On the significance of Caledonian pahoehoe, aa, and pillow lava from Bømlo, SW Norway

HARALD FURNES & STEPHEN JOHN LIPPARD

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A subaerial metabasalt sequence containing pahoehoe flow units showing a transition to aa type occurs in Caledonian rocks on the island Bømlo, southwest Norway. The pahoehoe flow units occur as flattened tube-like bodies and are highly vesicular. It is proposed that most of the lava represents shelly pahoehoe, a type produced very close to the crater by the welling out of gas-charged lava. As the lava flowed away from the vent it graded into the beginning stage of aa type lava as the viscosity increased. The pahoehoe lava is overlain by pillow lava indicating local submergence of the area subsequent to the pahoehoe lava flow. The palaeo-flow directions have been estimated from the elongation of pillow lava and pahoehoe tongues and the direction of the pahoehoe-aa transition. The predominance of subaerial volcanics in this area is discussed in relation to older, thick submarine pillow lava sequences in other parts of the Norwegian Caledonides.

H. Furnes, Geologisk institutt, avd. A, Allégt. 41, 5014 Bergen, Norway.
S. J. Lippard, Geology Department, Bedford College, Regent's Park, London NW1 4NS England.

The basic volcanic rocks of the Finnås area on Bømlo are part of the Caledonian igneous complex in Sunnhordland, SW Norway (Fig. 1). Some aspects of the general geology, lava stratigraphy, petrology, and geochemistry have been investigated on the island Stord (Fig. 1) (Kvale 1937, Priem & Torske 1973, Furnes & Færseth 1975, Lippard 1976). Lippard has established that the sequence in the Katnakken area on Stord consists of predominantly subaerial volcanics, including thick sheets of rhyolite lava and ignimbrite intercalated with basalt lava flows. A Rb/Sr isochron from the rhyolite lava gave an upper Ordovician (Caradoc) age of 455 ± 5 m.y. (Priem & Torske 1973). Upper Ordovician–Lower Silurian (Ashgill–Llandovery) volcanics occur in the Dyvikvågen Group on the west coast of Stord (Færseth & Ryan 1975). These consist of 220 m of pillow lavas over- and underlain by shallow water sediments. The Caledonian volcanic rocks on Bømlo have so far not been investigated in any detail. The Finnås metabasalt sequence apparently occurs within a thick pile of volcanics of varied composition (acid to basic), but its exact stratigraphic position is uncertain. It is part of the Caledonian allochthon of west Norway (Strand 1960, 1972, Naterstad et al. 1973) but it is not known whether it forms a separate nappe or is part of a larger structure. On Bømlo and Stord the southeastern edge of the igneous rocks is marked by a NE-SW trending high-angle fault. The metabasalt sequence in the Finnås area is situated about 2 km northwest of this structure (Fig. 1).

The first person to draw attention to the lava succession at Finnås was Reusch (1888). Although he did not appreciate the full significance of what he observed, his field sketches and descriptions made it clear that pahoehoe flow units are present at this locality. It was this work that prompted the present study.

Geological relationships

The volcanic stratigraphy in the local area of investigation is as follows:

Massive metabasalt (top), 80 m.
Pillow lava/hyaloclastite, 12 m.
Subaerial (pahoehoe to incipient aa flow units) metabasalt, 15 m.
Conglomerate, 1 m.
Massive metabasalt (base), 30 m.

The thicknesses quoted are maxima for each unit.

This lava sequence is intruded by granite/quartz porphyry and dolerite/gabbro to the north and west of Finnås (Fig. 1). To the north at the contact between the volcanics and the intrusive rocks there is a breccia composed of angular to

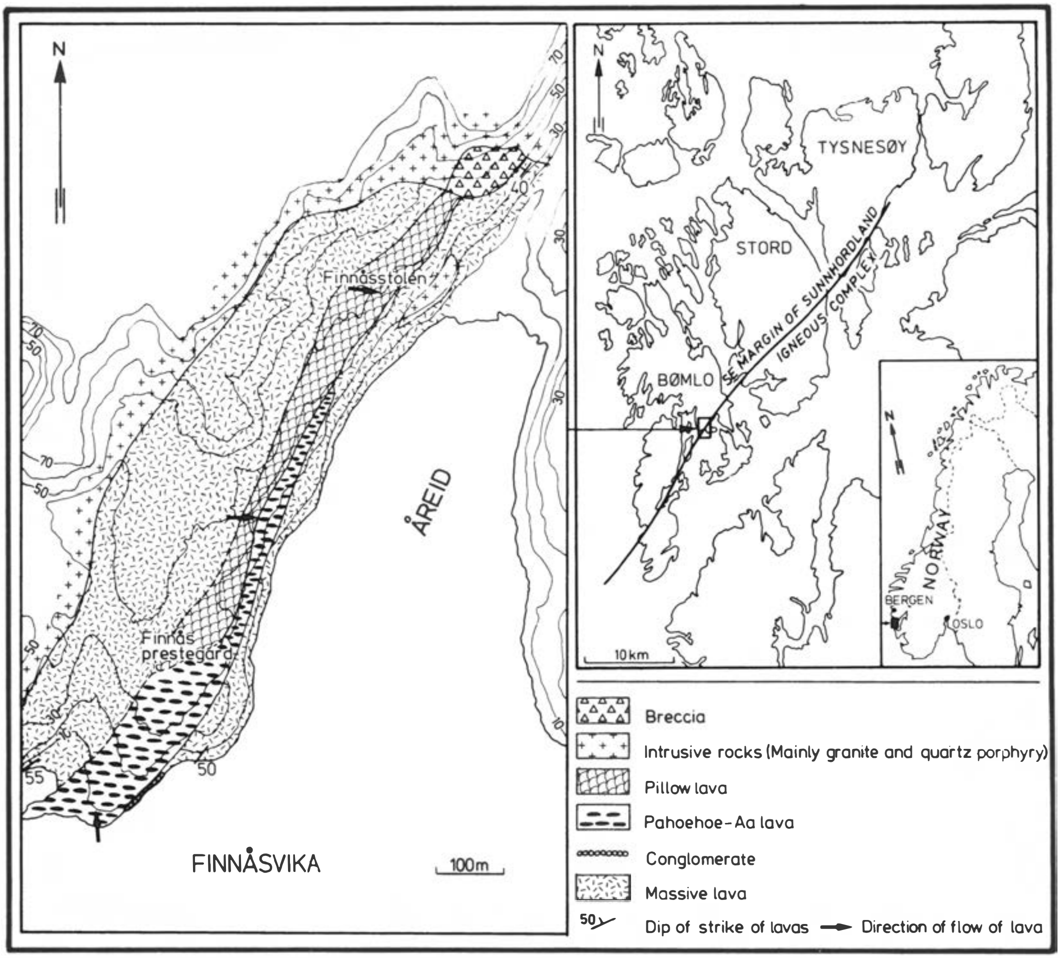

Fig. 1. Geological map of the Finnås area at Bømlo.

rounded blocks of quartz porphyry, granite, chert (including jasper) schist, and metabasalt in a sandy tuffaceous matrix. In addition the volcanics are cut by several dykes and sills of fine-grained basalt.

The rocks dip to the northwest at 40–50° and, from the shapes of the pahoehoe and pillow tubes, are right-way up. The rocks do not appear to be cleaved.

Petrography

In thin section the rocks show relict igneous textures but are composed wholly of secondary minerals (albite, chlorite, actinolite, haematite, and sphene) formed by lower greenschist facies metamorphism. In addition, there are scattered secondary crystals of pyrite and numerous veins of carbonate, quartz, and chlorite.

Lithological and structural description

The following definitions are used throughout the paper: *A lava flow* is a circumscribed body of lava produced by one volcanic eruption. Commonly such a lava flow is divisible into *flow units;* a great many flow units may develop during the course of one eruption. A lava flow which is divisible into flow units is called a *compound lava flow* (Walker 1971).

Fig. 2. A series of pahoehoe flow units molded against each other.

Massive metabasalt

The stratigraphically lowest member of the basic lava succession at Finnås consists of a series of thin flow units, some 5–7 m in thickness. The upper 1–2 m and sometimes also the basal part of each flow unit are vesicular with a massive non-vesicular central part. The shape of the vesicles varies from spherical to lenticular, and slaggy, irregular cavities formed by the accumulation of gasses, occur. Relatively big cavities up to 20 cm long, with a flat floor and arched roof, were probably formed by the draining out of lava. This shows that the physical properties of the lava occasionally approached those necessary for forming pahoehoe flow units, relatively low rate of extrusion, and low viscosity (e.g. Walker 1971). Poorly developed pahoehoe of rather massive type, produced from lava tubes (Swanson 1973), can occasionally be seen. Some of the flow units are separated by thin layers of basic, medium-grained tuff which occur as detached and disrupted lenses up to about 15 cm thick. The overall characteristics of the flow units indicate that they are subaerial.

Conglomerate

On the top of the rather massive lava succession is a conglomerate bed reaching a maximum thickness of about 1 m (Fig. 1). It can be traced northwards for about 40 m along the coast and consists predominantly of well-rounded basic lava and grey to white chert pebbles. The most frequent size range is 2–5 cm. A feature of the conglomerate is the presence of large (up to 40 cm long) angular fragments of red jasper. The big size of the jasper fragments relative to the other pebble material, and furthermore the angular shape, indicate erosion of a nearby bed of jasper. The conglomerate probably represents a beach conglomerate.

Pahoehoe member

This member has many of the characteristic features of pahoehoe lava. It occurs as a pile of flattened tube-like bodies, each representing a separate flow unit. The shape of the bodies is variable and, like pillow lava, the bottom part of a flow unit is controlled by the morphology of underlying units (Fig. 2). In cross-section the bodies are ellipse-shaped and the thickness of each flow unit is normally considerably less than the width. This relationship is, however, controlled by the size of the flow units; the smaller the body, the more it tends to approach a spherical shape. Walker (1971, 1973) stated that the aspect ratio (the ratio between lateral extent and the thickness as seen in cross-section) of the units in a pillow lava tends to be smaller than in a compound pahoehoe flow. In Fig. 3 the ratios between the vertical axes (thickness of flow unit) and the horizontal axes (lateral extent normal to the direction of movement of the flow unit) of the pahoehoe and overlying pillow lava at Finnås are shown, and there is no overlap between the two fields. The pahoehoe lava is highly vesicular; in

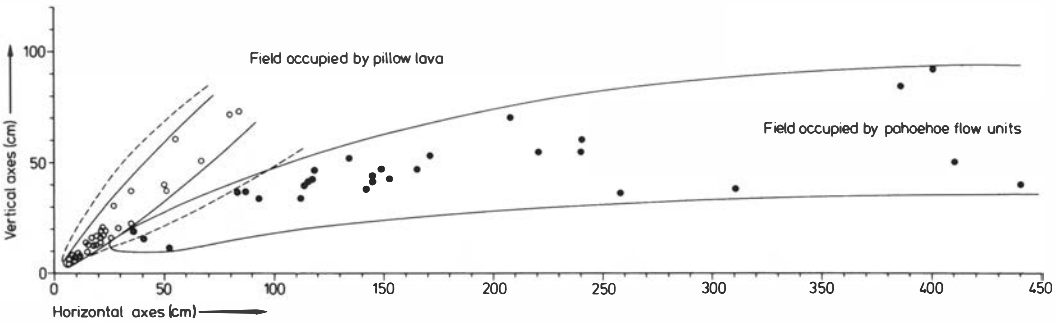

Fig. 3. Axial ratios of pahoehoe flow units and pillow lava from Finnås. The dashed line defines the field occupied by three hundred basaltic pillows from three different subglacial pillow lava/hyaloclastite sequences in Iceland.

each flow unit there are discrete bands about 1–3 cm wide, densely populated with vesicles which become progressively bigger towards the central part of the flow unit (Fig. 4). In the bottom and central parts of the bodies the vesicles are randomly scattered and in the biggest units the core is completely massive. Some of the pahoehoe flow units have fragile gas cavities in the upper part which are dome shaped and have a flat floor. The surface of each body has a glassy rind about 1 cm thick; this is commonly striated or filamented due to the walls of broken and unbroken bubbles that streaked out during flowage (Wentworth & Macdonald 1953, Swanson 1973).

The long dimensions of the pahoehoe bodies trend approximately N–S (the dip of 20–30° is tectonic dip, as shown by the orientation of flat-floored gas cavities) indicating the general direction of flow.

Associated with the pahoehoe flow units are more massive tabular flow units. They are commonly between 0.5 and 1 m thick, and much less vesicular than the pahoehoe. Occasionally the lava has a flaggy appearance which could easily be confused with a tectonic foliation. However, most of the vesicles in this lava are spherical, hence the structure is a primary one. This type of lava shows transitions between pahoehoe and completely massive flow units.

Transition to aa flows

The pahoehoe flow units occupy only a small area at the southern end of the Finnås peninsular (Fig. 1). Northwards, over a distance of approximately 0.5 km, the smooth-surfaced pahoehoe is progressively replaced by lava consisting of layers of angular jagged semi-detached fragments, some of which are covered by sharp spines (Fig. 5). The slaggy material is confined to

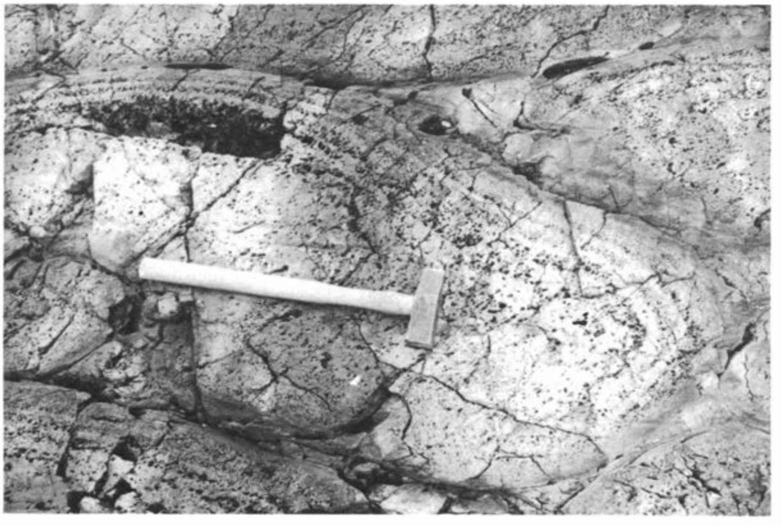

Fig. 4. Part of pahoehoe flow unit, with highly vesicular bands and gas cavity in the upper part of the body. Note how the vesicles become progressively bigger in the bands towards the central part and attain a more random orientation.

Fig. 5. Strongly brecciated metabasalt lava, showing the beginning stage of development of aa type lava.

the top and bottom of flow units; in the central part the lava is fairly massive. Due to poor and discontinuous exposure, it is difficult to establish confidently the thickness of flow units, but certainly they vary from about 1–2 m up to several metres. The vesicularity is generally lower than in the case of pahoehoe flow units. This structural type of lava is probably comparable to what Wentworth & Macdonald (1953) called *slabby pahoehoe*. This south to north transition from pahoehoe to aa-type lava is taken to indicate a general northward movement of the flow from a source not far from the present southern end of Finnås.

Pillow lava

The subaerial pahoehoe and transitional aa lava is overlain by pillow lava (Fig. 1). This is distinctly different from the pahoehoe. The flow units are nearly spherical in cross section normal to the direction of flow (Fig. 3). The highly compound character of the pillow lava is well demonstrated; from the same flow unit several small pillows can be seen to have emerged. Sometimes one can see only an incipient bulging on the surface of a flow unit indicating the failed birth of a new pillow (Fig. 6). The pillows characteristically show radial jointing, have

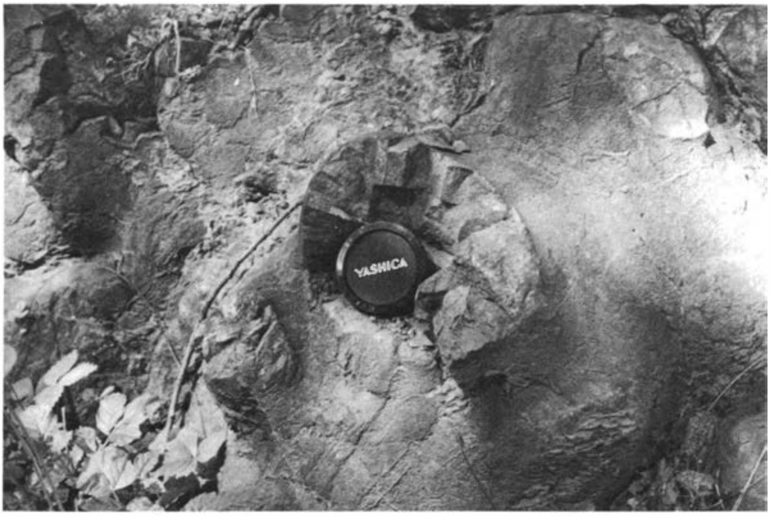

Fig. 6. Non-vesicular pillow lava. Note the several buds on the same body, showing the beginning stage of pillow formation.

well-developed chilled margins, and they are mostly non-vesicular. A number of measurements on the long axes of flow units indicate an E–W flow direction, and the observation of some flow units' termination shows a movement of lava from the west. Such a determination of flow direction has been shown to be very consistent with the flow direction as indicated by the orientation of foreset beds in a recent pillow lava/hyaloclastite delta in Iceland (Furnes & Fridleifsson 1974).

Cavities in pillows, formed by the draining out of lava, can occasionally be seen. The hollows are now filled with quartz and calcite.

Associated with the pillow lava are minor quantities of hyaloclastite, mainly occurring as interstitial filling between the pillows. The hyaloclastite is mixed with a muddy limestone, which presumably represents the sediment onto which the lava was erupted. Above the pillow lava is a massive metabasalt. These are commonly separated by a breccia bed which is similar to the type of breccias formed when basalt lava flows on a semi-wet substrate (Furnes & Sturt 1976). Due to poor exposure it is impossible to map the extent of the breccias, but their association with pillow lava and massive lava may indicate that the transition zone from pillow lava to massive lava might have been controlled by tidal variation, as observed in recent examples in Iceland and Canary Islands (Furnes & Friedleifsson 1974, Furnes & Sturt 1976).

The pillow lava probably formed from a later flow than the one that produced the pahoehoe lava, at a time when the area was partly submerged below a locally fluctuating sea level.

Mode of formation of pahoehoe lava

It has been a long-standing dispute in the literature how to distinguish between pillow lava and pahoehoe (e.g. Johnston 1969, Jones 1969), and, due to their similarity, the two have undoubtedly been confused. However, some diagnostic differences do exist. Hyaloclastite is invariably associated with pillow lava, representing spalled-off glass fragments, often filling the interstices between pillows. Also a vitreous chilled margin is more consistently developed around pillows than around pahoehoe flow units. The most unequivocal evidence for pillow lava is an intimate association with subaqeous sediments (Walker 1971).

Detailed studies of Hawaiian volcanoes have shown how a lava changes its morphological character with increasing distance from the crater. During the 1969–71 Mauna Ulu eruption in Hawaii, Swanson (1973) was able to demonstrate that three general types of pahoehoe formed, governed by different modes of flow and gas content:

Shelly pahoehoe, characterised by fragile gas cavities and small tubes (Jones 1943). This type forms when gas-charged lava wells out of the erupting fissure or vent without any significant fountaining.

Dense, smooth-surfaced pahoehoe, characterised by surface channels and low vesicularity, and formed from voluminous flows of partly degassed fallout away from the foot of high fountains.

Hummocky pahoehoe, associated with abundant low tumuli on the surface of the flow. This relatively dense type of pahoehoe forms when partly degassed lava issues from tubes after flowing underground for long distances.

Although there is a clear warning by Swanson that the structures described from this Hawaiian flow should not be extrapolated to flows of different compositions, the importance of gas content and mode of flowage is generally valid (Jones 1969, Moore 1970).

The pahoehoe lava at Finnås shows most similarity with *shelly pahoehoe;* for example, the very high vesicularity, fragile gas cavities and the association with thin flow units of massive and flaggy lava. Shelly pahoehoe forms on flat to gently inclined surfaces having slopes of generally less than 4° to 5° (Swanson 1973), and with a low rate of extrusion (Walker 1971). The massive lava may be equated with the *sheet-flow variety* of shelly pahoehoe, which represents 'run-out' on relatively steep slopes, depositing only a thin, relatively dense, non-cavernous layer (Swanson 1973). The flaggy lava at Finnås may possibly be another criterion for its recognition as shelly pahoehoe.Since the cavernous nature of shelly pahoehoe flows makes them very fragile, they will, to a varying extent, tend to collapse beneath an overriding flow. If a shelly pahoehoe flow unit collapses while the lava is still hot, it results in a comparatively dense rock with wispy, discontinuous layers marking the broken down cavities (Swanson 1973). This mechanism is thought to account for the formation of the flaggy lava associated with the pahoehoe at Finnås.

Shelly pahoehoe is seldom found in ancient lava piles since such flows are of small volume and extent, being confined to localities near the eruption site (Swanson 1973). The finding of such a lava type in the Lower Palaeozoic rocks of western Norway is unique and important. In particular, it shows without doubt that the area under consideration was above sea level during part of this period.

With increasing distance from the source, lava flows increasingly lose heat and gasses. Thus a low viscosity pahoehoe flow will change into a transition stage, sometimes called slabby pahoehoe (Wentworth & Macdonald 1953), and finally into a higher viscosity aa flow. We believe that such a transition can be recognised in the Finnås area, although the lava never attains the typical features of thick aa flow units.

Comparisons with other metabasalt sequences

The lower Palaeozoic metabasalt sequences of the Trondheim Region, the Stavfjord–Solund district, and in the Major Bergen Arc appear to be, without significant exception, submarine in origin as shown by the dominance of pillow lava and hyaloclastite. They are also all pre-Middle Ordovician in age. The pahoehoe structures at Finnås show that at least part of the metabasalt on Bømlo was erupted on land, and, coupled with the identification of acid ignimbrites on Bømlo (Songstad 1971) and Stord (Lippard 1976), suggest that the greater part of the volcanics in Sunnhordland were erupted subaerially. The work by Furnes et al. (1978) has shown the existence of a thick (approximately 1000 m) subaerial metabasalt sequence further to the southwest on Nordøyane in the Sunnhordland area. All age determinations and stratigraphic evidence available show that these rocks are Late Ordovician to Lower Silurian in age. This has interesting palaeogeographic and tectonic implications. In the Bergen Area, Sturt & Thon (1976) have shown that the polymict Moberg Conglomerate is resting unconformably upon an earlier Caledonian metamorphic complex which includes a thick metabasalt pillow lava pile. The older complex had suffered polyphasal deformation and metamorphism to at least upper greenschist facies metamorphism during the pre-Moberg orogenic phase. This deformation and metamorphic event can most probably be related in time with the Grampian event in Scotland and Ireland, dated at approximately 500 m.y. (Dewey & Pankhurst 1970, Dunning 1973, Pankhurst 1973). The implications of the work by Sturt & Thon (1976) are that a considerable cover to an early Caledonian mountain belt was removed before the deposition of the Moberg Conglomerate. Thus, the pre-Moberg submarine metabasalt sequences in west Norway should perhaps be regarded as part of the basement to the later subaerial volcanicity.

At the present state of knowledge about the volcanicity in the Sunnhordland region, it is clear that it significantly differs in age and tectonic environment from the above-mentioned Caledonian volcanic sequences further to the north in west Norway. The Sunnhordland volcanics in many respects more closely resemble the Ordovician volcanics in the Anglo-Welsh area. Examples of these include those in the Welsh Borderland, particularly the Llanvirn volcanic sequence in the Builth Wells area (Jones & Pugh 1949), the Caradoc volcanics in Snowdonia, North Wales (e.g. Francis & Howells 1974), and the Borrowdale Volcanics (Llandeilo) of the Lake District (e.g. Oliver 1954).

Conclusion

The late Caledonian metabasalt sequence at Finnås, Bømlo, is predominantly subaerial and partly submarine in origin. The subaerial metabasalt is partly made up of compound shelly pahoehoe flow units.These features indicate an eruption site in the near vicinity. The transition from pahoehoe lava to a beginning stage of aa-type flow units, through an intermediate stage of slabby pahoehoe, can be traced.

The subaerial character and age of the Finnås, and Sunnhordland in general, metabasalt sequence distinguish it from those in other parts of the Caledonian fold belt further to the north in west Norway, which are predominantly submarine and of Lower Ordovician age or older.

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