Basaltic macadam-breccias in the Girvan-Ballantrae Complex, Ayrshire

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SYNOPSIS

Many supposed "volcanic agglomerates and tuffs" in the Girvan-Ballantrae complex of southern Ayrshire are considered to be non-pyroclastic in origin. These macadam breccias are accumulations of lava breccia derived mainly from the autoclastic disintegration of pillow basalts during, or shortly after, extrusion. The breccia-forming process is considered to be mainly a function of supercooling, glass formation and retention of volatiles, all of which are directly related to external hydrostatic pressure.

INTRODUCTION

Throughout the Girvan-Ballantrae igneous complex of southern Ayrshire a group of fragmental rocks, generally referred to as "volcanic breccia, agglomerate and tuff" (Peach and Horne 1899; Geol. Surv. Scotland, 1″ sheet 7), are closely associated with Ordovician basaltic pillow lavas. The most extensive exposures of these particular volcaniclastic rocks occur on Knockdolian and Sallachan Hills [NX 113 848; NX 128 848] about three kilometres north-east of Ballantrae; around Knockormal Hill [NX 132 881]; Lochton Hill [NX 133 875]; Carleton Hill [NX 128 893] and on the coast at Pinbain [NX 137 916] (Fig. 1).

The most extensive exposures on Knockdolian Hill have been briefly mentioned by Pringle (1948, p. 11) who notes that these "agglomerates and breccias" are unusual in ". . . the absence of any fine-grained matrix, the rock being composed of angular fragments of a vesicular lava presenting the appearance of consolidated macadam". The present authors conclude that these extensive "macadam breccias" are not pyroclastic in origin but represent thick accumulations of lava breccia derived predominantly from the mechanical (autoclastic) disintegration of pillow lavas either during, or shortly after, their extrusion (Lewis 1975). Bluck (1978) has also reclassified many of the coarse, heterogeneous "agglomerates" (e.g. Bennane Head) as conglomerates.

THE OCCURRENCE OF MACADAM BRECCIAS

The Knockdolian Hill volcanic sequence is about 1100 m thick, a large proportion of which is composed of macadam breccias. The breccias appear to overlie some 90 m of aphyric pillow lavas which in turn overlie highly feldsparphyric, porphyritic, and

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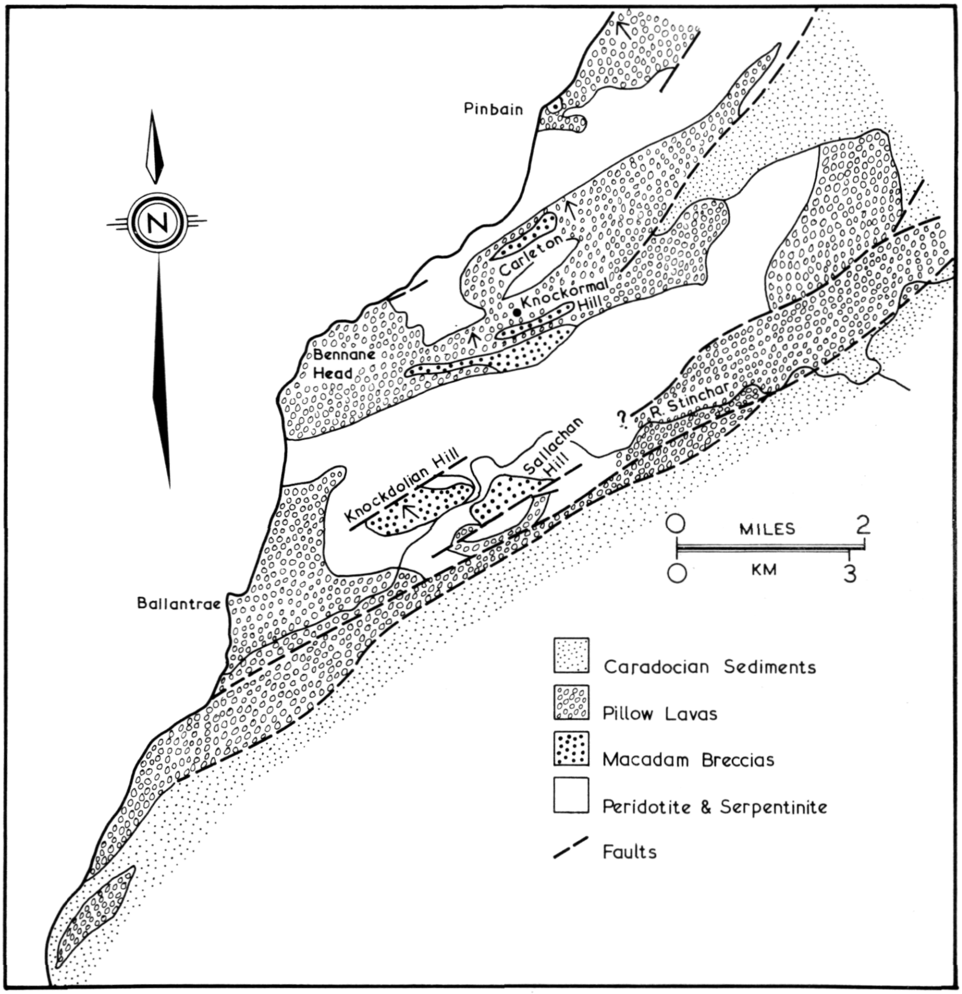


FIG. 1. Sketch-map of the Girvan-Ballantrae complex showing the distribution of exposures of macadam breccias. Only major pillow-lava and ultramafic rock outcrops are shown.

vesicular basaltic rocks about 200 m in thickness, which are particularly well exposed along the north-east flank of the hill. The latter exhibit no definite pillow-form and may be lavas or shallow intrusions.

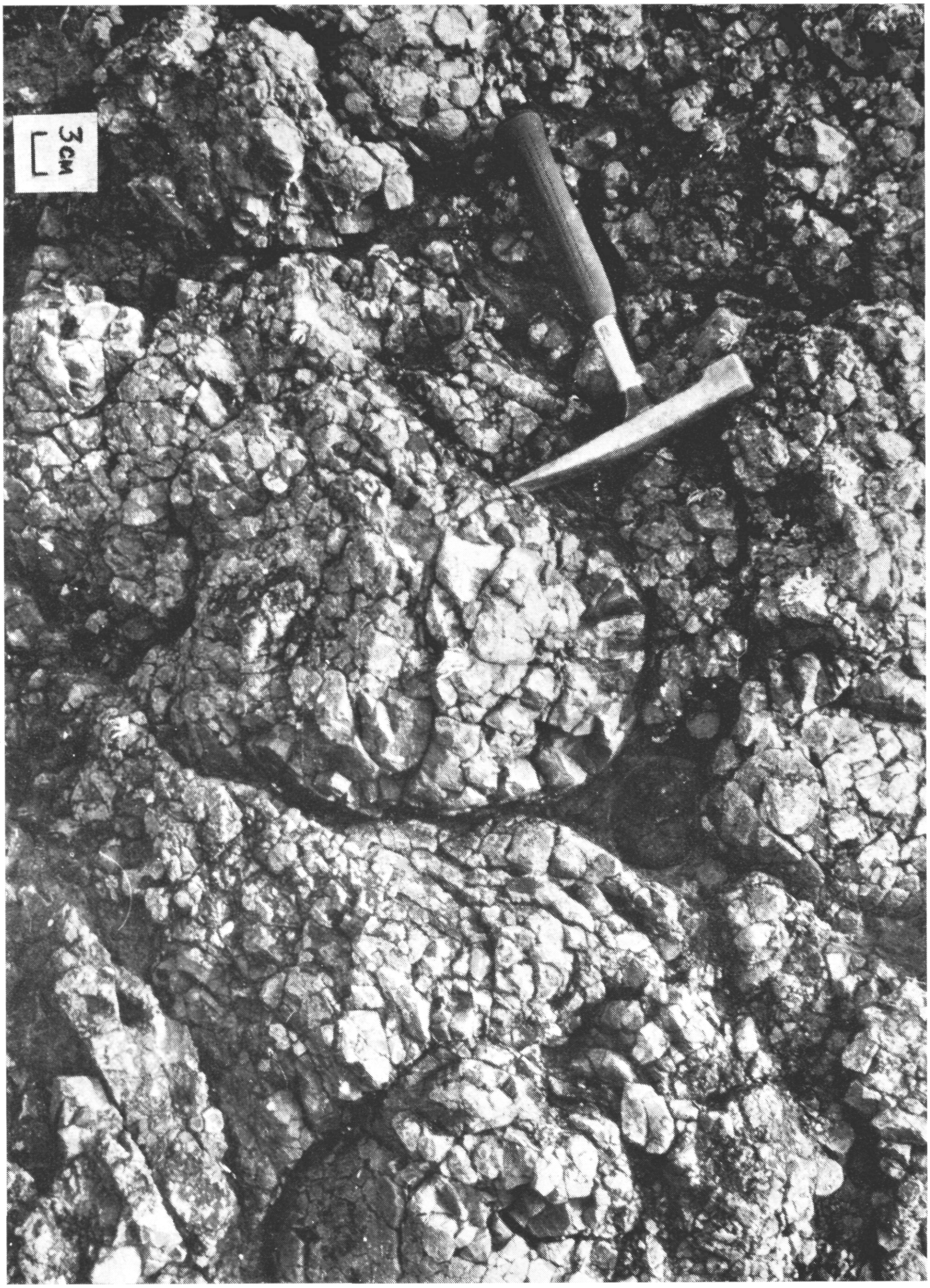
The macadam breccias are composed of non-vesicular and occasionally vesicular basaltic lava clasts. Bedding is generally absent or very indefinite except near the west end of the hill where it dips 50° to the west or north-west. The lava clasts (Pl. 1) are commonly roughly rectangular in shape and usually restricted to the size-range 0·5 to 4 cm (fine to coarse gravel grade). They are angular, or at most only slightly subrounded, with no sign of former weathering or other alteration along their margins, implying lack of sedimentary transport and swift burial.

Plate 1

Macadam breccia, Knockdolian Hill [NX 116 851] composed of angular lava clasts, a few of which are vesicular. There is virtually no fine-grained matrix. Carbonate, quartz and chert (light-coloured) may sometimes occur between clasts and in fractures traversing the clasts.

Plate 2 (*overleaf*)

Pillow basalt (middle zone) on the shore at Pinbain [NX 137 916]. The pillows are disaggregating into clasts which are comparable in size and shape to those comprising the macadam breccias of Knockdolian Hill (Pl. 1) and elsewhere in the igneous complex.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Those clasts in direct contact with each other are loosely cemented by surface films, while others are separated by very thin partings of carbonate, chlorite and chert. Where clasts touch there is no evidence of subsequent tectonic disturbance.

Very occasionally it is possible to identify bodies with a definite pillow-form outline by 'fitting together' some detached clasts, but otherwise the breccias bear no obvious geometric relationship to pillows. Unlike hyaloclastites in which the curved outer (glassy) rinds of pillows predominate, and in which the grain size is variable, the macadam breccias are essentially blocky and of more uniform size.

Individual clasts of lava show no evidence of chilled margins implying that fragmentation post-dated solidification and precluding disruption by vesiculation or by liquid-coolant interaction (Colgate and Sigurgeirsson 1973; Peckover *et al.* 1973). In any case, most of the clasts are non-vesicular (Pl. 1). Hyaloclastites or hyalotuffs (Honnorez 1963; Honnorez and Kirst 1976) have not been found either as matrix between clasts or as interbedded material.

On Knockormal and Lochton Hills large numbers of outcrops consist of macadam breccias previously regarded as agglomerates and tuffs (Peach and Horne 1899). Frequently gradations can be followed from solid pillow flows into highly jointed and segmented blocky lava and eventually into macadam breccia. Such gradations are displayed even more clearly at Pinbain.

Carlisle (1963) has described "pillow breccias" composed of large broken pillows set in a fine-grained matrix composed of hyaloclastite fragments (aquagene tuffs), the latter constituting as much as 80% of the whole rock. Similar rocks are also described by Solomon (1969), but both appear to be quite different from the Ballantrae macadam breccias.

FORMATION OF MACADAM BRECCIAS

On the shore at Pinbain (Bluck 1978) a pillowed basalt about 22 m at its thickest point (Pl. 2) provides evidence of the process by which Ballantrae macadam breccias may have been produced; similar phenomena being also displayed along the shore further north towards Kennedy's Pass (Peach and Horne 1899, p. 443). Although almost vertical, the way-up of the basalt can be deduced from load structures in mudstones on its southern (lower) side.

The central zone of the basalt is clearly pillowed (Pl. 2), but each pillow is segmented into a mosaic of roughly cuboidal or rectangular fragments which are identical in general size and shape to those constituting the thick macadam breccias of Knockdolian Hill and elsewhere. The particular shape of the clasts has resulted in part from the intersection of radial and concentric joints and cracks. However, in many cases fragmentation is more complex and develops along a multitude of roughly polygonal cracks resembling "breadcrust" fracturing, but without vesiculation. The fracturing is not tectonic since the fractures terminate at the edge of each pillow and do not traverse inter-pillow cementing material.

Towards its base the rock becomes increasingly disaggregated until pillow-form finally disappears, macadam breccia forming the bottom 2 to 3 m. The base itself is more heterogeneous consisting of a mixture of macadam breccia, clasts of carbonated serpentinite, shale and rounded pebbles of dolerite, gabbro, glaucophane schist, garnet peridotite and pyroxenite (Bailey and McCallien 1957, p. 47; Bloxam and Allen 1960; Bluck 1978; Bloxam 1979). A similar zone of macadam breccia forms the top of the basalt and is succeeded by a pebbly conglomerate containing igneous and metamorphic clasts like those at the base.

Hence, an important source for the clasts comprising the thick Ballantrae macadam breccias is from the essentially non-explosive, autoclastic break-up of pillowed basalts. An examination of Plate 2 shows that the fracture-system in the central portion of the Pinbain basalt must have formed after cessation of flow since individual pillows and pillow-margins remain well defined. This contrasts with the completely disaggregated lava breccias forming the top and bottom zones of the flow.

PETROGRAPHY

The petrography of the basalt and lava clasts at Pinbain and Knockdolian also provides some evidence which may have a bearing on the origin of the macadam breccias. The Pinbain basalt is aphyric and essentially non-vesicular although a few microvesicles and amygdales (about 0·2 mm in size) do occur. There is also a lack of conspicuous grain size variation between margin and interior of individual pillows and within the sheet as a whole. Samples from margins and interiors of disintegrating pillows show that glass was originally a major constituent (70% or more by volume), now forming a brown sub-isotropic, devitrified mesostasis riddled with microlitic plagioclase, together with larger (0·2 mm) "hollow" quench crystals (Bryan 1972). The devitrified glass commonly consists of small (1 mm) sub-rounded varioles composed of radiate and plumose sheafs of dendritic feldspar, while variolitic aggregates of acicular pyroxene are also common.

These textural characters indicate that the basalt was very rapidly chilled throughout. The non-vesicular character of the rock implies either a volatile-poor magma, early degassing, or retention of volatiles. The latter alternative seems the most likely, with the volatiles being retained in the glassy phases under the hydrostatic pressure of seawater (McBirney 1963; Moore 1965). The hydrous nature of the mesostasis is also made evident by the abundance of chloritic devitrification products, while the water content of analysed rocks (H_2O^+) may exceed 3%.

Thin sections of several lava clasts from the Knockdolian and Pinbain macadam breccias show that all are similarly fine grained and contain a major proportion of variously devitrified glassy basalt.

DISCUSSION

Eruption of magma into deep water is a well documented means by which volatiles (mainly water)may be retained under external hydrostatic pressure. The water content of average tholeiitic basalt melts (0·5%) provides a partial pressure of about 80 bars, so that vesiculation would be largely prevented in water deeper than about 800 m (McBirney 1963; Moore 1965; Sigvaldason 1968). Hence deep water, together with rapid pervasive cooling, would explain the non-vesicular, nature of the Pinbain and other pillow basalts.

Variolitic textures have been considered as the equivalents of spherulitic textures in more acid glassy rocks (Carstens 1963). Vuagnat (1946) concluded that variolitic texture is indicative of eruption in deep water, a view also favoured by Walker (*in* Furnes 1973), who suggested that the formation of such a texture is due to the retention of water and other volatiles. The general absence of variolites in modern ocean floor basalts dredged from depths shallower than about 1·6 km lends support to those conclusions (Cann 1969; Furnes 1963). Dimroth (1976) also noted the presence of variolitic textures and the absence of vesicles and explosive products in some Archaean submarine pillow basalts to which he assigned an eruption depth in excess of 2 km. We therefore support Walker's view that variolite formation is related to retention of volatiles which is in turn a function of depth.

We conclude that macadam breccias form as the result of pervasive cooling of terminal pillow lava lobes or flow-fronts emplaced on the sea floor at depths of not less than about 2 km. The lava breccias and parent rock are glass-rich and the fragmentation process may be related to the glass-content; perhaps resembling a form of crude spherulite or perlitic fracture system.

The uniform grain and highly glassy texture throughout the Pinbain pillow flow suggest that rapid cooling in contact with seawater may not be the only process involved. Although Moore (1965) found no definite relationship between glass content and depth of eruption of pillow basalts off Hawaii, the present authors suggest that a relationship may exist on the bases of the following observations.

Glass and spherulite/variolite are typical of large-scale undercooling where nucleation and growth rates are much greater than diffusion rates (Lofgren 1974). The presence of an aqueous vapour phase also exerts a considerable influence over nucleation and crystallization. Studies by Lofgren (1974), Swanson (1977), and Fenn (1977) show that, contrary to expectations, increasing water pressure inhibits nucleation and reduces nucleation density while simultaneously shifting the nucleation density maxima towards the liquidus (i.e. towards higher temperature and less undercooling) (Fenn 1977, pp. 151–2). Hence, high water vapour pressures allow glass formation at lower amounts of undercooling.

The reasons for this are not fully understood (Fenn 1977, p. 152) but are clearly the effects of interaction between water vapour and silicate melt. The present authors suggest that water inhibits nucleation and crystallization by breaking the siliconoxygen bonds and maintaining depolymerization of the melt. Hence, although it has been suggested by several authors (see: Furnes 1963) that varioles are evidence of liquid immiscibility, we suggest that this form of crystallization is indicative of higher water vapour pressure in the magma which may lead to a variolite–forming supersaturated vapour phase of crystallization.

The thick sequences of macadam breccias at Knockdolian and elsewhere probably represent talus accumulation along the margins of extensive submarine lava piles, and may also fill deeper submarine depressions and fault zones. Photographs of modern ocean floors show the widespread occurrence of thick aprons of talus along the foot of submarine lava scarps. In particular, photographs by Aumento (1968) and McGregor and Rona (1975) of "talus, angular debris from gravel to boulder size", illustrate material exactly like that outcropping at Ballantrae. Ballard and Moore (1977) have also obtained photographs of "flow foot rubble and talus", some of which form thick ramps against the fault walls of submarine lavas.

Apart from modern ocean floor examples, lava breccias which also appear to be like those at Ballantrae have been described from Mesozoic ophiolites in E. Liguria (Barrett and Spooner 1977) and from the Archaean of Canada (Dimroth *et al.* 1978).

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