Antarctic Science 15 (3): 393–398 (2003) © Antarctic Science Ltd Printed in the UK DOI: 10.1017/S0954102003001408

Mobilization of fluidized sediment during sill emplacement, western Dronning Maud Land, East Antarctica

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Abstract: Large mafic sills in the Ahlmannryggen region of western Dronning Maud Land were intruded into partially lithified sediments of the mid-Proterozoic Ritscherflya Supergroup. Clastic sedimentary dykes intruding the thick mafic sills have been identified, and show evidence for fluidization of the partially lithified sediments. Previous work had demonstrated *in situ* fluidization and localized anatectic melting. This study demonstrates mobilization of the fluidized sediments, with penetration at least 50 m into the fractured, intruding sill. Physical features within the clastic dykes (e.g. sediment balls, flame structures) suggest that the sediments were largely unconsolidated, or at most only partially lithified. The presence of a thin zone of anatectic melt along the dyke–sill contact suggests that the mafic sill was still hot (*c*. 700°C) at the time of sedimentary dyke injection.

Received 2 September 2002, accepted 20 May 2003

Key words: Ahlmannryggen, Borgmassivet Intrusions, clastic dyke, Ritscherflya Supergroup

Introduction

The fluidization of wet, partially lithified sediments along the contacts of intruding igneous bodies is responsible for a variety of textural and field relationships that have been documented by several authors (e.g. Walton & O'Sullivan 1950, Kokelaar 1982, Krynauw *et al.* 1988). The fluidization process is dependent on the attainment of a minimum vapour flow velocity and reflects several variables, including vapour density, sediment particle size and particle distribution. Water vapour can be generated over a wide range of temperature and pressure conditions.

In the Ahlmannryggen region of western Dronning Maud Land (Fig. 1), flat-lying, undeformed sedimentary rocks in contact with massive mafic sills display textural and intrusive relationships that indicate the sediments were wet and underwent fluidization at the time of emplacement of the mafic sills (Krynauw *et al.* 1988). Krynauw *et al.* (1988) concluded that localized fluidization of the sediments occurred *in situ* (stationary fluidization) and was not associated with any mobilization or transport of the fluidized sediment. In this contribution, we report the presence of clastic sedimentary dykes that intrude thick mafic sills of the same igneous suite as those described by Krynauw *et al.* (1988) and appear to represent at least local mobilization of the fluidized sedimentary rocks.

The processes involved in the generation of the clastic dykes in the Ahlmannryggen have many similarities to those that generate peperites (see Skilling *et al*. 2002), which are formed by the *in situ* disintegration of magma intruding and mingling with unconsolidated wet sediment (White *et al.* 2000). However, peperites display a mix of both sediment and igneous components in the same rock, whereas the clastic dykes are entirely sedimentary and have back-dyked into the intruding sill.

Geological setting

The stratigraphy and general geology of the Grunehogna area of the Ahlmannryggen (western Dronning Maud Land; Fig. 1) has been mapped and described by several workers (e.g. Wolmarans & Kent 1982). Relevant to this study is the Precambrian Ritscherflya Supergroup, which covers all areas of the Ahlmannryggen. The Ritscherflya Supergroup consists of relatively undeformed sedimentary and volcanogenic rocks of the Ahlmannryggen and Jutulstraumen groups. The Ritscherflya Supergroup has been intruded extensively by large-scale tholeiitic sills and dykes of the Borgmassivet Intrusions (Wolmarans & Kent 1982).

The Ritscherflya Supergroup has been interpreted as a sedimentary sequence of shallow marine, tidal flat, braided stream and alluvial fan deposits (Wolmarans & Kent 1982). The volcanogenic sedimentary rocks of the Jutulstraumen Group, which form the upper part of the Ritscherflya Supergroup have been correlated geochemically with the Borgmassivet Intrusions (Moyes *et al.* 1995). Moyes *et al.* (1995) attempted to date the lithification age of the Högfonna Formation of the Ritscherflya Supergroup using a combination of Rb–Sr and Sm–Nd whole rock geochronology. Assuming a homogenized source region they obtained ages of 1085 ± 27 Ma (Rb–Sr) and 1180 ± 367 Ma (Sm–Nd). Direct dating of the Borgmassivet Intrusions has also proved difficult with Rb–Sr and Sm–Nd whole rock geochronology yielding ages in the range 842 ± 15 to 1429 ± 124 Ma (Moyes *et al.* 1995), although Wolmarans & Kent (1982) produced an Rb–Sr whole rock isochron of 1073 ± 40 Ma based on seven mafic sills from the Ahlmannryggen. A further emplacement date of the mafic sills has been obtained from the granitic zone at the sill–sediment interface. The granite–granophyre–syenite

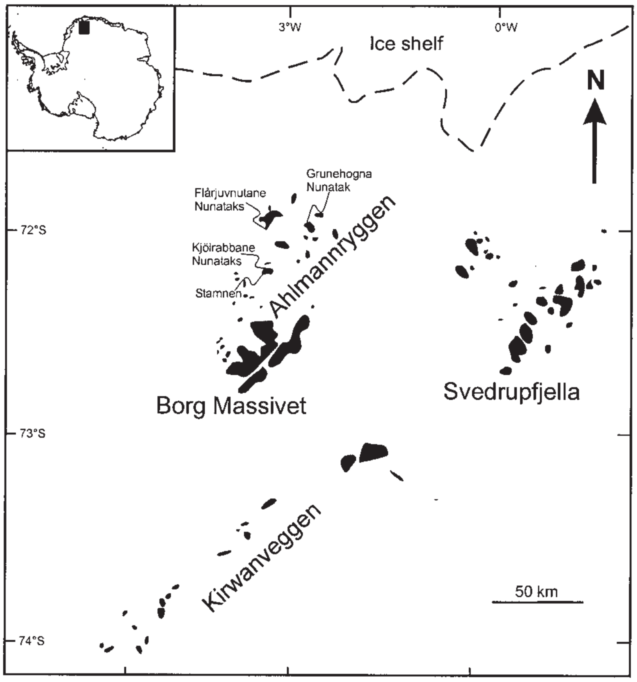

Fig. 1. Location map of the central Ahlmannryggen showing the position of the clastic dykes relative to Grunehogna nunatak.

units (Nils Jörgennutane suite) are interpreted to be the result of contact melting under hydrous conditions (Moyes *et al.* 1995). These contact melts have been dated by Moyes *et al.* (1995), who obtained Rb–Sr whole rock ages in the range 939 ± 29 to 1008 ± 16 Ma. Therefore an approximate age for the intrusion of the Borgmassivet Intrusive mafic sills is considered to be in the range 900–1100 Ma, which may be coeval with the Umkondo large igneous province of southern Africa (1100 Ma; Hanson *et al.* 1998). This date is close to the inferred lithification age of the Ritscherflya Supergroup sedimentary rocks (1085 ± 27 Ma; Moyes *et al.* 1995) and therefore supports the field observations of Krynauw *et al.* (1988) that the Borgmassivet Intrusions were emplaced into wet, partially lithified sediments. This interpretation was based on several observations, e.g. destruction of sedimentary structures, large-scale soft-sediment deformation (including sediment balls and flame structures), pegmatites at the sedimentary–igneous contact, and fusion of sedimentary rocks. Some of these features are typical of the establishment of a fluidized system (Kokelaar 1982).

Krynauw *et al.* (1988) interpreted the wet sediment–sill interaction to have taken place at shallow crustal levels (< 1.6 km or = 312 bar) with stationary fluidization of the host sediments occurring within a 3 m zone of the sill contact. Not all Ritscherflya Supergroup sedimentary rocks in contact with the Borgmassivet Intrusives have been fluidized, e.g. the Schumacherfjellet Formation, which may have been completely lithified at the time of intrusion, or indicates that wet sediment only occurred in pockets.

Clastic dykes - morphology and geological relationships

Three clastic dykes were identified in the central Ahlmannryggen; one located within the Kjölrabbane nunatak group (72º14.998'S 003º23.718'W), another at Flårjuvnutane (72º00.978'S 003º32.904'W) and a third at Stamnen (72º 15.482'S 003º25.978'W) (Fig. 1). The dykes from Kjölrabbane and Flårjuvnutane will be described here.

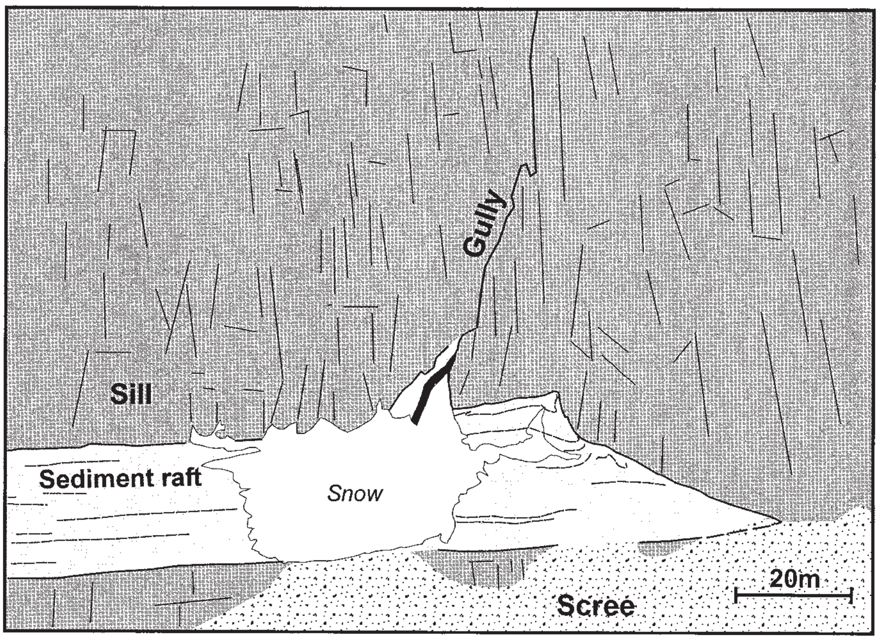

Fig. 2. Line tracing from a photograph of the sediment–sill relationships at Kjölrabbane. Note the folding within the raft of sedimentary rock adjacent to the discordant segment of the sill. Mesozoic dyke exposed at the base of the gully.

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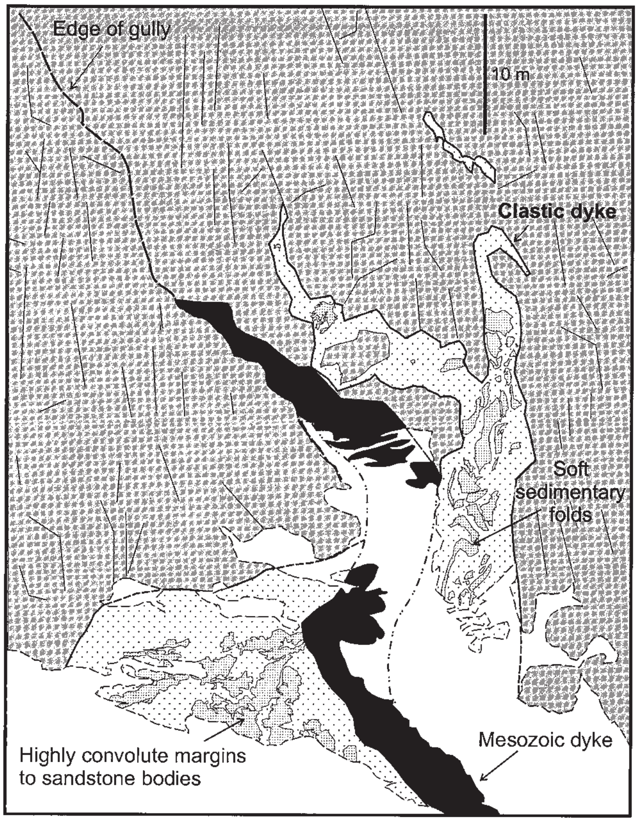

Fig. 3. Line tracing from a photograph taken looking obliquely up the gully of the Kjölrabbane clastic dyke. In this foreshortened view the lower 'funnel' region of the clastic dyke, displaying highly convoluted sedimentary units, narrows into the main dyke, which has irregular margins that exploit jointing within the sill.

Fig. 4. Interbedded arenites–siltstones of the Schumacherfjellet Formation forming a disaggregated soft sedimentary fold hinge, with extensive flame structures developed along the lithological boundaries. Photograph shows part of the lower section of the Kjölrabbane clastic dyke.

Kjölrabbane clastic dyke

The most extensively exposed clastic dyke found during our study is located in the most north-easterly nunatak of the Kjölrabbane area (Fig. 1). A 150 m cliff section exposes a thick, flat-lying mafic sill of the Borgmassivet intrusive suite. Near the base of the cliff a 15–20 m thick screen of sub-horizontally bedded sedimentary rocks of the Schumacherfjellet Formation is bounded along its basal and upper surfaces by mafic sills that display columnar jointing (Fig. 2). The upper sill is approximately 100 m thick, while the lower sill is at least 10 m thick although its base is unexposed. The sills appear to coalesce toward the east of the cliff exposure, with the upper sill truncating the sedimentary bedding along a ramp inclined at 25º. Some folded and disrupted bedded sedimentary rock is present immediately beneath the ramp. Similar disharmonic folds along discordant ramps within sedimentary rocks have been related to emplacement of the sills into unconsolidated sediments (Krynauw *et al.* 1988).

The clastic dyke is located within the recesses of a prominent gully, also intruded by a Mesozoic dyke, approximately 20 m from the top of the ramp in the screen of sedimentary rock. At the base of the gully the clastic dyke appears to narrow upward to a width of approximately 2 m, and extends up into the mafic sill for an estimated 50 m. The dyke displays a pronounced bifurcation at its midpoint (Fig. 3). The margins to the clastic dyke are irregular and appear to, in part, exploit jointing within the sill. Binocular observation of the termination of the dyke revealed an apparently isolated segment of clastic dyke, implying that this segment and the main dyke are connected in the unobserved third dimension. Discrete, well-defined blocks and sheet-like bodies of sandstone dominate the lower levels of the dyke between the funnel and the bifurcation point, and are supported within a homogeneous clastic matrix. A gradual increase in disaggregation of these sandstone bodies occurs from the base of the dyke upward, from folded bedded sandstone units, through sub-angular blocks that commonly possess a 'jigsaw-fit', to a generally homogeneous clastic fill containing small decimetre and smaller bodies of sandstone. The folded sandstone units within the funnel and base of the dyke show abundant evidence that their deformation occurred in an unconsolidated state, with well-developed flame structures, incipient sandstone ball formation and highly convolute depositional boundaries (Figs 3 & 4). Decimetre-scale pale coloured ovoid structures possessing concentric internal zonation and laminations are also prevalent throughout the dyke. These ovoid structures are identical to those described from the reconstituted sediments that lie parallel to and along sill contacts elsewhere in the Ahlmannryggen, which have been interpreted as centres of advanced lithification prior to intrusion of the sill. These ovoid centres are resistant to later processes, such as fluidization,

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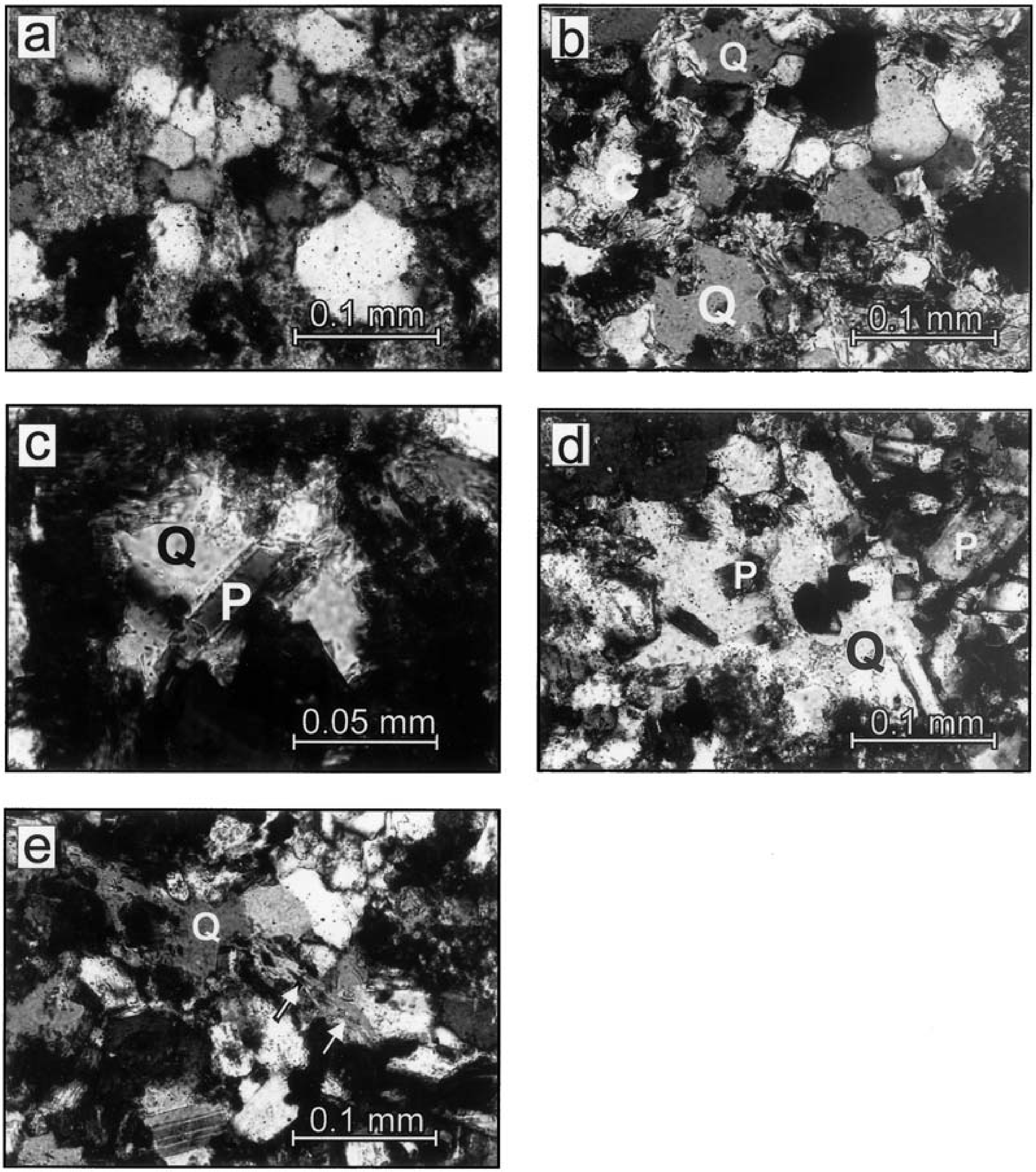

Fig. 5. Selection of textures developed within the clastic dykes. All photomicrographs taken using crossed polarized light. **a.** Typical textural variety of quartz within the homogeneous matrix of the dykes, with small aggregates of quartz grains displaying 120° grain boundaries, as well as individual grains (Q). **b.** Quartz grains displaying varying degrees of corrosion and embayment. **c.** Pseudogranophyric texture formed by euheral plagioclase (P) within an anhedral quartz (Q) crystal. **d.** Pseudogranophyric texture with several small euhedral and subhedral feldspar crystals (P) surrounded by optically continuous interstitial quartz crystal (Q). **e.** Rare example of anhedral interstitial quartz forming thin veinlets (arrowed) that intrude the adjacent grains. Photomicrographs c–e were taken from within 3–4 mm of the dyke contact with the tholeiite sill.

recrystallization and partial melting (Krynauw *et al.* 1988).

Flårjuvnutane clastic dyke

The Flårjuvnutane clastic dyke is located at the eastern end of the central nunatak within the Flårjuvnutane nunatak group (Fig. 1). The nunataks are composed mainly of massive mafic sills intruded concordantly into sedimentary rocks of the Schumacherfjellet Formation. Exposure of the dyke is limited and from adjacent rock exposures appears to be approximately 30 m above the sediment/sill contact. The dyke is 1.2 m wide and planar sided, with a NE–SW trend, and contains clasts of both sedimentary and mafic igneous origin. Decimetre-scale sedimentary clasts possess folded and planar laminations and also occur as pale ovoid structures. The mafic clasts are heavily altered, with relics of plagioclase and clinopyroxene replaced by chlorite and clay minerals.

Petrography of clastic dykes

The homogeneous matrix component of the clastic dykes is composed of sub-angular to sub-rounded, quartz (50–60%) and feldspar (≤ 20%) with the original pore space (up to 30%) filled by interstitial clays, chlorite, mica and calcite. Detrital quartz grains form both single grains and small aggregates (Fig. 5a), as well as arenaceous lithoclasts up to 5 mm in length. The quartz aggregates and lithoclasts generally possess 120º grain boundaries together with evidence for grain boundary suturing. Most of the single quartz grains display a varying degree of embayment, particularly where adjacent to mica–chlorite intergrowths, whereas lithoclasts display embayments and corrosion along their peripheries only.

The pale ovoid structures are characterized as fine grained quartz arenites displaying recrystallized, sutured grain boundaries with significantly reduced porosity and interstitial clays relative to the homogeneous dyke sediment. The laminations within the ovoid structures are a product of original depositional variations in grain size.

Sill/clastic dyke contact

In hand specimen the contact of the clastic dyke with the sill is characterized by a pale coloured zone, 3–4 mm wide. In contrast to the bulk homogeneous dyke matrix, the contact zone is dominated by euhedral to subhedral plagioclase crystals up to 0.1 mm in length, that form aggregates with anhedral quartz crystals commonly forming the interstitial material to the small aggregates of feldspar (Fig. 5b & c). This interstitial quartz is often in optical continuity across neighbouring areas of interstitial quartz, suggesting the areas link to form a single quartz crystal connected outside of the plane of thin section. Such textural relationships were described by Krynaw *et al.* (1988) and referred to as pseudogranophyric textures. In rare examples interstitial quartz forms veinlets that intrude adjacent grains (Fig. 5e). Chlorite and opaque minerals are also present within the contact zone, although the reduced porosity due to the presence of interstitial quartz crystals is accompanied by a significant reduction in the amount of fine-grained phyllosilicates present.

Discussion

The presence of clastic sedimentary dykes intruding thick mafic sills implies that the adjacent sedimentary unit has been mobilized, and in the case of the dyke at Kjölrabbane, intruded from beneath the sill as opposed to infilling fractures along the upper surface of the intrusion. This conclusion is consistent with the gradational disaggregation of original depositional units up the dyke and supports the contemporaneous deposition of the Ritscherflya Supergroup sedimentary rocks with the emplacement of the Borgmassivet Intrusions. Abundant outcrop-scale evidence, e.g. flame structures, sediment balls and convolute margins, suggests that much of the sedimentary units being mobilized and disaggregated were generally unconsolidated, although the apparent 'jigsaw-fit' of a few of the disaggregated clasts suggests that some of the sedimentary units were at least partially lithified. We interpret the ovoid structures, arenaceous lithoclasts and quartz aggregates as evidence of pockets of partial lithification.

Many textural features of these dykes are consistent with descriptions of sedimentary rocks lying concordantly adjacent to the margins of the Grunehogna sill, central Ahlmannryggen. Ovoid structures, pseudogranophyric textures and embayed quartz grains, together with the wholesale destruction of sedimentary structures, were all described by Krynaw *et al.* (1988), who interpreted them as being the product of the fluidization of predominantly wet sediments during the emplacement of mafic sills at confining pressures of < 312 bars. Based on observed field relationships, together with textural and petrological similarities, we interpret these dykes as being the mobilized product of this fluidization process. The physical dimensions of the dykes encountered in Ahlmannryggen indicate that fluidized sediments have been transported for at least 50 m (Kjölrabbane) and at least 30 m (Flårjuvnutane), which are similar penetration distances to that described by Kokelaar (1982) from the Moelwyn Hills, Wales, UK.

Emplacement of the clastic dykes is envisaged to have occurred due to the formation of joints and fractures as the sill rapidly cooled from its emplacement temperature of *c.* 1100ºC to approximately 660ºC (60% of emplacement temperature) (Jaeger 1968). The opening of such fractures can result in rapid, transitory reductions in pressure that can locally approach zero, and would result in momentary

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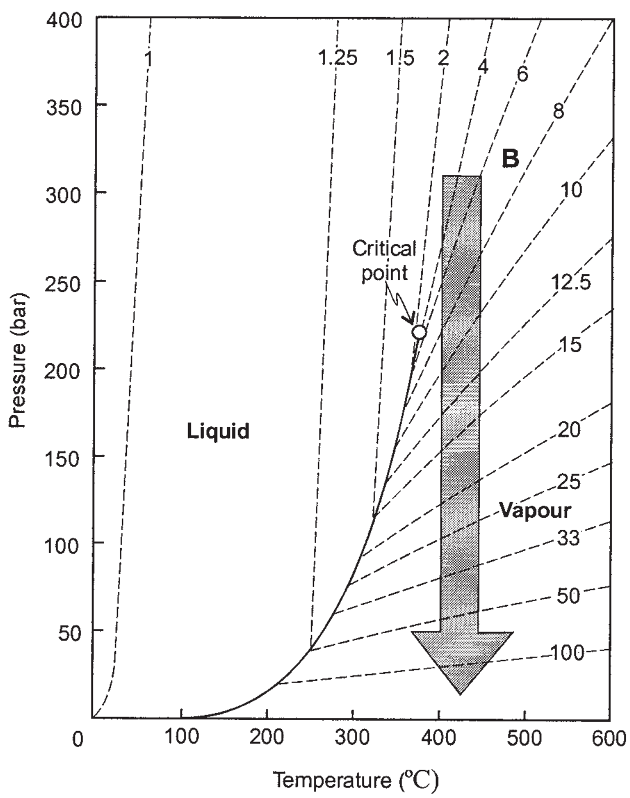

Fig. 6. Variations in the specific volume of water with temperature and pressure (after Kokelaar 1982). Grey arrow represents the inferred fluidisation pathway of sediments adjacent to sills in the Alhmannryggen. A reduction in pressure associated with joint opening above the critical temperature results in rapid increase in the percentage of vapour.

fluidization and reconstitution of wet sediments over the temperatures ranges to be expected with the emplacement of a mafic igneous body (Kokelaar 1982). Under such conditions rapid, local flow of sediment may occur along cooling joints. This process of fracture-induced pressure reduction was proposed by Krynauw *et al.* (1988) to explain the stationary fluidization of sediments adjacent to the contact of the Grunehogna sill. The presence of the clastic dykes, as documented here, provides the physical evidence that links the well-documented fluidization and reconstitution of sediments along the sill contacts with fracturing within the sill that is central to the fluidization mechanism.

Consideration of pressure–temperature–volume relationships of water reveals that the rapid, high-volume transition of water from liquid to vapour phase can be a product of pressure reduction at low, as well as, high temperatures (Kokelaar 1982). In the case of the Ahlmannryggen clastic dykes the presence of a thin zone of anatectic melt along the dyke/sill contact, characterized by euhedral plagioclase crystals forming a pseudogranophyric texture with interstitial quartz, suggests that the mafic sill was still hot (~ 660°C) when the clastic dyke was injected. Therefore, the seawater within the sediments immediately adjacent to the sill would have been at boiling point at the time of dyke injection, which at confining pressures of 300 bars, equates to a boil temperature of 400–450°C (Krynauw *et al.* 1994). Under such physical conditions (temperature 400–450°C, pressure 300 bars) unconsolidated wet sediments experience a low percentage vapour flow (< 6%), which can rapidly increase due to momentary pressure decreases associated with the opening of cooling joints within the sill (Fig. 6), resulting in emplacement of a fluidized sedimentary dyke.

Acknowledgements

This paper has benefited from the constructive reviews of Chris Harris and James White. Martin Cooper, Steve White and the support staff of Halley research station are thanked for support during the field season.

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