Volcanostratigraphy and Eruptive Products of the Jonsvatn Greenstone Formation, Central Norwegian Caledonides

TOR GRENNE & DAVID ROBERTS

Grenne, T. & Roberts, D. 1983: Volcanostratigraphy and eruptive products of the Jonsvatn greenstone formation, central Norwegian Caledonides. *Nor. geol. unders. 387, 21–38.*

The predominantly volcanic, Ordovician, Jonsvatn greenstone formation comprises approximately 500 m of tholeiitic basalts and associated volcanic products, with interbedded sediments totalling some 100–200 m in thickness. In the Nidelv river profile at least 25 separate phases of lava effusion can be distinguished with flows ranging in thickness from 5 m to more than 40 m. Although the majority of the flows are pillowed, some massive flows characterize the middle portion of the formation.

Pillowed flows show a wide range of pillowed form, but elongate pillows are predominant. Linear zones of hollow elongate pillows probably indicate the location of master feeding tubes near the top of a pillowed flow. Other prominent forms exposed in three dimensions include flattened pillows, knobbly pillows and hollow, hollow-layered and collapsed hollow forms. Some hollow pillows were partly filled by new lava after initial drainage. Multiple lava shelves within hollow layered pillows are common in some flows. This shelving, which is considered to represent the palaeohorizontal plane, shows a fairly consistent SE dip throughout the profile even though the attitude of pillows and their elongation may vary appreciably. These variations may be partly due to eruption across an irregular ocean bottom. Data indicate that the main lava flow direction was towards ca. WSW, but there is also a good deal of directional variation. Pillow breccias occur throughout the basalt pile; these are of differing origin, although the majority are assumed to be of flow-foot rubble type. The Jonsvatn metabasalts, which are predominantly of ocean floor tholeiite chemistry, are interpreted as products of local volcanic centres situated along rift zones in a back-arc marginal basin environment.

Tor Grenne[1], Geologisk Institutt, NTH, 7034 Trondheim – NTH, Norway.
David Roberts, Norges geologiske undersøkelse, Postboks 3006. 7001 Trondheim, Norway.
1 Present adress: Orkla Indutrier A/S, 7332 Løkken Verk, Norway.

Introduction

The Lower Palaeozoic metavolcanic and metasedimentary rock successions of the western part of the Trondheim region have provided a target for copious description and interpretation over the last few years, with emphasis varying from stratigraphy and palaeontology to the geochemistry of magmatic and especially greenstone volcanite complexes (Bergström 1979, Bruton & Bockelie 1980, Grenne & Roberts 1980, 1981, Grenne et al. 1980, Ryan et al. 1980). In addition, there is a 1:250,000 map-sheet description (Wolff 1979), and the district geology is covered in several general syntheses of one form or another
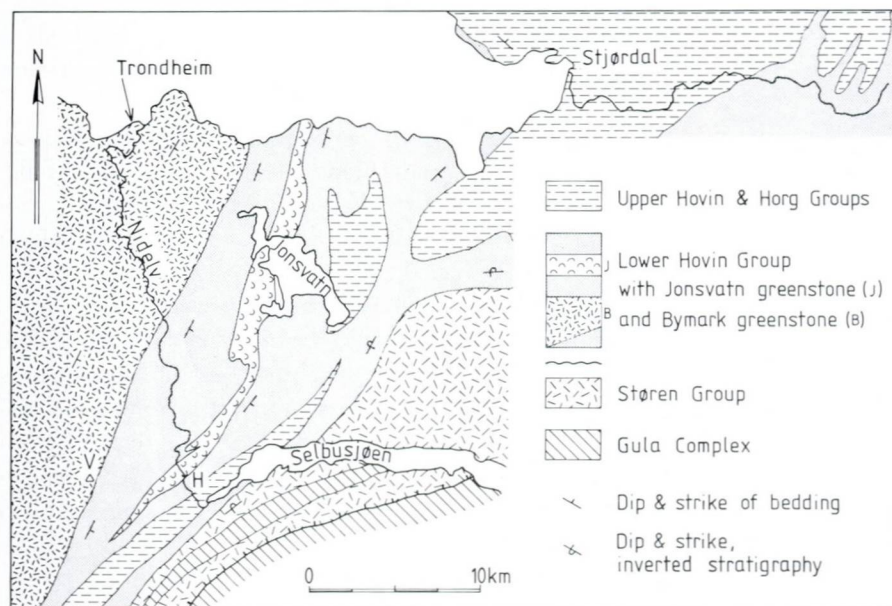
Fig. 1. Geological sketch map showing the location of the Jonsvatn greenstone formation within the tectonostratigraphy of the area just southeast of Trondheim. The map is simplified from the 1:250,000 map-sheet 'Trondheim' (Wolff 1976). H – Hyttfossen: V – Vassfjell.

(Roberts 1978, Oftedahl 1980, 1981, Roberts & Wolff 1981, Roberts et al. 1983, Gee et al. in press).

The metabasaltic 'greenstone' lava units constitute a substantial component of the Caledonian stratigraphical successions in the district. Of these, the thicker lava piles such as those at Støren, Vassfjell and Løkken have attracted most attention (Fig. 1), not least in the case of Løkken on account of the presence of massive stratiform Cu-Zn sulphide deposits (Grenne et al. 1980, Grenne 1981), but also in view of their forming segments of ophiolite complexes (Furnes et al. 1980, Grenne et al. 1980, Grenne & Roberts 1981).

Thinner greenstone units are also present, however, which merit attention for a variety of reasons. One such formation is the Jonsvatn greenstone (Fig. 1). This particular volcanic sequence affords some of the best profiles illustrating internal volcanostratigraphy from this part of the Caledonides, thus providing a valuable insight into the character and environment of accumulation of these effusive rocks. The purpose of this contribution is basically to describe some of the main features of volcanite stratigraphy and the varied volcanic products found in the Jonsvatn greenstone, with emphasis on one particular section along the valley of the Nidelv river north of the dam at Hyttfossen (Fig. 1: grid reference 735153). This profile provides some of the most spectacular examples of volcanic forms and features in Trøndelag. The profile was demonstrated to participants on the 1981 Uppsala Caledonide Symposium B12 excursion (Grenne & Roberts 1981) and affords an easily accessible excursion locality in the immediate vicinity of Trondheim.

Geological setting and history of research

The Jonsvatn greenstone formation occurs within the greenschist facies Lower Hovin Group of classical Trondheim region stratigraphy (Vogt 1945), part of the Trondheim Supergroup succession (Gale & Roberts 1974, Roberts 1978) and an integral part of the Støren Nappe. This nappe unit constitutes the western, upper segment of the Trondheim Nappe Complex; in terms of tectonostratigraphic subdivision of the Scandinavian Caledonide orogen this is positioned within the Upper Allochthon (Roberts & Gee 1981).

Situated just east to southeast of Trondheim (Fig. 1), the metabasaltic Jonsvatn greenstone crops out over a strike length of some 25 km from the shores of Trondheimsfjord in the north via lake Jonsvatn and south-southwestwards until it eventually thins out some few kilometres southwest of the valley of the Nidelv. The greenstone occurs within a sequence of grey to grey-green phyllites and metagreywackes, with minor banded quartzites and cherts (Grenne & Roberts 1980). Dips are consistently towards the southeast at moderate to high angles, and primary structures in the metasediments together with pillow forms in the greenstone indicate that the succession here is the right way up. The true thickness of the greenstone varies from at least 500 m in central and southern areas to some 50–100 m in the north.

In the southern half of the outcrop the lavas and highest breccia unit are directly overlain by green-grey calcareous metagreywackes with phyllite interbeds and sporadic thin-banded chert layers. These sediments pass up via dark phyllites and tuffaceous metasediments into the Upper Hovin Group (Wolff 1976). In the north the Jonsvatn greenstone is positioned directly beneath a rhyolite tuff which immediately underlies the basal conglomerate of the Upper Hovin Group. In this general area the bulk of the 'rhyolite tuffs' are volcanogenic sandstones of dacitic to rhyolitic composition (D. R., unpubl. data); rhyolite tuffs and flows are of more restricted occurrence.

Structurally, this portion of the Lower Hovin Group, including the Jonsvatn greenstone, is located within the normal limb of a major, early, tight, synclinal fold. Further northeast, in the Stjørdal-Forbordfjell district where the Silurian major fold structures are more clearly defined (Roberts 1968), the early (F1) recumbent Skatval syncline is refolded by open (F2) antiforms and synforms. The southwesterly extension of the early syncline into the Jonsvatn area, however, is difficult to trace precisely, although the presence of a fairly large, tight, synclinal fold just south of Hyttfossen has recently been reported by Dr. Michael Heim (pers. comm. 1983). No modern structural studies have yet been carried out in the intervening area, but the general picture (Wolff 1976) in our view is consistent with the presence of tectonic slides causing repetition of sequences and dissection of the syncline. In this connection it is of interest that Bruton & Bockelie (1980) and Oftedahl (1979, 1980) invoke high-angle thrusts or faults dissecting the successions and fold structures in the Hølonda-Horg area some 30–40 km southwest of Jonsvatn. Along the Nidelv profile the most evident mesostructure is a fairly flat-lying crenulation cleavage in the metasediments. Dipping at 20–25° towards NE, this is a comparatively late (S3) structure of wide regional extent, related to minor open to close folds

(F3) ascribed to a gravitational sagging process (Roberts 1969, 1971). This Silurian S3 cleavage can also be detected throughout the Jonsvatn greenstone sequence, though it is far less pervasive than in the Lower Hovin metasediments; it tends to be better developed in small-pillowed horizons and in pillow breccias. In this profile the earlier deformation phases appear to have had only insignificant effect on the lava pile, although the orientation of the elongate pillows could possibly have been affected to a minor degree by the D1 deformation. F2 folds are absent in this particular area.

Biostratigraphic constraints on the age of the Jonsvatn greenstone are lacking in the actual area of outcrop, but regional mapping and correlation have shown that the greenstone is stratigraphically younger than the late Arenig to early Llanvirn Hølonda Limestone (Roberts 1975, Oftedahl 1981). Phyllitic shales in the uppermost part of the Lower Hovin Group some 15 km south of the southernmost outcrop of the greenstone, but above the greenstone level, have provided graptolites of late Caradoc age (Bruton & Bockelie 1982). The Jonsvatn volcanic rocks were thus erupted within the time-range early Llanvirn to late Caradoc.

It was C. W. Carstens (1920) who first realised that basic volcanic rocks locally formed an integral part of the Lower Hovin, and were therefore not necessarily coeval and correlatable with the underlying Støren Group metabasalts. Although his map did not do justice to the true extent of the Jonsvatn unit, Carstens' opinion was clear (1920, p. 85): "Under min kartlægning av traktene omkring Jonsvandet fik jeg imidlertid den opfatning, at de her optrædende grønstensbænke direkte repræsenterer vulkanske perioder inden Hovindgruppen, saaledes at grønstensbænkene er yngre end sin liggbergart, ældre end sin hængbergart." Carstens also concluded that the Forbordfjell greenstone, north of Stjørdal, occurred within the Lower Hovin and was broadly equivalent to the Jonsvatn volcanites, an opinion subsequently confirmed by Roberts (1975). Mapping in the 1950's by H. Carstens (1960) and student mapping supervised by the late Prof. Oftedahl provided the basic map compilation for the Jonsvatn area adopted by Wolff (1976) on the 1:250,000 map-sheet 'Trondheim'. More recently, the geochemistry of both the Jonsvatn and the Forbordfjell greenstone formations has been investigated by Grenne & Roberts (1980).

The Jonsvatn greenstone

GENERAL STRATIGRAPHIC FEATURES ALONG THE NIDELV RIVER PROFILE

From Hyttfossen northwards the Nidelv river valley cuts through greenstones of the Jonsvatn formation over a distance of ca. 1 km (Fig. 1). With SSE dips ranging from 25° in the north to 50–60° or steeper in the southern part of the section, the true thickness of the composite volcanic-sedimentary formation can be estimated to between 600 and 700 metres. Interbedded with the ca. 500 m of volcanic rocks, inter-lava sedimentary units range in thickness from a few tens of centimetres up to some 50–60 m (Fig. 2). Banded quartzites reminiscent
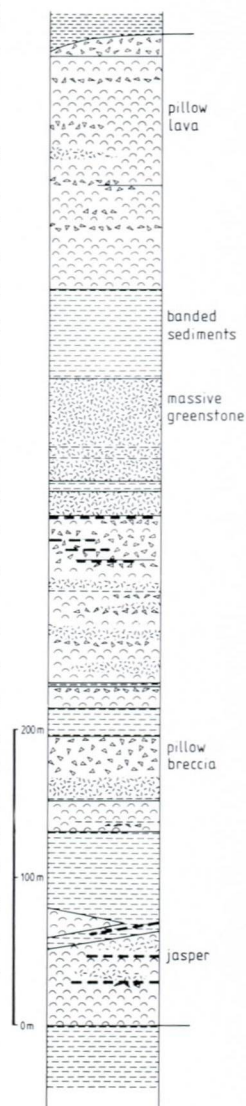

Fig. 2. Simplified and schematic stratigraphic column through the Jonsvatn greenstone formation, Nidelv river profile. The same ornament is used throughout for one and the same rock-type. The scale is only approximate.

of ribbon chert are abundant and are also found beneath the lowermost lava flow (Fig. 3a). Jasper, commonly magnetite-bearing, is particularly abundant in the lower and middle parts of the profile where it forms massive, discontinuous lenses up to 1 m thick separating individual flows; it also occurs as beds within the banded sedimentary units. Subordinate, thin, calcite-rich silty and sandy layers occur throughout the sequence, as well as thin units of finely banded epidote-quartz sediments. Thin laminae rich in magnetite or pyrite occasionally accompany the quartzitic sediments. Banded or more homogeneous deposits of fine-grained, green, tuffaceous material are abundant both between the individual lavas and as beds within the banded quartzitic rocks, and commonly appear to form transitional types of impure tuffaceous quartzites (Fig. 3b) or alternatively tuffaceous calcite-rich sediments.

The volcanic rocks in the Nidelv section comprise a thick pile of lavas and associated breccias which can be divided into at least 25 separate phases of eruption on the basis of interbedded sediments, pillow breccias and characteristic flow-top features (see p. 28). Ranging from 5–10 m up to more than 40 m across, the average flow thickness is thus in the order of 20 m which accords well with thicknesses of recent submarine basalts as observed, for instance, along the Mid-Atlantic Ridge rift valley (Ballard & Moore 1977).

Although the majority of the basaltic flows are pillowed many lavas, particularly in the middle portion of the sequence, display a massive, non-pillowed lower or interior part . A few units here are largely, or almost completely massive (Fig. 2); however, it is not inconceivable that some of the thicker ones may represent subvolcanic sills rather than lava flows. This middle part of the
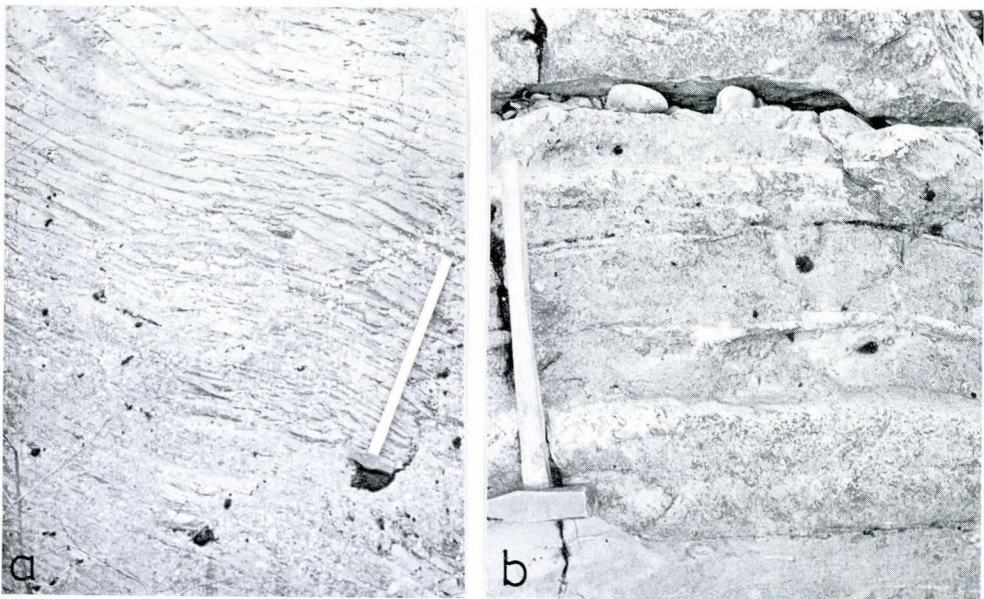

Fig. 3. Metasediments associated with the Jonsvatn greenstone formation. (a) Banded quartzites reminiscent of ribbon cherts, with thin, darker, phyllite laminae, underlying the lowermost pillow lava in the Nidelv river profile. Locality: cliff near small track above Løkaunet hydro-power plant, north of Hyttfossen. (b) Banded, green, tuffaceous sediments with thin quartzitic (cherty) layers; middle part of the greenstone sequence, Nidelv profile.
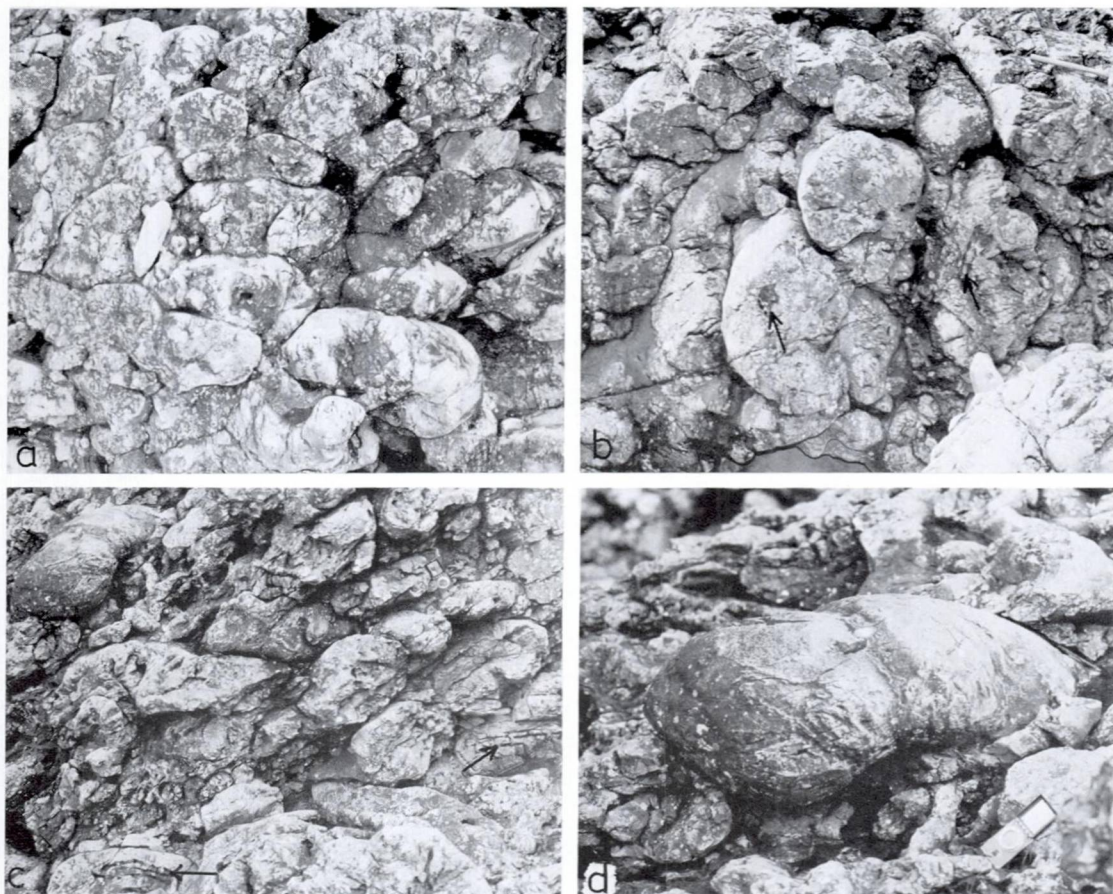
Fig. 4. Pillow lava forms, middle to upper part of the Jonsvatn greenstone, Nidelv profile. (a) Truncated cross-sections of elongate, relatively close-packed pillows. Cross-sections show variable but roughly equidimensional shapes. A crude radial jointing in some pillows may represent primary, radial, cooling joints. (b) Elongate pillows, approximately transverse to pillow orientation, looking c.WSW. Note the elongate tube below hammer. Small, flat-floored, open cavities (arrowed), partly filled with calcite, can be seen in the upper parts of two large pillows suggesting that the original horizontal plane is dipping steeply SSE. (c) Truncated elongate pillows, looking ca.ENE along the original horizontal plane as defined by horizontal-shelved pillows (arrows). The photograph is purposely rotated, bringing the lava shelves into horizontal attitude (the compass is actually oriented roughly vertically). The surface photographed is approximately normal to the direction of flow advance. The flow direction is unambiguously defined by the rounded end of a pillow in the upper-left corner, where the drooping elongate pillow has terminated downslope on the advancing, steep flow front. (d) Close-up of the rounded termination of the elongate, slightly flattened 'phallic pillow' (Bellaiche et al. 1974) seen in Fig. 4c. The markedly constricted form of the pillow is probably reflecting a zone of transverse fault slivers. These tend to form adjacent to slowly opening spreading cracks in the pillow crust, perpendicular to the direction of flow, where lava pressure has broken the brittle, glassy crust and new pillow crust formed as the crack opened (cf. Moore 1975, Ballard & Moore 1977). Possible remnants of 'bread-crust cracks' can be seen particularly on the rounded end and side of the pillow (see text). (e) Slightly flattened, close-packed, elongate pillows, looking ca.ENE along pillow orientation. Cross-sections vary from pedunculate through subcircular to bean-shaped depending on the surface on which they rest. Their generally flattened character, together with a very
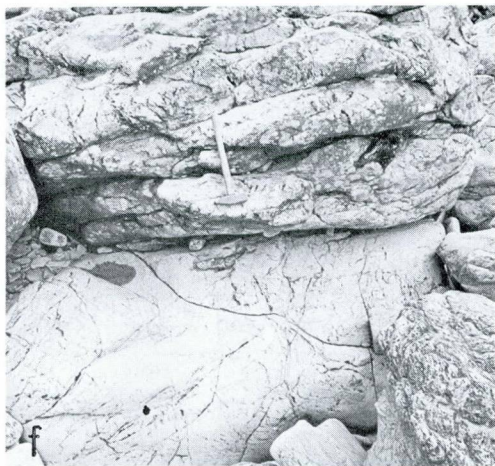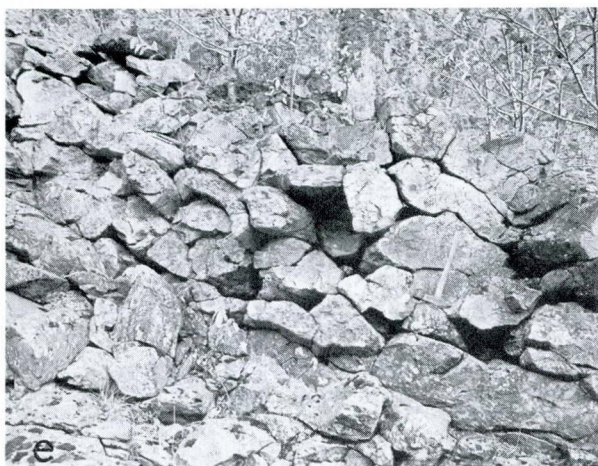
close packing and little or no hyaloclastic material between the pillows, suggest relatively high rates of lava delivery (as far as pillowed flows are concerned) and rapid accumulation of the lava pile. Pillow growth has been sufficiently fast to prevent the formation of thick glassy crusts before the pillows were covered by new lava, and the thin-skinned still plastic pillows were able to spread and flatten under the influence of gravity. (f) Flattened pillows overlying part of a massive lava flow. The pillows are roughly equidimensional in plan and may represent *bulbous pillows* that have grown very rapidly and spread, or were partly drained back into the connecting underlying feeding tube (possibly the massive lava in the photograph) while the pillows were still plastic. Such features may mark sites of eruption, with higher rates of lava delivery compared with the situation where normal bulbous pillows form on top of master feeding tubes. (g) Knobbly elongate pillow, looking ENE. Numerous small pillow buds and fingers (one is arrowed) have grown out from the lower half of the larger, elongate, 'parent' pillow tube. According to Ballard & Moore (1977) such pillows indicate relatively high rates of lava delivery. Rapid pillow growth and high liquid pressure led to frequent rupturing of the thin crust and feeding of the many pillow fingers or buds. Because the small protuberances that form along the side walls of such parent tubes tend to hang down vertically, the plunge relationships between the elongation of parent and 'daughter' pillows unambiguously give the direction of flow advance; it may also indicate the slope of the flow front. At this locality the lava has evidently moved in a westerly direction (towards bottom-left). (h) Elongate pillow (looking NE) with corrugated surface on lower half. The corrugations formed parallel to the pillow tube axis, perpendicular to relatively fast-spreading transverse cracks in the glassy pillow crust.

investigated profile also comprises abundant and commonly thick pillow brec-
cias, and many of the lavas are separated by thin sedimentary units. The upper
part and some of the lowermost portion of the greenstone formation, on the
other hand, comprises thicker, relatively homogeneous, pillow lavas and sub-
ordinate, thin, pillow breccias with little or no sediment between the individual
lava flows.

PRODUCTS OF EFFUSION AND THEIR SIGNIFICANCE

The *pillowed flows* are by far the most abundant lava type in the Jonsvatn
greenstone formation. The more *massive flows* which dominate the middle
part of the formation generally seem to have either a thin or a thick pillowed
flow-top, indicative of a submarine origin. Although a wide range of pillow
forms may be observed, and commonly in three dimensions, the bulk of the
lava flows are evidently made up of *elongate pillows*. In view of the unusually
low degree of deformation within this lava formation, this pillow elongation is
considered to be essentially a primary feature. This predominance of elongate
pillows also accords with recent observations in the Mid-Atlantic Ridge rift
valley (Ballard & Moore 1977) where the lava sequences are dominated by
thick piles of foreset-bedded elongate pillows formed from very long intercon-
nected tubes (Jones 1968, Torske 1972) that flowed down the relatively steep
front of the advancing lava. Such pillow tongues are fed by thicker master
feeding tubes overriding the foreset-bedded elongate pillows as the lava flow
continues to advance (Ballard & Moore 1977), and it is possible that the mas-
sive interior parts of some flows in the Jonsvatn greenstone formation actually
represent such master feeding tubes. The loci of feeding tubes can also be de-
fined by linear zones of hollow pillows where the fluid lava has drained back
into the underlying master tube, sometimes leaving a flow-top of plastically
flattened hollow pillows (see Fig. 5a).

The cross-sectional shape of the elongate pillows varies from sub-circular to
pedunculate and bean-shaped (cf. Vuagnat 1975) or reniform, depending largely
on the form of the surface on which they rest (Fig. 4). While most elongate
pillows are roughly equidimensional in cross-section, some flows comprise
slightly more *flattened pillows* (Fig. 4e, f), a primary feature that according to
Ballard & Moore may indicate rapid pillow growth and consequently thinner
solidified crust due to higher rates of lava delivery; conditions which favour
flattening and spreading of the pillows under the influence of gravity. Rela-
tively high or intermediate flow rates for the lavas of the pillowed flows are
also suggested by the presence at some localities of *knobbly elongate pillows*
(Fig. 4g), where the high liquid pressure and comparatively rapid growth led
to frequent rupturing of the pillow crust and formation of numerous small pil-
low buds and fingers. It must be emphasized, however, that all types of pil-
lowed basaltic flows are associated with low rates of lava delivery as com-
pared with massive or 'sheet' flows in which the very high eruption rate in-
hibits the formation of crusts that are strong enough to contain fluid lava with-
in pillow structures. In the Nidelv river section exposures oblique to pillow

orientation generally exhibit truncated cross-sections of the very elongate lava tubes. Longitudinal sections show that the pillows have, to a large extent, bifurcated and tangled with each other in the flow direction, such that any one pillow can rarely be traced more than a couple of metres in outcrop. A pinch-and-swell shape of the individual pillow tubes can be attributed to growth from successive, transverse, spreading and accreting cracks in the glassy pillow crust as the lava tube advances down the flow front (cf. Ballard & Moore 1977). In rare cases the good three-dimensional exposures allow one to observe the characteristic rounded termination of individual, elongate, pillow tubes, indicating clearly the flow direction of the lava (Fig. 4c,d).

Except for the knobbly nature of many pillows, pillow surfaces are generally fairly smooth in these greenstones. However, corrugated pillow crusts are preserved locally as ridges, with wavelengths of about 3–4 cm, parallel to the pillow elongation (Fig. 4h). According to Moore (1975), such corrugations form perpendicular to spreading cracks on the pillow crust when the widening of the crack is moderately rapid (ca. 5 cm/sec.). Transverse fault slivers, on the other hand, form parallel to very slow-spreading cracks (ca. 0.2 cm/sec.) and can occasionally be seen in the Nidelv river profile as constrictions of the elongate pillow tubes (Fig. 4d). A final growth of some pillows is represented by breadcrust cracks (Fig. 4d); irregular cracks on the pillow crust which have opened only a few millimetres before the pillow solidified and obtained its ultimate shape and form.

Hollow pillows, now partially filled with calcite and in some cases quartz, are abundant, particularly in the upper part of the Nidelv profile. The majority of these are elongate pillows from which varying proportions of the lava drained before the pillows were completely solidified. In some cases complete drainage has left only the thin, originally glassy crust of the lava tube (Figs. 5c, 6c); but more commonly the lava had time to solidify almost completely before the central still fluid part of the flow lobe was emptied (Figs. 4b, 5b). Flat floors of such open cavities indicate that fluid lava within the tube was chilled and solidified at this level, after only partial drainage of the tube. Representing the upper surface of fluid lava within a partly filled tube, these flat-floored cavities, sometimes colloquially termed 'drainouts', must have been horizontal, or nearly so, at the time of formation. Thus they can be used in determining the attitude of the originally inclined elongate pillows relative to the original horizontal plane, and consequently indicate the flow direction of foreset-bedded pillows at the many localities where pillow tube terminations are not exposed (Waters 1960).

Commonly, hollow pillows exhibit a series of flat-floored cavities separated by thin, parallel, *lava shelves* (Figs. 4c, 6) and are then termed *hollow layered pillows.* Such structures probably formed when sea-water entered a partly filled tube through cracks in the pillow crust and chilled the top of the fluid lava. A successively diminishing lava supply and eventually total cut-off at the source of the flow lobe led to a periodically falling lava level in the tube, and by temporary standstills the lower shelves could form by chilling from continuously entering sea-water. Up to eight separate cavities, each of them reflecting
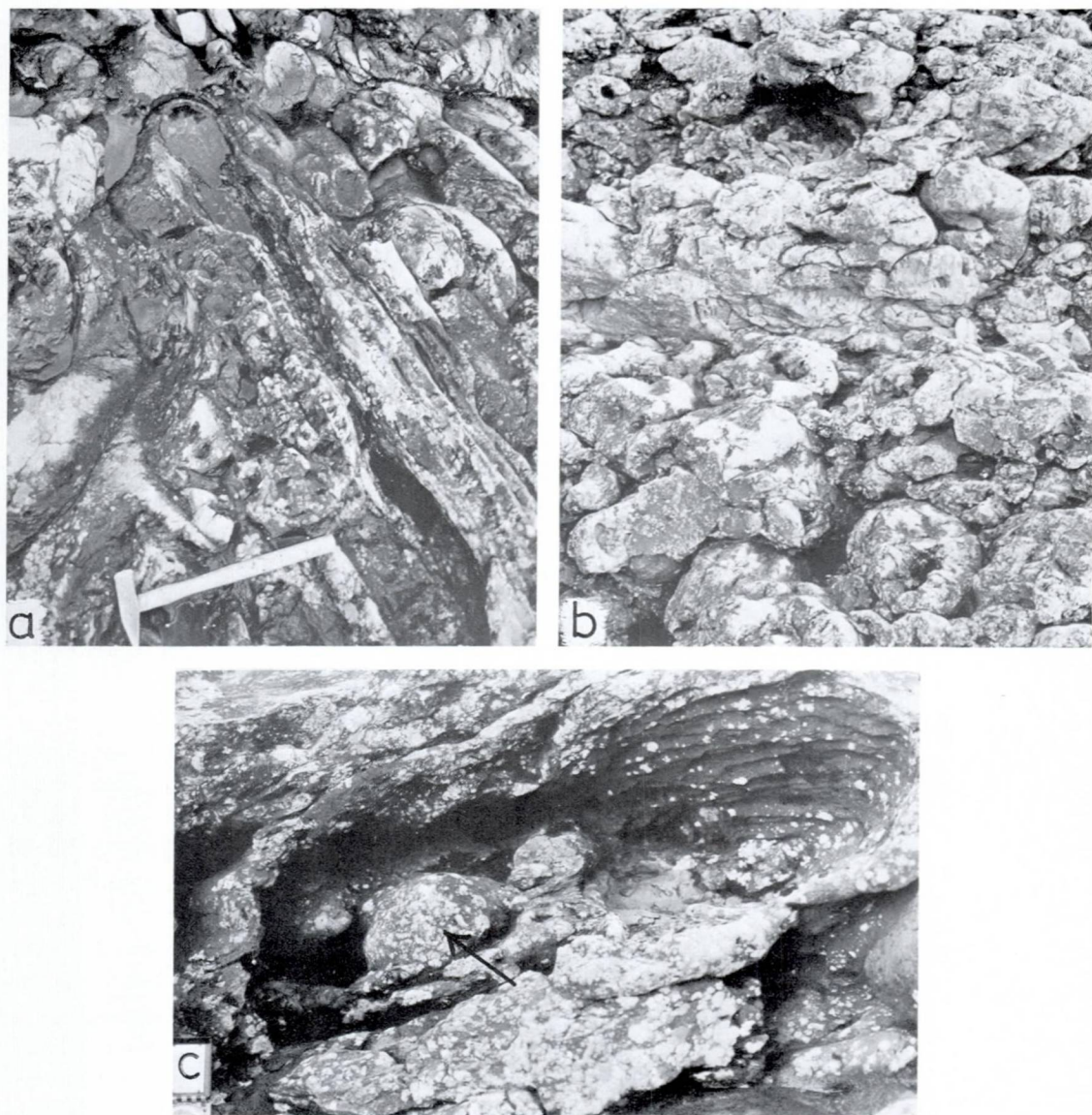
Fig. 5. Hollow pillows from the upper part of the Nidelv profile, near Hyttfossen. (a) Plastically collapsed hollow pillow. The pillow was drained shortly after its formation while it was still plastic. A very thin solidified 'skin' allowed the pillow to collapse plastically as the fluid interior was drained, inhibiting breakage and fragmentation of the pillow crust. Zones of such plastically collapsed, hollow pillows may indicate formation at the top of a pillowed lava flow by rapid upward growth followed by more or less immediate drainage into the underlying master feeding tube. (b) Hollow pillows in a pile of elongate pillows, looking ENE, normal to the elongation trend. Both partially drained (e.g. upper-left corner) and completely drained (upper-centre) pillows can be seen. The very irregular cross-sectional forms, particularly in the foreground, are reminiscent of features of knobbly pillows (see also Fig. 4g). (c) Close-up of a completely drained hollow pillow. Such hollow pillows probably had a somewhat longer cooling history than the plastically collapsed ones (see Fig. 5a), and the ca. 5 cm crust was strong enough to resist collapse and fragmentation after the pillow was drained. Sharp-edged corrugations on the inner surface of the crust (upper-right corner) appear to be nearly transverse to the pillow tube, and may possibly represent the underside of fault slivers formed adjacent to slow-spreading cracks in the glassy crust. Note that the drained tube is partly filled by new lava. These small internal pillows (arrow) signify that the drained tube was immediately filled with seawater before the time of this second lava advance: the rounded terminations of the internal pillows clearly indicate a flow direction or slope of the elongate pillow tube, towards the camera.
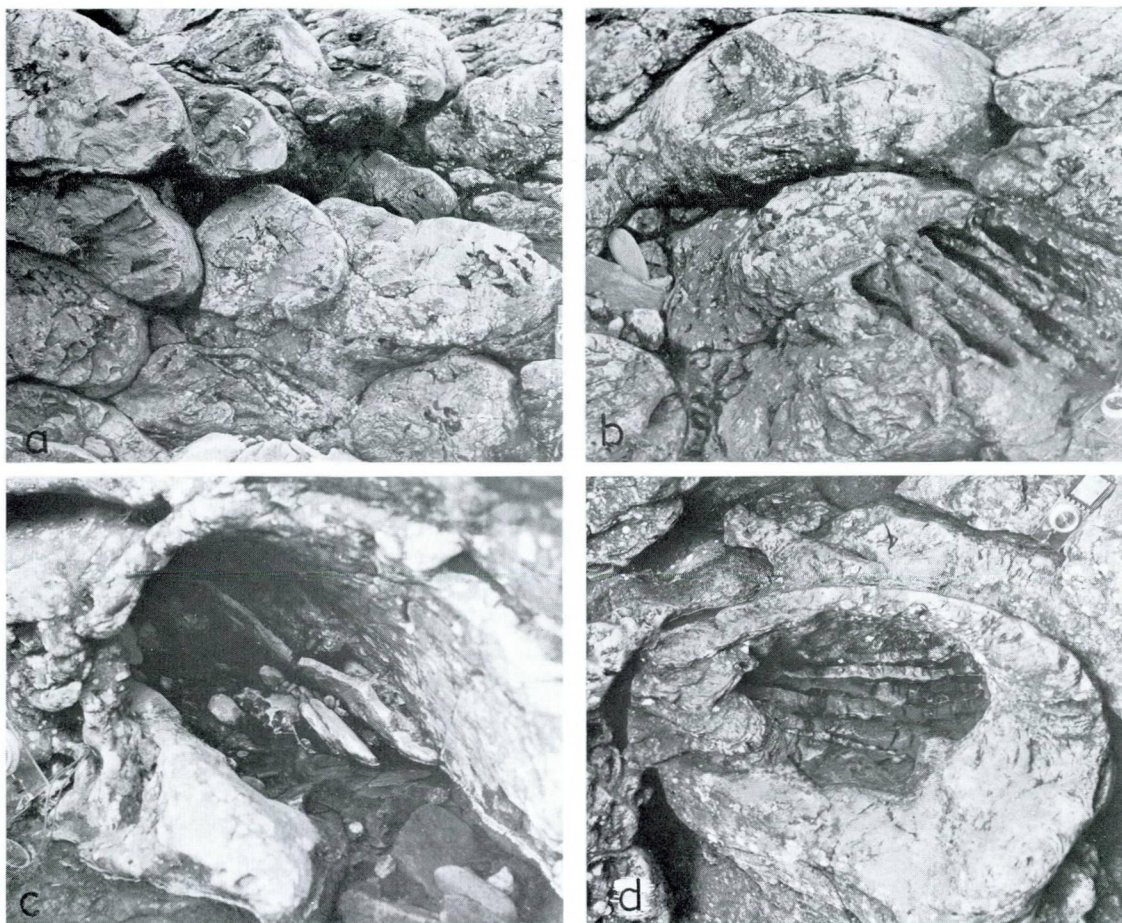
Fig. 6. Hollow layered or shelved pillows, Jonsvatn greenstone, near Hyttfossen. (a) Hollow layered or shelved pillows. The truncated cross-sections of the elongate pillows are normal to the ENE elongation. Calcite-filled cavities in the upper part of many pillows are separated by several flat-floored shelves 1–5 cm thick. The cavities and shelves were nearly horizontal originally and were formed by a successively falling lava level in the pillow tubes, with periodic chilling of the top of the fluid lava. Note that the original horizontal plane, as defined by the shelves, is dipping more steeply (SE) than the xy-planes of the pillows (see text for explanation). (b) Hollow layered pillow with six flat-floored cavities in its upper portion. each reflecting successive falls in the level of fluid lava in the pillow. Note that, as in Fig. 6a, the lava shelves indicate a considerably steeper dip than the general pillow attitude. (c) Completely drained, hollow shelved pillow; looking ca. east. The main shelf is only about 1 cm thick, but has remained more or less unbroken after drainage. (d) Hollow layered pillow with several calcite-filled cavities separated by lava shelves in upper part of the pillow. The side-walls of the pillow are thickening downwards, a feature ascribed to a longer cooling history of the successively falling lava at lower levels in the pillow. In fact, it may be calculated that the ca. 5 cm-thick top crust of the pillow required approximately 20 minutes to cool and solidify with stagnant magma (considerably longer if hot lava was flowing through the tube), while the 20–30 cm-thick side-walls must have had a solidification history (under comparable magma conditions) of at least 1½–2 hours before the lowermost cavity here exposed was finally drained (cf. Moore 1975). Note that the attitudes of the shelves are gradually changing from top to bottom, probably a reflection of a slight tilting of the pillow tube during these final stages of its active history.

periodic falls in the level of the fluid lava, can be seen in pillows in the Nidelv river profile near Hyttfossen; in general these are smaller and narrower towards the tops of the pillows. A downward thickening of pillow side-walls (Fig. 6d) also suggests a successively diminishing lava level with a longer solidification history at lower levels . Although the lava shelves within any one pillow are mutually parallel, examples have been found wherein the strike and dip of the lowest shelf diverge from that of the uppermost shelf (Fig. 6d). This indicates that these particular pillows have tipped or rotated between the times of the first and last internal chillings, as represented by the sections through the pillows.

The cross-sectional xy-planes of the elongate pillows commonly deviate from the original or palaeohorizontal plane, as defined by the flat lava shelves, by some 20–30°, and in nearly every case the pillow xy-plane is shallower than the shelving plane (Fig. 7). This can be seen from data presented in stereographic plots in Fig. 8a, b from pillows in the uppermost 200 m of the formation, along the Nidelv profile. Here, the fairly consistent attitude of the shelves contrasts strikingly with the wide scatter of poles to pillow xy-planes. The varying angle· of divergence of these lava shelf and xy-planes is a measure of the attitude of the flow front slope, and possibly also the relatively irregular ocean bottom topography over which the lava flowed. The general direction of flow of the advancing lava can be determined primarily by direct observation of such features as terminations of elongate pillows (Fig. 4c, d) and pillow bifurcation and budding. Measurements of the long (or x) axes of pillows in the Nidelv section (Fig. 8c) show a directional scatter of some 50° in the NE-E sector, with plunges consistently towards this same direction. Observations show, however, that the true lava flow direction is the opposite to this, i.e. towards W-SW. To obtain a more correct picture of the lava flow vector, in Fig. 8d we have rotated the great circle to the mean pole to lava shelves back to horizontal, and made corresponding rotations of the mean pillow xy and pillow elongation data. As the shelves of pillows are considered to approximate to the
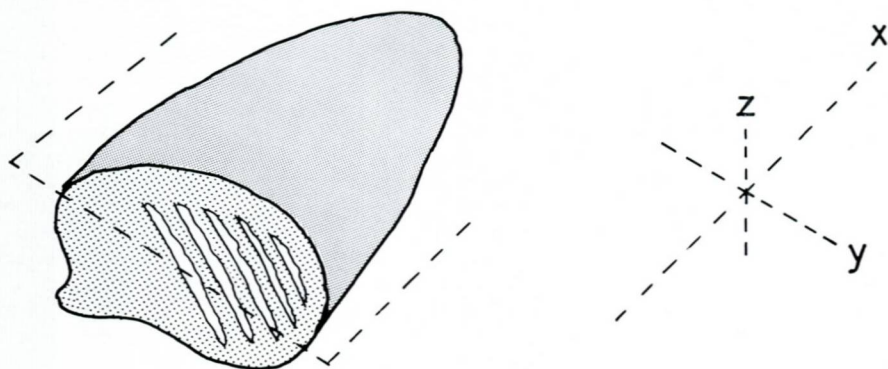

Fig. 7. Diagrammatic sketch showing the general relationship between the mean attitude of lava shelves and the pillow xy-plane in an 'average' pillow from the Jonsvatn greenstone formation.
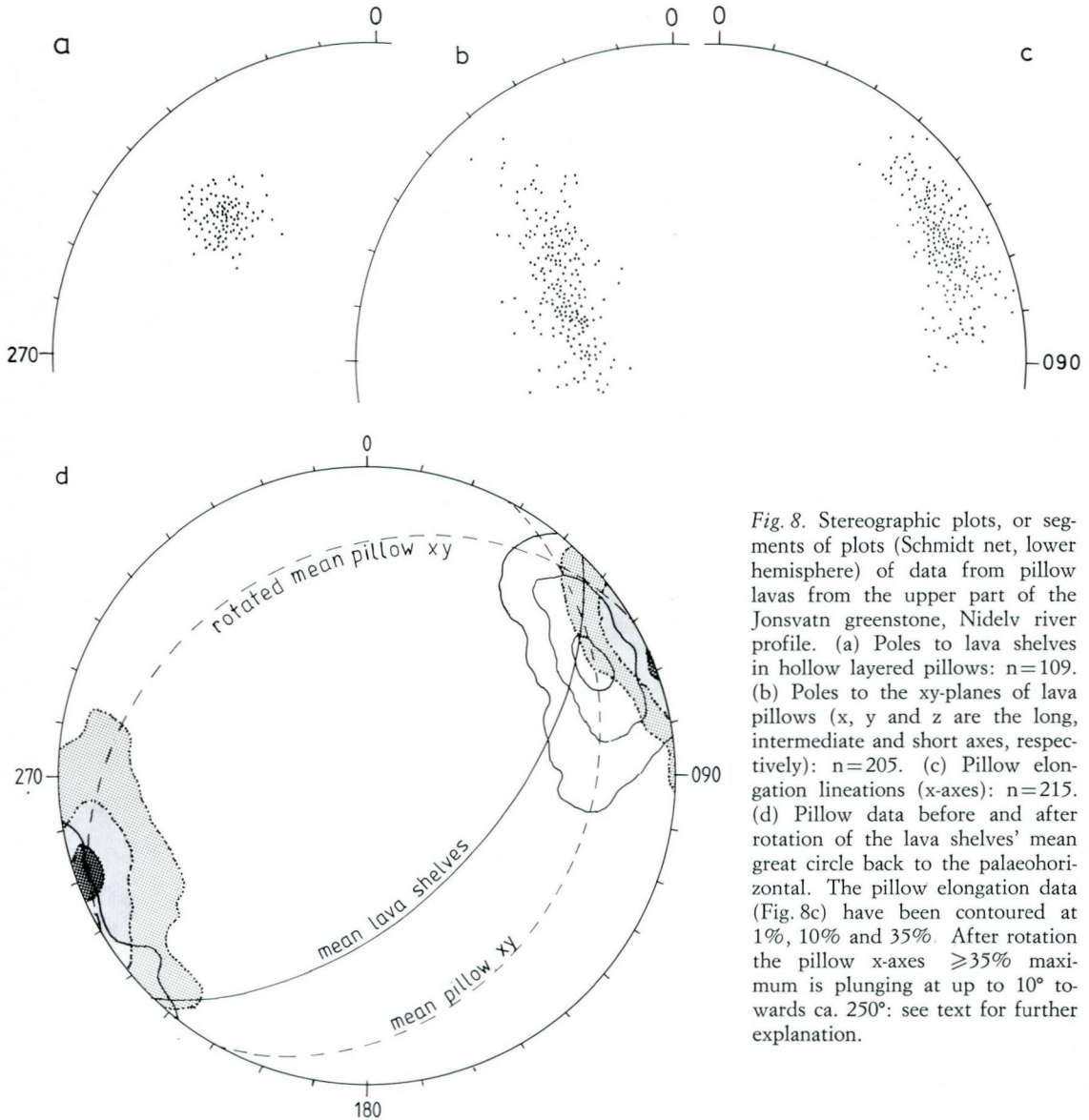
Fig. 8. Stereographic plots, or segments of plots (Schmidt net, lower hemisphere) of data from pillow lavas from the upper part of the Jonsvatn greenstone, Nidelv river profile. (a) Poles to lava shelves in hollow layered pillows: n=109. (b) Poles to the xy-planes of lava pillows (x, y and z are the long, intermediate and short axes, respectively): n=205. (c) Pillow elongation lineations (x-axes): n=215. (d) Pillow data before and after rotation of the lava shelves' mean great circle back to the palaeohorizontal. The pillow elongation data (Fig. 8c) have been contoured at 1%, 10% and 35%. After rotation the pillow x-axes ⩾35% maximum is plunging at up to 10° towards ca. 250°: see text for further explanation.

palaeohorizontal (Waters 1960, Ballard & Moore 1977), the >35% maximum (rotated) cluster of pillow elongations then gives the principal lava flow direction; it also provides an indication of the slope of the flow front in relation to this palaeohorizontal surface, which is up to 10° towards WSW (Fig. 8d) or 20° for 10–35% of the data. It is conceivable of course that these angles have been modified slightly as a result of the regional D1 deformation.

From the data presented in Fig. 8 it is clear that there is quite a spread of pillow x-axes (and therefore lava flow) and xy-planes, in comparison with a relatively consistent attitude of lava shelving. This is a significant disparity and would indicate that there have been widely differing directions of lava

advance throughout the sequence of eruptions. Marked variation of pillow attitude within flow units has been noted, possibly a reflection of the actual location of generation of pillows as well as the irregular nature of the lava flow front down which the individual flow lobes were advancing. Future studies along this profile, and other favourable sections through the formation, will aim at collecting data from separate flows, which will help in determining intra-flow directional variation and in constructing a more detailed picture of the accumulating lava pile.

Pillow breccias are found throughout the volcanic pile, although in the Nid-elv river profile they are definitely most abundant in the middle part of the formation (Fig. 2). Here they constitute units up to 20–30 m thick, composed essentially of angular greenstone fragments (Fig. 9). Partially preserved pillow rims denote that a high proportion of the clasts were derived from broken pil-lows; a few units also comprise some apparently whole pillows, resembling the *isolated-pillow breccias* of Carlisle (1963). The thicker breccia units may in-clude non-volcanic material such as thin sedimentary bands of jasper, chert and calcite-rich rocks, indicating deposition over a considerably longer time period than would be expected for lava flow breccias. In view of their greater thick-ness and relatively long depositional history, a more reasonable explanation for the formation of these units is as talus deposits either adjacent to active sea-floor fault scarps, or at the bases of the steep, unstable fronts of formerly ac-tive pillowed flows down which pillow rubble may have periodically avalan-ched. This mode of formation may also possibly explain the *broken pillow breccia,* or autoclastic breccia, which is found directly on top of the last pillow lava in the Nidelv river section. Most of the pillow breccias, however, are com-paratively thin (generally less than 3–4 m) with no non-volcanic clasts or asso-ciated sediments. These units, which are discontinuous and lensoid and thus disappear along strike, are found both on the top surfaces of some pillow lavas and at the base of flows. The latter breccia type may represent *flow-foot rubble* (cf. Ballard & Moore 1977), formed when fragile pillow blocks tumbled down to the base of the front slope of the advancing lava where the accumulated rubble was subsequently overrun by the active flow. By analogy with recent submarine basalts the frequent, thin, flow-top breccias, on the other hand, are thought to have formed from broken and collapsed hollow pillows on the up-per surfaces of lava flows. Such pillows may have grown upwards from a mas-ter feeding tube into which fluid lava drained back after the lava supply ceased.

Concluding remarks

On the basis of their general geological setting and geochemical characteristics, the metabasalts and associated volcanic products of the Jonsvatn greenstone formation have been interpreted as having formed in a back-arc marginal basin environment (Grenne & Roberts 1980, Roberts et al. 1983), and to have con-stituted part of what was probably a more extensive basic volcanite assemblage including greenstone formations further to the north and northeast. The nature
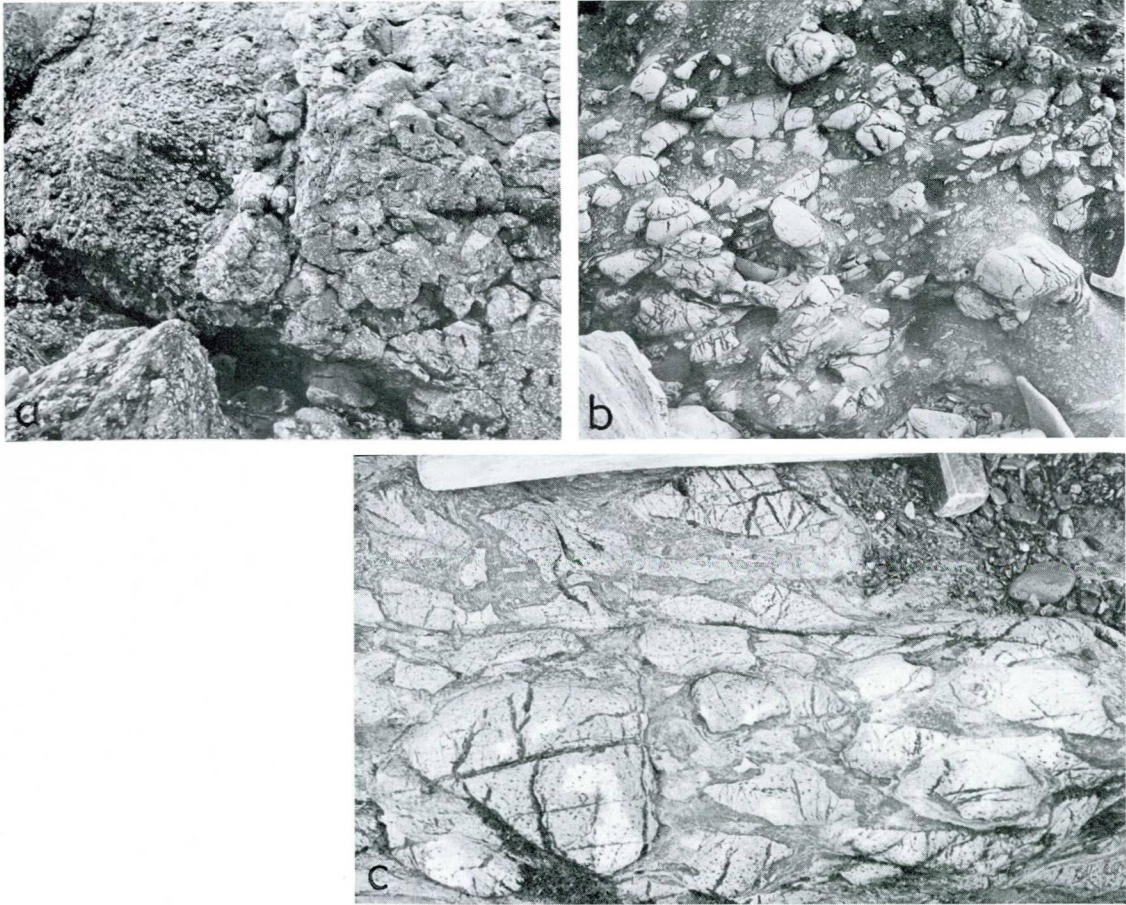
Fig. 9. Breccias within the Jonsvatn greenstone formation, Nidelv profile. (a) Steep SE-dipping contact between pillow lavas and the uppermost greenstone breccia overlying the volcanic pile: looking WSW. Note the hollow interior parts of many of the elongate pillows, indicating drainage before the lava tubes were completely solidified. The surface photographed is approximately normal to the elongation of the pillows. (b) Close-up of the breccia pictured in Fig. 9a, showing angular greenstone clasts in a green gravelly to sandy matrix composed solely of lava detritus. The fragments have obviously suffered very little or no transport, and the lithology may possibly be regarded as an autoclastic pillow breccia formed by fragmentation of the highest pillow lava, adjacent to either the steep unstable flow front or a sea-floor fault scarp. The weak planar structure trending bottom-left to top-right is the S3 cleavage. (c) Pillow breccia from the middle of the Jonsvatn greenstone, with angular fine-grained greenstone fragments in a green, finer-grained matrix. The large clast (bottom-left) displays a partially preserved pillow rim.

of these rocks, moreover, would suggest that the lavas were erupted from fairly local volcanic centres situated along rift zones within the main axial zone of spreading.

In general terms, the lower and upper members of the investigated volcanic pile are dominated by pillow lavas, whereas partly massive or sheet flows are more common in the middle part of the formation. The sheet flows are indicative of very high rates of delivery of voluminous magma. In contrast to this, a variety of mesoscopic volcanic forms such as sinuous elongate pillows,

hollow pillows, hollow shelved pillows and pillow breccias, as well as the feature of local back-drainage of lava from partially consolidated pillows and tubes, denote that extrusion rates were considerably lower in large parts of the sequence. In some cases, previously hollow pillows were partly filled by new lava during a second advance of fluid lava through the pillow tubes. Within the pillowed part of the lava pile, however, there is also evidence of large variations in the rates of lava delivery and pillow growth, reflected by widely differing pillow morphologies and features of pillow crusts.

Measurements of pillow orientation and lava shelves in hollow-layered pillows in the upper part of the formation have indicated that the flow direction of the lava was predominantly towards WSW. The spread of pillow long axis orientation is such, however, that one is clearly dealing with an irregular palaeoslope and probably varying sites of eruption. Although the majority of pillow axial plunges are towards the westerly quadrant, down the palaeoslope, some appear to be directed ENE in relation to the palaeohorizontal suggesting that some lava flows may have advanced in that direction. However, a more detailed logging of the lava profile – with emphasis on measurement of pillow tube axes and lava shelves within one and the same flow and recording the mutual relationship of these parameters within each individual pillow – will be required to determine more precisely the stratigraphical variations in the flow vector.

The palaeotopographic instability of this ocean-bottom volcanic environment is also reflected in minor angular unconformities within the intraformational sediments, denoting slight tilting towards a 'westerly' point before deposition of the succeeding sedimentary bed. The sediments overlying the Jonsvatn formation in the Nidelv profile are slightly steeper dipping than the subjacent lavas. Rotation of the dip of this sediment package back to horizontal indicates that the lava pile dipped towards a W-WNW point immediately prior to post-Jonsvatn formation sedimentation. Part of this dip may possibly be ascribed to post-volcanism tilting in roughly the same direction as the pre-existing palaeoslope.

REFERENCES

Ballard, R. D. & Moore, J. G. 1977: *Photographic atlas of the Mid-Atlantic Ridge rift valley.* Springer Verlag, New York, 114 pp.
Bellaiche, G., Cheminée, J. L., Francheteau, J. Hekinian, R., Le Pichon, X., Needham, H. D. & Ballard, R. D. 1974: Inner floor of the rift valley: first submersible study. *Nature 250,* 558–560.

Bergström, S. 1979: Whiterockian (Ordovician) conodonts from the Hølonda Limestone of the Trondheim region, Norwegian Caledonides. *Nor. Geol. Tidsskr. 59*, 295–307.

Bruton, D. L. & Bockelie, J. F. 1980: Geology and paleontology of the Hølonda area, western Norway – a fragment of North America? *Proc. IGCP Symp., Blacksburg, Virginia*, 41–47.

Bruton, D. L. & Bockelie, J. F. 1982: The Løkken-Hølonda-Støren areas. *Paleont. Contr. Univ. Oslo 279*, 77–86.

Carlisle ,D. 1963: Pillow breccias and their aquagene tuffs, Quadra Island, British Columbia. *Journ. Geol. 71*, 48–71.

Carstens, C. W. 1920: Oversigt over Trondhjemsfeltets bergbygning. *Kgl. Norske Vidensk. Selsk. Skr. 1*, 152 pp.

Carstens, H. 1960: Stratigraphy and volcanism of the Trondheimsfjord area, Norway. *Nor. geol. unders. 212a*, 27–39.

Furnes, H., Roberts, D., Sturt, B. A., Thon, A. & Gale, G. H. 1980: Ophiolite fragments in the Scandinavian Caledonides. *Proc. Int. Ophiolite Symp. Cyprus, 1979*, 582–600.

Gale, G. H. & Roberts, D. 1974: Trace element geochemistry of Norwegian Lower Palaeozoic volcanics and its tectonic implications. *Earth Planet. Sci. Lett. 22*, 380–390.

Gee, D. G., Guezou, J. C., Roberts, D. & Wolff, F. C. 1983: The central-southern part of the Scandinavian Caledonides. *Proc. Uppsala Caled. Symp., Wiley* (in press).

Grenne, T. 1981: The Høydal deposit, Løkken – an ophiolite-hosted massive sulphide deposit in the Central Norwegian Caledonides. (Abstract) *Trans. Inst. Min. Metall. B 90*, 58–59.

Grenne, T. & Roberts, D. 1980: Geochemistry and volcanic setting of the Ordovician Forbordfjell and Jonsvatn greenstones, Trondheim region, central Norwegian Caledonides. *Contr. Mineral. Petrol. 74*, 374–386.

Grenne, T. & Roberts, D. 1981: Fragmented ophiolite sequences in Trøndelag, central Norway. *Exc. guide B 12, Uppsala Caled. Symp. 1981*, 40 pp.

Grenne, T., Grammeltvedt, G. & Vokes, F. M. 1980: Cyprus-type sulphide deposits in the western Trondheim district, central Norwegian Caledonides. *Proc. Int. Ophiolite Symp. Cyprus 1979*, 727–743.

Jones, J. G. 1968: Pillow lavas and pahoehoe. *Journ. Geol. 76*, 485–488.

Moore, J. G. 1975: Mechanism of formation of pillow lava. *Amer. Scientist 63*, 269–277.

Oftedahl, C. 1979: Hølonda-Horg området – tre separate skyvedekker. (Abstract) *Geolognytt, 12*, 16–17.

Oftedal, C. 1980: Geology of Norway. *Nor. geol. unders. 256*, 3–114.

Oftedal, C. 1981: *Norges geologi*. Tapir, 207 pp.

Roberts, D. 1968: Tectonic features of an area NE of Hegra, Nord-Trøndelag, and their regional significance. *Nor. geol. unders. 255*, 10–20.

Roberts, D. 1969: Deformation structures in the Hovin Group schists in the Hommelvik-Hell region. Norway: a discussion. *Tectonophysics, 8*, 157–161.

Roberts, D. 1971: Stress regime and distribution of a conjugate fold system from the Trondheim region, Central Norway. *Tectonophysics, 12*, 155–165.

Roberts, D. 1975: The Stokkvola conglomerate – a revised stratigraphical position. *Nor. Geol. Tidsskr. 55*, 361–371.

Roberts, D. 1978: Caledonides of south-central Norway. *Geol. Surv. Canada Paper 78–13*, 31–37.

Roberts, D. & Gee, D. G. 1981: Caledonian tectonics in Scandinavia. (Abstract) *Terra Cognita 1*, 69–70.

Roberts, D. & Wolff, F. C. 1981: Tectonostratigraphic development of the Trondheim region Caledonides, Central Norway. *Journ. Struc .Geol. 3*, 487–494.

Roberts, D., Grenne, T. & Ryan, P. D. 1983: Ordovician marginal basin development in the central Norwegian Caledonides. *Journ. Geol. Soc. London* (in press).

Ryan, P. D., Williams, D. M. & Skevington, D. 1980: A revised interpretation of the Ordovican stratigraphy of Sør-Trøndelag. *Proc. IGCP Symp. Blacksburg, Virginia*, 99–103.

Torske, T. 1972: Interconnected pillow structures in greenstone in the Os area, western Norway, with remarks on pillow terminology. *Nor. geol. unders. 273*, 37–42.

Vogt, T. 1945: The geology of part of the Hølonda-Horg district, a type area in the Trondheim region. *Nor. Geol. Tidsskr. 25*, 449–527.

Vuagnat, M. 1975: Pillow lava flows; isolated sacks or connected tubes? *Bull. Volcanol. 39*, 581–589.

Waters, A. C. 1960: Determining direction of flow in basalts. *Am. Journ. Sci. 258A,* 350–366.

Wolff, F. C. 1976: Geologisk kart over Norge, berggrunnskart Trondheim 1:250,000. *Nor. geol. unders.*

Wolff, F. C. 1979: Beskrivelse til de berggrunnsgeologiske kartbladene Trondheim og Øster-sund, 1:250,000. Nor. geol. unders. 353, 77 pp.