 1985; Fig. 1). The
formation occurs as a thick, up to 1 km scale sequence of flood basalt, consisting of multiple flows
with conspicuous columnar jointing (Ricketts et al. 1985). In the few places that a succession of
flows is less than 100 m thick, near the limits of the formation, the flows are associated with
volcaniclastic strata (Ricketts et al. 1985); no volcaniclastic strata were found in the study area
either in outcrop or talus blocks. If the igneous body at Mokka Fiord is Strand Fiord Formation, a
fault is required between the body and subhorizontal Isachsen Formation 200 m downstream to
account for loss of Christopher Formation between the two units. Discordance of the body with
bedding to the northwest (Fig. 7) may potentially be explained by an angular unconformity. This explanation is dismissed because, with the exception of one unique situation, angular unconformities are not known in the Isachsen through Strand Fiord formations, despite excellent exposure across the Arctic Islands, although several disconformities exist (e.g. Galloway et al. 2013, 2015; Hadlari et al. 2016). The unique situation, restricted to an area with a high density of evaporite diapirs on western Axel Heiberg Island, resulted in local angular unconformities during the formation of minibasins on the immediate flanks of evaporite diapirs (Harrison and Jackson 2014). This complex wall-and-basin geometry is not known to exist elsewhere in the Sverdrup Basin. Another explanation for the angular discordance between the igneous body and bedding could potentially be a hypothetical fault, as shown on Fig. 7. The hypothetical fault would need to have significant throw to separate Strand Fiord Formation from Eureka Sound Formation or Isachsen Formation. In summary, interpretation of the igneous body as volcanic rock requires a number of special circumstances that are not typically recognized in strata of the Sverdrup Basin. It would be an unknown volcanic succession older than, and outside the geographic limits of, Strand Fiord Formation, and bounded on both sides by faults.

5.2.2 Interpretation of the Igneous Body as Intrusive Rock

Interpretation of the body as intrusive rock solves contradictions of known relationships in the study area. The Ar-Ar age is within the range of magmatism in the HALIP, and an intrusive origin explains the observed discordance with host strata. The geochemical similarity of the Mokka Fiord mafic rocks with basalts of the slightly younger Strand Fiord Formation (Estrada and Henjes-Kunst, 2004; Saumur and Williamson, 2016) is consistent with the Ar-Ar age, is inconsistent with interpretation as Isachsen Formation, and further reinforces an intrusive origin. There are no relationships that preclude an intrusive origin, other than its description as a flow (Thorsteinsson
1971), or three flows (Embry and Osadetz 1988). It should be noted that those authors did not provide outcrop observations or photographs to support an extrusive origin, and no evidence of flows was seen in the current study.

5.3. Implications of the Cretaceous Normal Superchron

5.3.1. Subchrons in the Cretaceous Normal Superchron

It is unclear why Wynne et al. (1988) did not interpret the reversed polarity data in the study area. However, we must still consider it as a possibility because one of the authors of that paper subsequently used the reversed polarity to support stratigraphic interpretations (Embry and Osadetz 1988). We have argued that the stratigraphic interpretation is not valid, but the question of reversed magnetic polarity remains in either interpretation of the igneous rocks, and is particularly important because the Ar-Ar age, 102.5 Ma, is in the midst of the Cretaceous Normal Superchron. Four short periods of reversed magnetism, which may include multiple short excursions, are proposed within this period (e.g. Ogg and Hinov 2012, their Fig. 27.6; Fig. 4). Three subchrons M’”-1r”, M’”-2r”, and M’”-3r” have been observed in deep sea drill cores but have not been clearly identified in marine magnetic anomaly studies. Subchron M’”-1r”, also known as ISEA, is accepted as a short reversal within the Cretaceous Normal Superchron because it has been recognized in both land-based and deep sea drilling studies (e.g. Tarduno 1990; Ogg and Hinov 2012). Subchrons M’”-2r”, and M’”-3r” are suspect because they have been observed only in deep sea drill cores, and have not been confirmed in independent studies. Factors that hinder the reliability of magnetostratigraphic studies that rely solely on core recovered by deep sea drilling are reviewed by Tarduno (1990); they include accidental inversion of core sections, which would result in a false magnetic polarity. A number of reversals occur in the well-studied Albian Contessa section in Italy, but it is uncertain whether those reversals represent primary magnetization at 104-
107 Ma or remagnetization during a later reversed polarity chron (Tarduno et al. 1992). These reversals are close in age to M”-3r” (ca. 103 Ma), and overlap, within error, with the Ar-Ar age of the Mokka Fiord igneous body. A period of reversed magnetism at ~115 Ma is based on a succession of dated flows in China (recalculated by He et al. 2008 from the 113 Ma interpretation of Sobel and Arnaud 2000). Thus it appears that there may be two, and possibly more, short periods of reversed magnetism within the Cretaceous Normal Superchron, as well as the possibility of multiple excursions that could be recorded as reversed polarity. If the Mokka Fiord igneous body preserves both normal and reverse polarity (e.g. Embry and Osadetz 1988) it may have cooled during an excursion, or one of the subchrons. Overlap of the Ar-Ar age, 102.5 ± 2.6 Ma (Estrada and Henjes-Kunst 2013), with subchron M”-3r” (ca. 103 Ma) is consistent with this possibility (Fig. 4). Alternatively, the locality may not be characterized by reversed polarity, and in this case there are no implications regarding reversals within the superchron.

5.3.2. Mokka Fiord Paleomagnetism Revisited

Independent of the question of the origin of the igneous body, the possibility that the Ar-Ar age may provide evidence for one of the poorly documented reversals within the Cretaceous Normal Superchron warrants closer examination of the paleomagnetic data. Although Embry and Osadetz (1988) highlight the reverse polarity of some of the Mokka Fiord data, the original report by Wynne et al. (1988) does not expressly interpret the polarity of the Mokka Fiord samples. Absence of Mokka Fiord data from all cases where reversed magnetism is discussed, figured, and interpreted in Wynne et al. (1988) leads us to infer that the authors were not committed to an interpretation of reversed magnetization for these samples. The topic of paleomagnetic reversals is a central theme in their paper, and therefore exclusion of the Mokka Fiord results is puzzling. Review of Wynne et al. (1988), and examination of the original lab results archived in the...
Geological Survey of Canada Paleomagnetism and Petrophysics Laboratory (R. Enkin, personal communication 2016) provides additional detail for discussion of the reversed magnetism attributed to the Mokka Fiord samples by Embry and Osadetz (1988). The Mokka Fiord data listed in Table 2 of Wynne et al. (1988) are:

1) 5 samples (all drill core, each split to result in 9 specimens) from site RUE41 with normal polarity, declination as expected for the Cretaceous (northwest), but significantly shallower inclination than expected.

2) 3 samples (all drill core, each split to result in 6 specimens) from site RUE42 with normal polarity; two of these have results similar to RUE41, but one has southerly rather than northwest declination; the average given for the 3 samples is the same as for RUE41.

3) 4 samples (all drill core, each split to result in 8 specimens) from site RUE42; the 4 samples are consistent, with reversed magnetism, unusual declination (NNE), and significantly shallower inclination than expected.

4) 7 samples; these are not additional samples, but the sum of the two RUE42 subsets, with the reversed samples flipped to normal, and averaged.

The polarity of all samples, including the four reversely magnetized RUE42 samples, are robust results that reflect the magnetic field at the time of cooling, and are not easily dismissed as being caused by later remagnetization (R. Enkin, personal communication 2016). Another possible explanation for the reversed polarities may be self-reversal, but the Mokka Fiord rocks exhibit only minor secondary alteration, and magnetite grains are fresh; therefore, magnetic self-reversal, as occasionally observed in oceanic basalts strongly affected by hydrothermal alteration (Doubrovine and Tarduno 2006), cannot be invoked. As noted earlier, the strike of the igneous body is at a high angle to that reported by Wynne et al. (1988), it cross-cuts host strata at a
moderate angle, and if it is an intrusion, it is younger than the host rocks. Consideration of these points would result in a more appropriate tilt correction, which may reduce the discrepancies from expected declination and inclination, but will not change the magnetic polarity.

If the intrusion includes reversely magnetized rocks, the implications are that: 1) the 28 m thick intrusion cooled in such a way, and at a time, as to retain both reversed and normal magnetizations, and different declinations and inclinations; 2) considering the Ar-Ar age, it likely cooled during an excursion, or possibly the M"-3r" subchron, within the Cretaceous Normal Superchron (Figs. 4A, B). If the Mokka Fiord igneous rocks preserve only normal polarity there are no restrictions or concerns with regard to its emplacement during the Cretaceous Normal Superchron.

5.4. Distribution of Cretaceous Volcanic and Sedimentary Rocks

At both Mokka Fiord (herein) and the Blue Mountains (Bédard et al. 2016), igneous bodies once interpreted as Isachsen Formation volcanic flows are now considered to be igneous intrusions. These new interpretations significantly reduce the extent of Isachsen Formation volcanic rocks from that indicated by Embry and Osadetz (1988; their Fig 4b). Isachsen Formation volcanic flows in eastern Sverdrup Basin are now limited to a north-trending region along the length of Axel Heiberg Island (Fig. 1). This change impacts regional tectonic interpretations that are based on the geographic distribution of volcanic flows. Within the study area, clastic rocks east of the igneous body should be mapped as mid- or upper Paterson Island or Walker Island member of Isachsen Formation. Rocks to the west are probably also Isachsen Formation and, considering the northwest dips farther west, may be higher in the formation, and the highest strata may include Christopher Formation, if no significant faults cut out or duplicate strata.

5.5. Future Work
The work of Embry and Osadetz (1988) and Wynne et al. (1988) continue to provide an important foundation for Cretaceous stratigraphic and paleomagnetic studies in Sverdrup Basin. Re-examination of the field relationships at Mokka Fiord show that the igneous body is most likely an intrusion; its previous interpretation as a volcanic layer resulted in an inappropriate tilt correction and age assignment for these rocks. Reinterpretation of the paleomagnetic data should include a more appropriate tilt correction. If, as suggested by the orientation of bedding 200 m southeast, the intrusion was emplaced in subhorizontal beds, no correction is required. The strike of the intrusion used by Wynne et al. (1988) for the tilt correction is inconsistent with all other evidence and is likely incorrect.

Considering the lack of exposed contacts, this locality is not the most ideal to pursue future studies. However, if additional field studies are undertaken, precise dating of the igneous body and additional palynological analysis of strata to its west, and the overlying shale, would help constrain its relationship to Strand Fiord magmatism and significance to the HALIP. We present a more clear understanding of the strike of the body, which may guide future workers to sample close to the centre, where grain size is possibly larger. Considering that Wynne et al. (1988) did not interpret the reversed magnetism at Mokka Fiord, future paleomagnetic fieldwork should sample with the strategy to perform all necessary tests to confirm that the results reflect the magnetic field at the time of cooling of the body, including those to exclude the possibility of partial self-reversal. Recognizing that different parts of the body may record different magnetic polarity, the body should be sampled across its width.

6. Conclusions

The suggestion of Embry and Osadetz (1988) that further study of the Mokka Fiord site could yield an age for M0 was based on the premise that the igneous unit is a volcanic flow in the
upper Isachsen Formation that has reversed magnetic polarity. No evidence for volcanic flows was
found in our examination of this site, nor was any provided by previous workers. With the origin
of the igneous body in question and significance of its reversed paleomagnetic data uncertain, the
stratigraphic / paleomagnetic argument for its age (Embry and Osadetz 1988), which was in
conflict with the Ar-Ar age (102.5 ± 2.6; Estrada and Henjes-Kunst 2013), is also in question, and
there is no reason to dismiss the Ar-Ar age of the body based on that conflict. We provide evidence
that the igneous rock is best interpreted as an intrusion and not a volcanic flow. However, we
cannot rule out the possibility that the rocks belong to an unknown volcanic succession that is
older than, and outside the geographic distribution of, Strand Fiord Formation, and is also bounded
on both sides by hypothetical faults. The new interpretation of the body as intrusive rock removes
conflict between previously interpreted stratigraphic position and the Ar-Ar age of 102.5 ± 2.6 Ma
reported by Estrada and Henjes-Kunst (2013). Sedimentary rocks 200 m southeast of the body are
constrained by palynological analysis to be between late Barremian and late Aptian age, and to be
part of mid- or upper Paterson Island Member or Walker Island Member of the Isachsen Formation.

The significance of the Mokka Fiord paleomagnetic data remains enigmatic because
Wynne et al. (1988) did not include the subset of Mokka Fiord samples with reverse polarity in
their discussion. If the Mokka Fiord igneous body preserves only normal polarity there are no
challenges to its interpretation as being emplaced during the Cretaceous Normal Superchron. If
the Mokka Fiord intrusion preserves both normal and reverse polarity, emplacement of the
intrusion may have occurred during one of the proposed short reversals, or an excursion, within
the Cretaceous Normal Superchron. The Ar-Ar age reported by Estrada and Henjes-Kunst (2013)
matches the age of the M”-3r” subchron at ~103 Ma. Considering the Ar-Ar age, and uncertainties
in origin and magnetic polarity of the body, the Mokka Fiord site is unlikely to provide time-
stratigraphic constraints on the age of M0 as suggested by Embry and Osadetz (1988). However, the presence of suitable igneous rocks in Sverdrup Basin that may record reversed magnetism during the Cretaceous Normal Superchron as well as detailed stratigraphic studies which have identified important events, including OAE1a (e.g. Herrle et al. 2015), highlight a potential in the basin for advances in calibrating the geomagnetic time scale.

Acknowledgements

The work was conducted under the High Arctic Large Igneous Province (HALIP) activity of the Western Arctic Project of GEM-2 (Natural Resources Canada), and contributes to that project by elucidating the nature and age of Cretaceous igneous rocks in the Western Arctic region. We thank the Polar Continental Shelf Project for logistics support in fieldwork. Thank you to Linda Dancey for palynological preparation of the material and to Richard Fontaine for curation. We particularly thank Randy Enkin (Geological Survey of Canada Paleomagnetism and Petrophysics Laboratory) for digging out details of archived paleomagnetic data and for his opinions of their meaning. Evenchick thanks Kirk Osadetz for helpful discussion of the geological issues at Mokka Fiord both before and after fieldwork. The manuscript was improved with the help of comments from Keith Dewing, and from reviewers John Tarduno and Henry Halls, and CJES Associate Editor George Dix.

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Footnote

1Supplementary data are available with the article through the journal website at

http://nrcresearchpress.com/doi/suppl/xxxxxx
References cited


Table 1. Volcanic rocks reported in Isachsen Formation; locations as shown in Fig. 1 (Ricketts 1985; Embry and Osadetz 1988 and references therein; Williamson et al. 2017).

<table>
<thead>
<tr>
<th>Member</th>
<th>Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walker Island</td>
<td>Geodetic Hills, central Axel Heiberg Island</td>
<td>11 m consisting of 3 flows</td>
</tr>
<tr>
<td></td>
<td>Bunde Fiord, NW Axel Heiberg Island</td>
<td>~220 m of basalt flows interbedded with quartzose sandstone and pyroclastic and epiclastic volcanic sediments</td>
</tr>
<tr>
<td></td>
<td>Li Fiord, Middle Fiord, and Strand Fiord, western Axel Heiberg Island</td>
<td>local 50-100 m scale exposures</td>
</tr>
<tr>
<td></td>
<td>Mokka Fiord, Axel Heiberg Island</td>
<td>28 m of basalt consisting of 3 flows</td>
</tr>
<tr>
<td></td>
<td>Blue Mountains, Ellesmere Island</td>
<td>previously interpreted to include 20 m of basalt at the top of Isachsen Fm; now interpreted as intrusions emplaced at the contact between Isachsen and Christopher formations (Bédard et al. 2016)</td>
</tr>
<tr>
<td>Paterson Island</td>
<td>Geodetic Hills, central Axel Heiberg Island</td>
<td>10.5 m of basalt</td>
</tr>
<tr>
<td></td>
<td>Bjarnason Island, NW of Geodetic Hills</td>
<td>two 10 m thick basaltic flows</td>
</tr>
</tbody>
</table>
Table 2. Previous data and interpretations of Mokka Fiord strata

<table>
<thead>
<tr>
<th>Quotes and Information from papers which present or discuss Mokka Fiord strata</th>
<th>Comments</th>
</tr>
</thead>
</table>
| Thorsteinsson (1971); note 1 on regional map  
“A basalt flow of uncertain stratigraphic position and about 100 feet thick crops out adjacent to the shore of Eureka Sound, north of the entrance to Mokka Fiord. The strike of the flow more or less parallels Mokka Fiord. The flow underlies conformably the Eureka Sound Formation, but no exposures are known beneath it. The flow is provisionally included in the *Strand* *Fiord* Formation.” | Our observations of orientation of the igneous body are described by Thorsteinsson. |
| Osadetz and Moore (1988), p. 2  
“Another volcanic flow occurs below rock types typical of the lower *Christopher* Formation (Albian) at Mokka Fiord, on eastern Axel Heiberg Island. It is believed to be roughly correlative with volcanic rocks in the *Isachsen* Formation in both the *Blue Mountains* and *Geodetic Hills*. Unfortunately, the lower contact is not exposed and its exact stratigraphic position is uncertain.” | Follows Thorsteinsson (1971) in interpreting igneous rocks as a flow, but reinterpreted as *Isachsen* Fm based on correlation with volcanic rocks in the formation elsewhere. Reinterpreted overlying rocks from Eureka Sound to *Christopher* formation. |

Table 1: Mokka sites  
RUE 41, 42; *Isachsen* basalt; dip-direction/dip of 07/38;  
RUE 41-9 samples assessed from 5 cores, with mean declination and inclination (relative to paleohorizontal) of 305/59. Site RUE42 – three different sub sites, with mean declination and inclination (relative to paleohorizontal): 035(78), 025(77), 224(71). The last of these is noted as exhibiting a change in the inclination because $\phi_m = 20^\circ$.  
RUE41 and RUE42 ‘sub site’ is the first two sites combined is not stated.  
RUE41: This table lists both Mokka Fiord and Blue Mountains samples as *Isachsen* basalt equivalent. Both are now interpreted to be intrusions (this paper, Bédard et al. 2016).  
RUE42: This statement suggests that the Mokka Fiord locality is not included in the list of reversely magnetized sites. Outcrop relationships are not presented for the Mokka Fiord locality. It is not discussed in the treatment of restoration of beds to paleohorizontal, nor is it listed in the interpretation of reversals of magnetization.

Table 3: The summary of rock-unit averages by locality only includes results for site RUE41 from Mokka Fiord, with declination and inclination of 305/59.  
Reversals of magnetization, p. 1233 (the text is split into 3 sections here for ease of reference):  
A: ‘Eleven of the 28 flows studied from the *Isachsen* are reversely magnetized. The reversed flows occur at two horizons: in the lower part of the *Isachsen* Formation and in the upper third. The uppermost *Isachsen* flows are normally magnetized (Table 2: Fig. 14).’  
B: ‘All of the flows that we sampled in the *Isachsen* Formation, which ranges in age from Valanginian to Aptian (Wall 1983), lie in the upper portion of the Walker Island Member, which is late Barremian to Aptian (*Emby* and Osadetz 1988), or in equivalent strata.’  
C: ‘… the normal magnetizations of the *Strand* *Fiord* Formation, the *Christopher* Formation, and the top of the *Isachsen* Formation were acquired during the Cretaceous normal polarity superchron. Hence we tentatively suggest that the uppermost horizon of reversed flows of the *Isachsen* Formation (site AXV01, AXV02, AXW10, Fig. 14) corresponds to $\phi_m$ of the youngest of the M sequence of reversed anomalies, and that the lower horizon of reversed flows (AXV10, AXV01, AXV02, AXV03, AXV30, AXV31, AXV32, AXW04, Fig. 14) correspond to the M, reversed anomaly.’  

Estrada and Henjes-Kunst (2004), p. 583  
Mokka Fiord samples: C148688 (AX37), C107586 (82-OE-11-1.5), C107587 (82-OE-11-3)  
“The only remarkable difference in trace element chemistry between the basalts of the two formations is the higher content of the *Isachsen* Formation basalts with an average of 133 ppm compared to 64 ppm for the *Strand* *Fiord* Formation basalts (Table 1). (Exceptions: The samples of the *Strand* *Fiord* Formation basalts from *Bals* *Fiord* with Cu contents in the range of the *Isachsen* Formation, and the samples from Mokka Fiord and *Blue Mountains* mapped as *Isachsen* Formation with low Cu contents.)”  

Estrada and Henjes-Kunst (2013), p. 120-121; *Sample C-107586*  
“… a 28 m thick volcanic unit consisting of three flows. Underlying strata are not exposed, and this volcanic unit is tentatively assigned to the Walker Island Member because it is overlain by shales of the *Christopher* Formation and has reversely polarised lavas (Wyinne et al. 1988).”  

Estrada (2014); *Sample C-107586*  
(no rock descriptions or specific reference to Mokka Fiord rocks are presented)  
“Basalt at Mokka Fiord, Axel Heiberg Island, was originally mapped as *Christopher* Formation (Thorsteinsson, 1971). It was later reassigned to the *Isachsen* Formation, based in part on reversed magnetic polarity (Osadetz and Moore 1988; Wyinne et al., 1988), and then reinterpreted to be *Strand* *Fiord* Formation based on an Ar-Ar age of 102.5 ± 2.6 Ma (Estrada and Henjes-Kunst, 2013). The Ar-Ar age is considered unreliable because it is inconsistent with the reversed polarity documented by Wyinne et al. (1988), which requires a pre–125.9 Ma age (Gradstein and Ogg, 2012).”  
}

Table 2. Previous data and interpretations of Mokka Fiord strata

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Figure captions

Fig. 1. Geologic map of Sverdrup Basin (after Dewing et al. 2007). The study area is indicated by the yellow star on eastern Axel Heiberg Island.

Fig. 2. Cretaceous lithostratigraphy of Sverdrup Basin (modified after Hadlari et al. 2016). Detailed summaries and discussions of age determinations of Lower Cretaceous strata are in Galloway et al. (2012, 2013, 2015), Schröder-Adams et al. (2014), and Herrle et al. (2015). *Age of Rondon Member, Isachsen Formation is after Galloway et al. (2015); Herrle et al. (2015) place Rondon Member in lower Aptian. Ages of igneous rocks are emplacement ages; stratigraphic position is not implied.

Fig. 3. Geologic setting of the study area. Geology is after Thorsteinsson (1971). The legend is as defined in that publication, but note that Eureka Sound Formation has since been elevated to group status (Miall 1986). The unit labels in parentheses indicate a reinterpretation of the distribution of units based on the results in this paper. Inclusion of Ke? in the reinterpretation is to acknowledge that dark and recessive weathering strata in the core of the syncline may be Christopher Formation. Igneous rocks discussed in this paper outcrop in the creek within the outline of Fig. 7, where the creek intersects the dashed line. The base map is NTS 049G/12. Outline shows the location of Fig. 7.

Fig. 4. Stratigraphic chart of the Cretaceous part of the Sverdrup Basin, modified after Embry and Osadetz (1988) and Evenchick et al. (2015), with previous interpretations of the stratigraphic position of Mokka Fiord strata, and the results of the current study. Precise stratigraphic positions of volcanic rocks in Isachsen Formation are approximate, and depicted based on relationships to bounding units. The ages of stratigraphic units are as cited in Fig. 2. Two combinations of interpretations of the Barremian-Aptian boundary and
position of the top of Paterson Island Member are shown in A and B. The base of Paterson Island Member, Early to Late Valanginian, is not shown. Stratigraphic range of the Isachsen Formation in the study area, at right in A and B, is from palynology presented in this paper. Magnetic polarity timescale is from Ogg and Hinnov (2012). (A) Stratigraphic relationships using the timescale of Gradstein et al. (2012) and ages of Isachsen Formation following Galloway et al. (2015), with late Barremian age for Rondon Member. (B) Fig. 4A modified after Midtkandal et al. (2016, and others) for Barremian-Aptian boundary at 121-122 Ma, and after Herrle et al. (2015) for Paterson Island Member extending into lower Aptian. The top of Walker Island Member is moved up to allow it an age range of greater than ~2 my. This arbitrary amount does not impact interpretations. The positions of M0r and M”-1r” are moved up to approximately similar positions within the Aptian as in Fig. 4A, with M0 at base of Aptian, and M”-1r” above OEA1a (as in e.g. Erba 1996), which according to Herrle (2015; his Fig. 2) overlaps Rondon and base of Walker Island members on Axel Heiberg Island.

**Fig. 5.** Photographs of the south side of the creek west of the mouth of Mokka Fiord, showing the relationships between rock units, and relative positions of features discussed in text. The dash-dot line in A, B, and C is the same belt of bedding traces. (A) View south southwest, almost along strike of the igneous body, identified by outcrops at i1, i2, and i3. The location of the subhorizontal fine clastic rocks downstream of the igneous rocks, shown in Figs. 6A, B, is indicated at left. The southern limit of the bedding traces shown in Figs. 5B, C is at upper right. The northwest dip of the igneous body is inferred from the limit of dark brown outcrop highly resistant to erosion, and the dip of the body is inferred from the dipslope of resistant rock. The bend in the creek at x is considered to be controlled by the strike of the
igneous body. The letters x and y indicate the same position in adjoining photographs.

Width of view is approximately 400 m at foreground. (B) View approximately south to the area upstream from the igneous body. (C) View south southwest to bedded sedimentary rocks upstream from the igneous body, with overlap with Fig. 5B identified by y. The inset shows the distinctly bedded section that results in the surface traces of bedding indicated by dash-dot lines. Width of view is approximately 400 m.

**Fig. 6.** Photographs of outcrops in the vicinity of the igneous body east of Mokka Fiord. (A) View southwest to the only outcrop downstream from the igneous body; location is indicated in Fig. 5A. Sub-horizontal bedding can be seen across much of the outcrop. Areas examined are indicated by ovals. (B) Close view of laminated and cross-laminated fine-grained quartz sandstone and siltstone from which the palynology sample was collected. The hammer is 33 cm long. (C) Outcrop of the igneous body near its northwestern boundary and upper contact; location is shown in Figs. 5A and 6D. A hammer 33 cm long is near centre image. (D) Northwestern, upper contact area of the igneous body, showing extent of igneous bedrock and quality of exposure at the contact. Position of the contact is based on the upstream limit of igneous bedrock. Viewed to the south.

**Fig. 7.** Map showing interpreted relationships in the study area. The base image is the centre of airphoto A16858-143. Intrusive rocks identified in Fig. 5 are outlined by heavy dotted lines. Bedding traces continuous with the well-exposed bedding at the creek in Fig. 5C are indicated by a dash-dot line. Rocks in the southwest corner labelled 'igneous rocks?' have similar weathering characteristics to those exposed in the study area; they may be a different intrusion, or an en echelon part of the same intrusion. The white line with black dots is a
hypothesised fault required to accommodate the discordance between the igneous body and bedding traces if the body is volcanic rock.
Table 1. Volcanic rocks reported in Isachsen Formation; locations as shown in Figure 1

<table>
<thead>
<tr>
<th>Member</th>
<th>Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walker Island</td>
<td>Geodetic Hills, central Axel Heiberg Island</td>
<td>11 m consisting of 3 flows</td>
</tr>
<tr>
<td></td>
<td>Bunde Fiord, NW Axel Heiberg Island</td>
<td>~220 m of basalt flows interbedded with quartzose sandstone and pyroclastic and epiclastic volcanic sediments</td>
</tr>
<tr>
<td></td>
<td>Li Fiord, Middle Fiord, and Strand Fiord, western Axel Heiberg Island</td>
<td>local 50-100 m scale exposures</td>
</tr>
<tr>
<td></td>
<td>Mokka Fiord, Axel Heiberg Island</td>
<td>28 m of basalt consisting of 3 flows</td>
</tr>
<tr>
<td></td>
<td>Blue Mountains, Ellesmere Island</td>
<td>previously interpreted to include 20 m of basalt at the top of Isachsen Fm; now interpreted as intrusions emplaced at the contact between Isachsen and Christopher formations (Bédard et al. 2016)</td>
</tr>
<tr>
<td>Paterson Island</td>
<td>Geodetic Hills, central Axel Heiberg Island</td>
<td>10.5 m of basalt</td>
</tr>
<tr>
<td></td>
<td>Bjarnason Island, NW of Geodetic Hills</td>
<td>two 10 m thick basaltic flows</td>
</tr>
</tbody>
</table>

(Ricketts 1985; Embry and Osadetz 1988 and references therein; Williamson et al. 2017).
Table 2. Previous data and interpretations of Mokka Fiord strata

<table>
<thead>
<tr>
<th>Quotes from papers which present or discuss Mokka Fiord strata</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thorsteinsson (1971); note 1 on regional map</td>
<td>Our observations of orientation of the gneiss body are as described by Thorsteinsson.</td>
</tr>
<tr>
<td>“A basalt flow of uncertain stratigraphic position and about 100 feet thick crops out adjacent to the shore of Eureka Sound, north of the entrance to Mokka Fiord. The strike of the flow more or less parallels the strike of Mokka Fiord. The flow underlies conformably the Eureka Sound Formation, but no sediments are exposed beneath it. The flow is provisionally included in the Christopher Formation.”</td>
<td></td>
</tr>
<tr>
<td>Osadetz and Moore (1988), p. 2</td>
<td>follows Thorsteinsson (1971) in interpreting igneous rocks as a flow, but interpreted it as Isachsen Fm based on correlation with volcanic rocks in the formation elsewhere. Reinterpreted overlying rocks from Eureka Sound to Christopher formation.</td>
</tr>
<tr>
<td>“Another volcanic flow unit occurs below rock types typical of the lower Christopher Formation (Albian) at Mokka Fiord, on eastern Axel Heiberg Island. It is believed to be roughly coeval with volcanic rocks in the Isachsen Formation in both the Blue Mountains and Geodetic Hills. Unfortunately, the lower contact is not exposed and its exact stratigraphic position is uncertain.”</td>
<td></td>
</tr>
<tr>
<td>Wynne, Irving, and Osadetz (1988)</td>
<td></td>
</tr>
<tr>
<td>Table 2: Site RUE41 - 9 samples analysed from 5 cores, with mean declination and inclination (relative to paleohorizontal) of 305/59. Site RUE42 – three different sub sites, with mean declination and inclination (relative to paleohorizon) of: 305/78, 028/-57, 224/71.</td>
<td>Table 1: Note that dip direction is significantly different than described by Thorsteinsson. Table 2. The fact that the third RUE42 ‘sub site’ is the first two sites combined is not stated. Table 3: This table lists both Mokka Fiord and Blue Mountains samples as Isachsen basalts equivalent. Both are now interpreted to be intrusions (this paper, Bédard et al. 2016).</td>
</tr>
<tr>
<td>“… at the mouth of Mokka Fiord there is a 28 m thick volcanic unit consisting of three flows. Underlying strata are not exposed, and this volcanic unit is tentatively assigned to the Walker Island Member because it is overlain by shales of the Christopher Formation and has reversed polarities (Wynn et al. 1988).”</td>
<td>Quote A: this statement suggests that the Mokka Fiord locality is normally magnetized because Embry and Osadetz (1988) and Osadetz and Moore (1988) interpret the flows to be overlain by Christopher Fm, and therefore at the top of Isachsen Fm. Quote B: appears to contradict quote A, which states that there are flows in the lower Isachsen with reversed magnetization. Quote C: the Mokka Fiord locality is not included in the list of reversely magnetized sites. Outcrop relationships are not presented for the Mokka Fiord locality. It is not discussed in the treatment of restoration of beds to paleohorizontal, nor is it listed in the interpretation of reversals of magnetization.</td>
</tr>
<tr>
<td>Estrada and Henjes-Kunst (2004), p. 583</td>
<td>The “reversed polarities” and stratigraphic position with respect to Christopher Fm are used to conclude that the flow is within the Isachsen Fm. No explanations are given for why the data in Wynne et al. (1988) are described as reversed polarity. Follows Osadetz and Moore (1988) reinterpretation of overlying strata as Christopher Fm. Mokka Fiord rocks are included in Isachsen Formation following Embry and Osadetz (1988) but the authors noted that the chemistry is more like Strand Fm. The only other, and similar, anomaly noted in the Isachsen geochemistry is with the Blue Mountains samples.</td>
</tr>
<tr>
<td>Estrada and Henjes-Kunst (2013), p. 120-121</td>
<td>This paper uses the outcrop description of Embry and Osadetz (1988). It is the first paper to interpret the Mokka Fiord igneous rocks as Strand Fm Formation; the interpretation is based on Ar dating and geochemistry.</td>
</tr>
<tr>
<td>“… a 28 m thick volcanic unit consists of three basalt flows and is overlain by shales, mapped as Christopher Formation (Embry &amp; Osadetz 1988). The underlying strata are not exposed. The basalt was assigned to the upper Isachsen Formation; however, its stratigraphic position is relatively uncertain (Osadetz &amp; Moore 1988). A whole-rock separate of sample C107556 from this volcanic unit yielded within error identical total gas, plateau and inverse-isochron ages. The plateau age 102.5 ± 2.6 Ma is the best estimate for the age of this basalt (Fig. 5r). This age does not correspond to the stratigraphic age of the upper Isachsen Formation (Aptian, c. 125 to 112 Ma; Gradstein et al. 2004) but correlates with the stratigraphic age of the Strand Fm Formation (late Albian to early Cenomanian, c. 110 to 95 Ma). A genetic relationship with the latter volcanic rocks is also supported by geochemical data. The U-Pb zircon data for samples C107556 and C107558 are consistent with a Ar-Ar age of 102.5 ± 2.6 Ma (both samples) and this interpretation is consistent with the reversed polarity documented by Wynne et al. (1988) which requires a pre-125.9 Ma age (Gradstein and Ogg, 2012).”</td>
<td>Geochemistry of the Strand Fm and Isachsen formations are presented and discussed. Mokka Fiord igneous rocks are included in Strand Fm, following the 2013 interpretation. This interpretation follows Embry and Osadetz (1988) in using the magnetic polarity to support the Isachsen stratigraphic position (incorrectly attributed to Osadetz and Moore (1988) and Osadetz and Moore (1988), Wynne et al. (1988)), and then re-interpreted the Ar-Ar age interpretation of Estrada and Henjes-Kunst (2013).</td>
</tr>
</tbody>
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Estrada (2014); Sample C-107556 (no rock descriptions or specific reference to Mokka Fiord rocks are presented)
Fig. 1. Geologic map of Sverdrup Basin (after Dewing et al. 2007). The study area is indicated by the yellow star on eastern Axel Heiberg Island.
Geochronology sources: Only U-Pb zircon or baddeleyite ages are considered for the igneous events, sources are: (1) Omma et al. (2011); (2) Evenchick et al. (2015); (3) Herrle et al. (2015); (4) Davis et al. (2016); (5) Dockman et al. (2018); (6) Kingsbury et al. (2017)

Fig. 2. Cretaceous lithostratigraphy of Sverdrup Basin (modified after Hadlari et al. 2016). Detailed summaries and discussions of age determinations of Lower Cretaceous strata are in Galloway et al. (2012, 2013, 2015), Schröder-Adams et al. (2014), and Herrle et al. (2015). *Age of Rondon Member, Isachsen Formation is after Galloway et al. (2015); Herrle et al. (2015) place Rondon Member in lower Aptian. Ages of igneous rocks are emplacement ages; stratigraphic position is not implied.
Fig. 3. Geological setting of the study area. Geology is after Thorsteinsson (1971). The legend is as defined in that publication, but note that Eureka Sound Formation has since been elevated to group status (Miall 1986). The unit labels in parentheses indicate a reinterpretation of the distribution of units based on the results in this paper. Inclusion of Kc? in the reinterpretation is to acknowledge that dark and recessive weathering strata in the core of the syncline may be Christopher Formation. Igneous rocks discussed in this paper outcrop in the creek within the outline of Fig. 7, where the creek intersects the dashed line. The base map is NTS 049G/12. Outline shows the location of Fig. 7.
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