AIRBORNE AND DETRITAL VOLCANIC MATERIAL IN THE LOWER CRETACEOUS SEDIMENTS OF SOUTH-EASTERN ALEXANDER ISLAND

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ABSTRACT. Unusual structures in the Lower Cretaceous shallow-water marine sediments of Alexander Island are described and interpreted as being altered material of direct aerial introduction from a volcanic source. Volcanogenic material derived from syndepositional lavas and tuffs to the east is also described.

THE object of this paper is to describe a number of unusual occurrences of airborne, water-lain pyroclastic material in the Lower Cretaceous sediments of south-eastern Alexander Island (Fig. 1).

The recognition of these occurrences of pyroclastic material of diıect aerial introduction raises the possibility that a significant proportion of the potash feldspar, plagioclase, quartz and biotite, frequently showing evidence of corrosion resulting from weathering and transportation, could also be of direct aerial pyroclastic introduction or derived from contemporaneous pyroclastic accumulations in the source area. This possibility was rejected in the earlier quantitative analysis of the sandstone provenance (Horne, 1968*a*) on grounds that were not fully discussed. It is argued that, in the area described by Horne (1968*b*), this contribution of crystalline pyroclastic material to the sediments in the form of aerial fall-out was a minor one and in no way invalidates the conclusion that the overwhelming proportion of the highly immature material forming the sandstones in this succession was essentially epiclastic and derived from plutonic igneous and metamorphic rocks (Horne, 1968*b*).

VOLCANIC MATERIAL OF DEFINITE AERIAL INTRODUCTION

A small part of the volcanic material in these sediments can be regarded with confidence as having entered the trough aerially, probably from gas clouds bearing crystal, vitric and lithic fragments which settled out onto the surface of the sea and finally into the upper sediment layers. These include zeolitized vitric crystal tuffs, vitric crystal blebs, crystal-cored ellipsoidal lapilli and axiolitic structures.

Vitric shard deposits

Zeolitized vitric shard deposits in this sedimentary sequence have previously been described in outline (Horne, 1968*c*). They are laterally persistent, very fine-grained grey rocks with a characteristic white, chalky weathered crust and frequently show extensive bioturbation structures which have been described as vermicular structures (Taylor, 1967). In thin section they have a distinct vitroclastic texture pseudomorphed by laumontite. One such deposit at station KG.91 is beautifully graded (Fig. 2a). The coarsest material at the base being largely zeolitized plagioclase crystals which have been impressed into the top of the underlying mudstone (Fig. 4a). The proportion of shards increases rapidly upwards to the exclusion of plagioclase crystals (Fig. 4b). These zeolitized vitric and vitric crystal tuffs are the most extensive deposits of undoubtedly aerially transported "fall-out" material in the Alexander Island succession.

Problematical structures in zeolitized vitriclastic tuff

At stations KG.71 and 74, Triton Point (Fig. 1), problematical structures are developed in zeolitized vitric tuff like those described above. At station KG.74, the structures are in the form of circular slabs, 1–1·5 m. in diameter and 25 cm. deep. They are aligned along the strike in beds of black close-jointed mudstones dipping at 40° towards the east (Fig. 2b). Fig. 2c illustrates one of these slabs in detail. At station KG.71, oval bodies, elongated lenses and tabular layers of this material are aligned along distinct bedding planes in a thick sequence of dark grey silty mudstones (Fig. 2d).

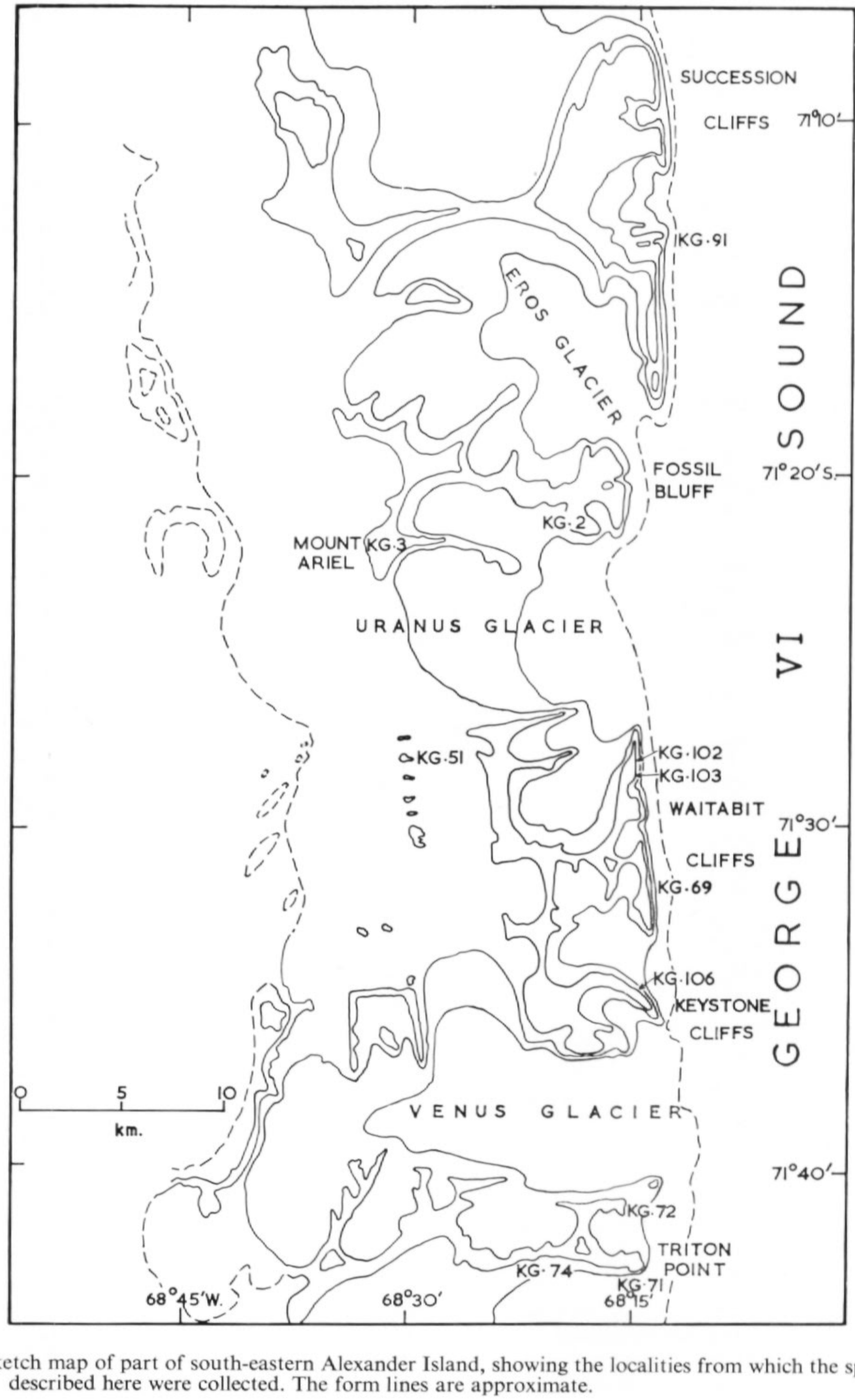


Fig. 1. Sketch map of part of south-eastern Alexander Island, showing the localities from which the specimens described here were collected. The form lines are approximate.

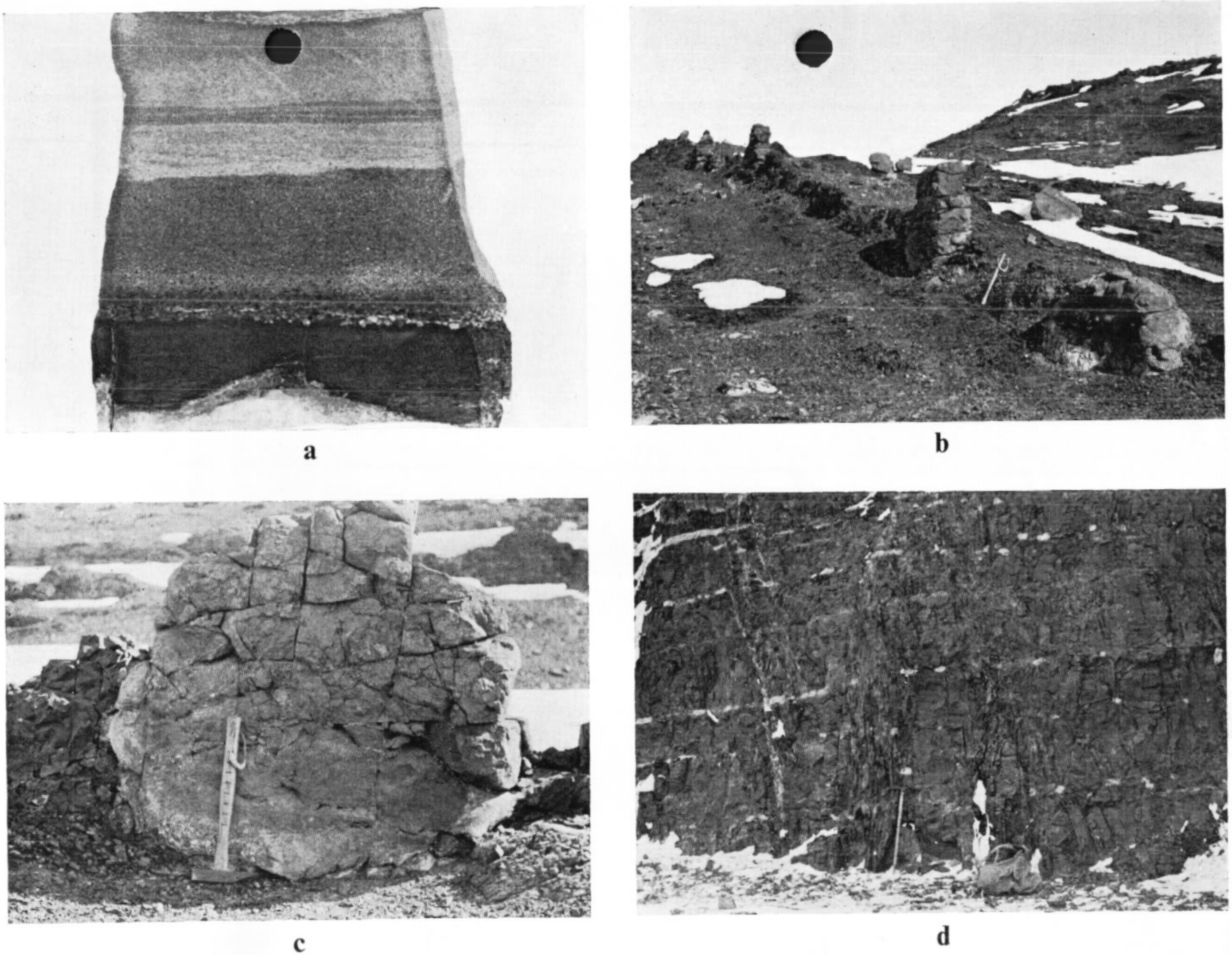
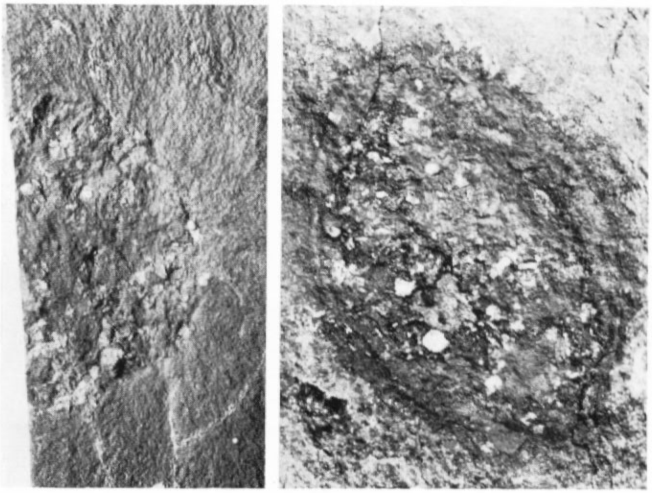


Fig. 2. a. A hand specimen of a graded vitric shard deposit from station KG.91; coarser plagioclase crystals at the bottom of the deposit are impressed into the underlying mudstone (KG.91.1; ×1).
b. The field occurrence of large problematical structures in zeolitized vitroclastic tuff at station KG.74. They are aligned along the bedding and appear to have originally constituted a single unit. The hammer shaft is 38 cm. long.
c. A close-up showing one of the problematical structures in Fig. 2b.
d. Small-scale structures in gently dipping sediments at station KG.71 which may be related to the larger ones at station KG.74 (Fig. 2b and c). The ice-axe is about 90 cm. long.

The only interpretation which can be suggested for the origin of these structures is that they resulted from the disruption of a once continuous but not homogeneous deposit of vitric tuff. Numerous structures in this succession (e.g. clastic dykes (Taylor, 1966)) indicates that the mudstones were at least partially lithified at a much earlier stage than the other components and that the disturbance of the sequence, either by tectonic or gravity forces, caused the mobilization and re-distribution of these more plastic horizons.

Vitric crystal blebs

In mudstones at various localities and levels throughout the succession exposed in the coastal cliffs, numbers of unusual small blebs occur in the plane of the bedding. They are subquadrate to elliptical in outline and up to 3 cm. across (Fig. 3a and b). Their colour varies



a b

Fig. 3. Vitric crystal blebs in the hand specimen.

a. An incomplete example in a mudstone from Keystone Cliffs (KG.106.17; ×1·5).

b. An example from station KG.3 (Mount Ariel) lying in a mudstone containing multitudes of prehnitized Radiolaria (white specks) (KG.3.107; ×1·5).

from black to rusty red (usually the latter) and they consist largely of a very fine matrix in which is set a sprinkling of plagioclase crystals up to 1 mm. across. All of the blebs examined were flattened in the plane of the bedding and were usually only one crystal grain thick. At station KG.2 (Fig. 1), B. J. Taylor recorded scores of these blebs on a bedding surface only a few feet square, although normally these structures are more scattered.

In one bleb (KG.103.143) sectioned parallel to the bedding (Fig. 4c) the plagioclase crystals (An_{55-60}) show Carlsbad/albite twinning and frequently exhibit beautifully developed oscillatory zoning. The crystals are traversed by irregular shatter cracks, and many which would otherwise be euhedral have some part broken off; others have sharp but irregular margins. One plagioclase crystal partly encloses remnants of (?) pyroxene and fragments of a similar ferromagnesian mineral are scattered throughout the bleb. The groundmass of the bleb is highly chloritized; flakes of a yellowish green chlorite are aligned in minute thin ribbons or describe small circles such that they seem to indicate a remnant micro-perlitic or possibly micro-vesicular structure (Fig. 4e). The interstices between the chlorite flakes are filled with a low-birefringence mineral, which might be feldspar, and a scattering of minute iron-ore octahedra is also present. An almost exactly similar micro-lithology has been observed in some fragments enclosed in a palagonite-tuff from Kilmundy, Fifeshire; flakes of a mineral similar to the chlorite, but brownish in colour, might be palagonite. As well as scattered grains,

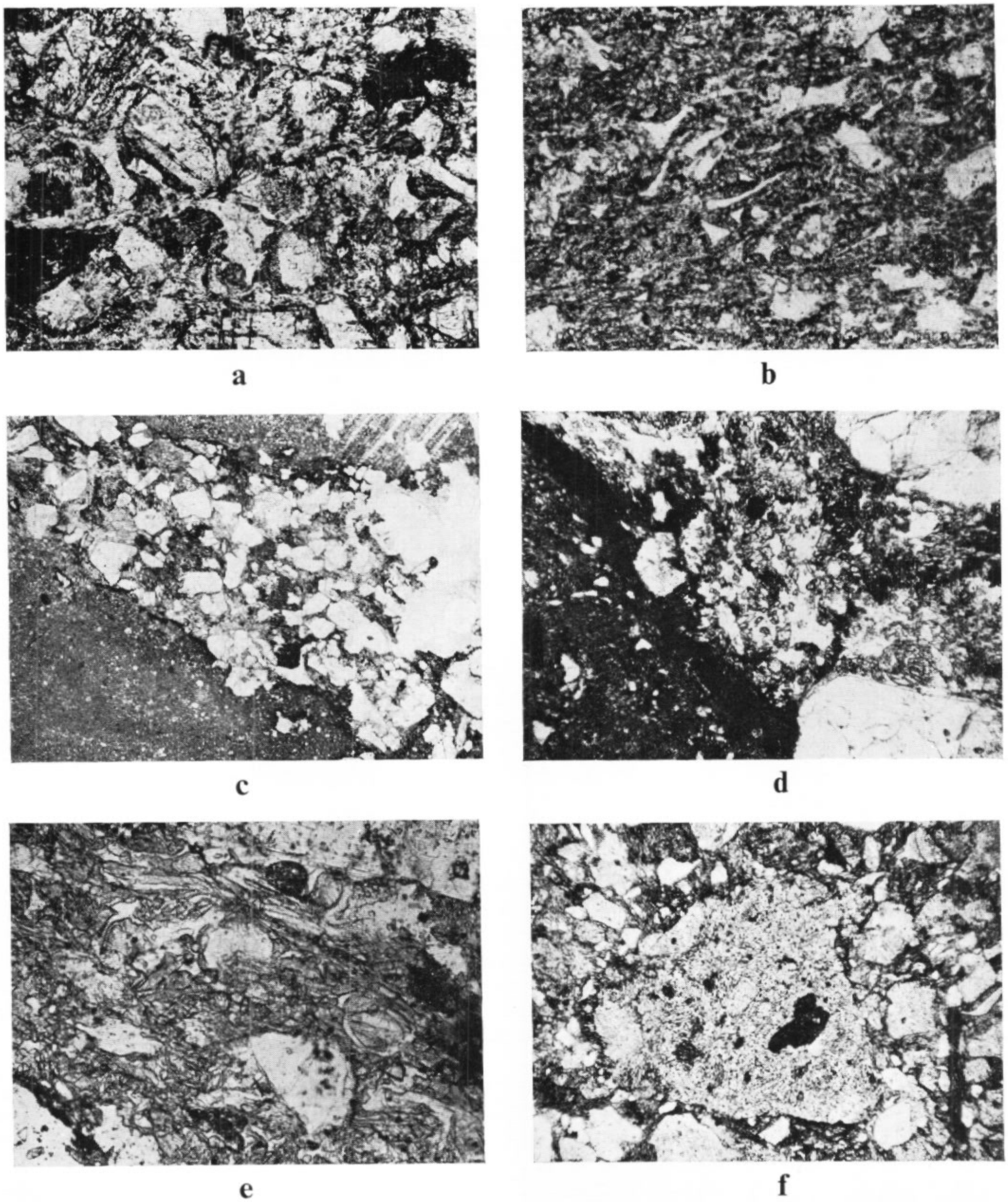


Fig. 4. a. A thin section of the lower part of the graded vitric shard deposit shown in Fig. 2a; the dominant clasts are laumontitized plagioclases (KG.91.1; ordinary light; ×35).
b. The upper part of the graded vitric shard deposit showing the vitroclastic texture (KG.91.1; ordinary light; ×35).
c. A general view of a vitric crystal bleb seen in thin section parallel to the bedding. The large crystals of plagioclase feldspar are particularly abundant in this example (KG.103.143; ordinary light; ×7).
d. A closer view of the same bleb showing the outer rim of iron ore (black), cracked plagioclase crystals (white) and the fine matrix (KG.103.143; ordinary light; ×45).
e. The yellowish green chloritic matrix of the vitric crystal bleb showing the remnant (?) micro-perlitic structure and scattered grains of iron ore (black) (KG.103.143; ordinary light; ×400).
f. A sandstone containing volcanic fragments of andesitic composition and probably of epiclastic origin, eroded from syndepositional tuffs (KG.51.11; X-nicols; ×35).

iron ore is present in localized concentrations especially around the margins of the bleb and to some extent around the margins of the plagioclase crystals (Fig. 4c and d). In the latter case, the iron ore is associated with corrosion of the crystal face. Much of this iron ore has been oxidized to limonite and this presumably was responsible for the reddish colour of the hand specimen. Small patches of iron ore remain unaltered; both ilmenite, showing alteration to leucoxene, and (?) magnetite, in minute exquisitely developed octahedra, are present.

Outside of the main body of the bleb are isolated plagioclase crystals with a thin envelope of matrix which probably represent true detached pieces of the original fragment rather than the effects of sectioning a structure that is not perfectly planar. Similar crystals with a thin skin of volcanic glass adhering to them have been described from a volcanic mudflow in Washington (Crandrell and Waldron, 1956).

The layer of sediment within the plane of the bleb contains a higher proportion of shards, largely pseudomorphed by prehnite, than is usually present in such mudstones. Also abundant are Radiolaria, similarly replaced by prehnite; in specimen KG.3.107 (Fig. 3b), Radiolaria are so common that they are clearly visible in the hand specimen as small white specks. This sudden increase in fossil Radiolaria in association with the volcanogenic blebs may have resulted from an influx of toxic chemicals due to volcanic eruption and which could have caused their sudden death.

It has not been possible to arrive at a satisfactory explanation for the development of these structures, except that they are of a volcanogenic origin. A puzzling feature is their extreme and constant thinness together with the possibility that, in that state, they would have been very fragile and could not have been transported far without breaking. Small lava droplets ejected from a volcano normally assume a three-dimensional, rather than a two-dimensional, shape and are cooled rapidly during flight through the air. Except in cases where the flight path was very short, such small droplets would be quite firm when they hit the ground and, if they fell into the sea, they would be solid when they came to rest on the sea bed. Although the enclosing sediments are part of a thick sequence, it is doubtful whether solid volcanogenic globules buried in the succession would ever have undergone the kind of pressures necessary to squash *every one* of them wafer-thin. There is no evidence of such flattening in thin section and none of the fossil invertebrates in the same sediments is distorted to the degree expected if such flattening had taken place.

Devitrified lapilli

A massive mudstone at station KG.91 (Fig. 1) contains large numbers of ellipsoidal lapilli, many of which enclose one or more crystals (usually plagioclase) or a pocket of calcite (Fig. 5a). They range from 0·5 to 1·5 mm. in diameter and possess an internal reticulate fracture pattern. The cryptocrystalline material composing the structures is pale green in transmitted light; under crossed nicols it has a weak bluish grey birefringence. These bodies have an incomplete outer skin of a substance with a higher birefringence than that of the main mass of the globules and which is penetrated by wedge-shaped cracks that are continuous with the internal reticulate cracking.

These structures are interpreted as globules of volcanic glass, cored in many cases by intratelluric crystals, and extruded explosively from nearby vents. These globules would have become spherical or ellipsoidal and largely solidified during flight. On entering the sea they would have been rapidly chilled and developed a hard cracked outer skin before settling into the mud below. They underwent subsequent devitrification, the glass being replaced by a pale green mineral, possibly celadonite.

They appear comparable to basalt fragments in the form of "rounded chilled lapilli with fine-grained borders and with large crystals and vesicles in the cores" described by Tryggvason and White (1955) from rhyolitic tuffs in Iceland.

Although they are reminiscent in general morphology and distribution of the accretionary lapilli described by Moore and Peck (1962), their detailed structure, composition and occurrence in a marine mudstone argue against a similar origin. Accretionary lapilli, bearing a closer resemblance to the Alexander Island structures than those illustrated by Moore and Peck, have been described by Bateson (1965) from Guyana. The first point of similarity is that they occur in marine sediments in association with shards and other volcanogenic material.

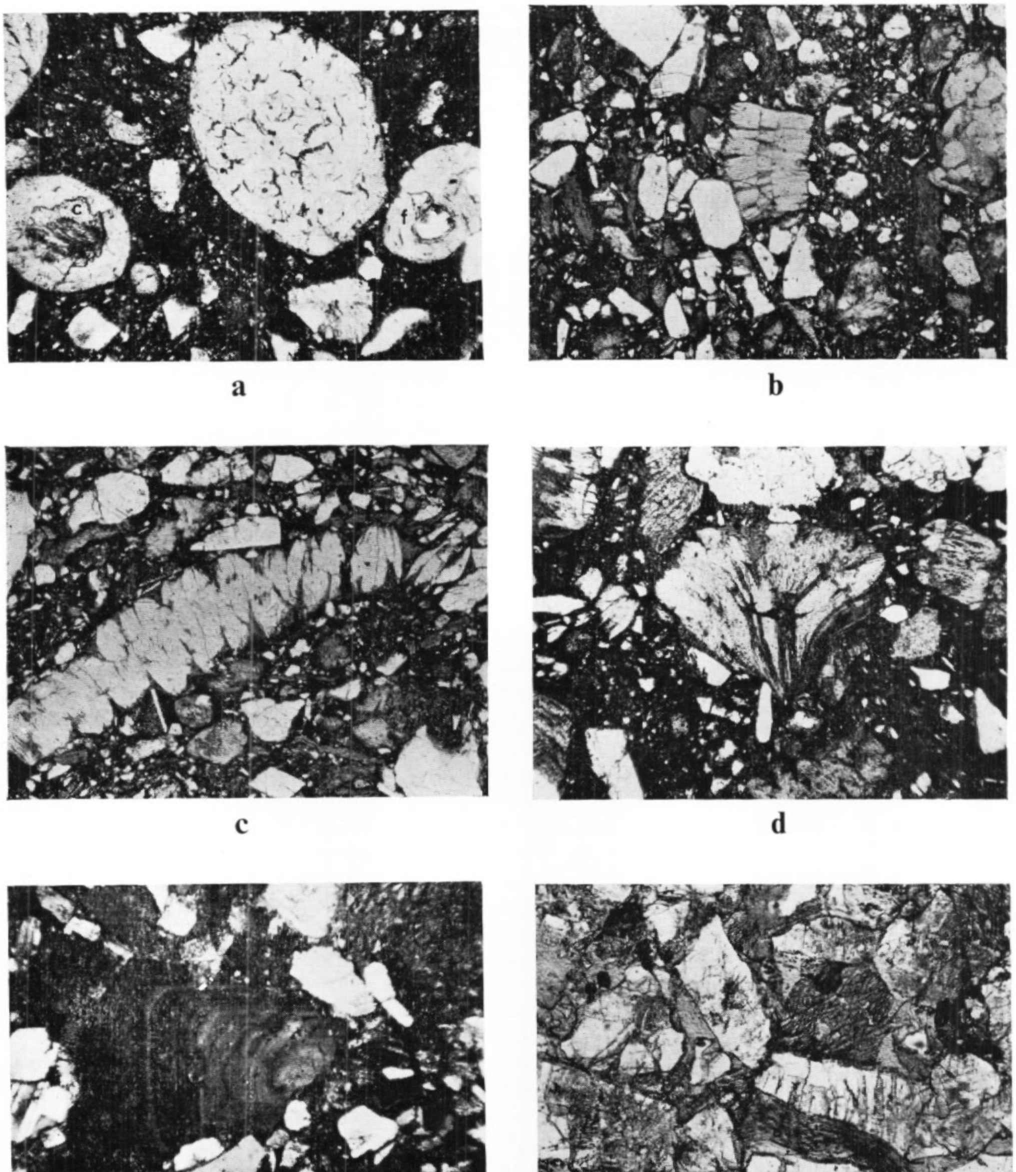


Fig. 5. a. Pale green devitrified lapilli showing reticulate cracking; two small examples have cores of feldspar (f) and calcite (c), respectively (KG.91.2; ordinary light; ×35).

b–d. Photomicrographs showing the variety of axiolitic structures found in the same sandy mudstone at station KG.102 (Waitabit Cliffs) (KG.102.1; ordinary light; ×35).

e. A sandstone containing broken plagioclase crystals with strong oscillatory concentric zoning and which are considered to be of a volcanic origin (KG.74.1; X-nicols; ×35).

f. A plagioclase-hornblende-biotite-sandstone probably derived from a plutonic igneous source (KG.69.6; ordinary light; ×35).

These Guyanan structures have a less well-developed concentric banding than that of true accretionary lapilli, being composed of a core containing shards and crystals, a finer-grained outer zone with fewer inclusions and a superficial pellicle that is commonly discontinuous like the outer rim of the globules from Alexander Island. However, Bateson has suggested that these structures resulted from the accretion of volcanic dust around a wet ash core and invoked a complex history to explain their cohesion when deposited in water.

Axiolitic structures

Abundant fragments of unusual and variable shape, and with an axiolitic structure, occur in mudstones at station KG.102 (Waitabit Cliffs) (Fig. 5b–d). In thin section they appear most commonly as curved, lath-shaped bodies pseudomorphed by a pale green fibrous material, the fibres radiating from the central axis of the laths and presenting an axiolitic structure. This material has a variable, moderate to anomalous birefringence and parallel extinction, and it is most probably a mixture of clay minerals such as montmorillonite, illite and kaolinite. An axiolitic structure commonly results from the devitrification of vitric pyroclastic material (Zirkel, 1876; Ross and Smith, 1961; Buxton, 1966). The curved axiolites in the Alexander Island mudstone strongly resemble the fibrous "sphaerolites" illustrated by Zirkel (1876, p. 163, pl. VIII, fig. 1) from a rock described as a rhyolite; Ross and Smith (1961, fig. 95) considered it to be a welded tuff. They are identical to kaolinite "vermicules" and biotite pseudomorphs from Carboniferous tonsteins in Europe (Williamson, 1970, figs. 5 and 11), also regarded as altered airborne pyroclastic material. These Alexander Island examples are thought to represent vitric pyroclastic fragments which were aerially introduced into the depositional trough along with the broken, oscillatory zoned, fresh plagioclase crystals present in the same mudstone.

Epiclastic Volcanic Material of Waterborne Introduction

The bulk of the volcanogenic material in the sediments is in the form of non-vesicular andesite fragments composed of plagioclase feldspar, either as fine elongated needles with a trachytic flow texture (Fig. 4f) or as more equidimensional coarser laths with a less distinct alignment set in a vitric matrix. This material is believed to be essentially epiclastic (Fisher, 1966) and eroded from weakly lithified, syndepositional andesitic lavas and lithic tuffs which accumulated in the eastern source area (Horne, 1968*a*, *b*, 1969).

The main reason for regarding them as epiclastic, waterborne fragments as opposed to pyroclastic aerial lapilli is that they occur exclusively as moderate- to well-sorted populations in sandstones with a grain-size of roughly equivalent hydraulic characteristics. Furthermore, they are never associated with any of the occurrences of volcanic material of definite aerial introduction described above.

Unstable Mineral Fraction of "Basement" Origin

The question as to whether a significantly large proportion of relatively unstable components such as plagioclase and biotite could have been added to the sands either directly by pyroclastic fall-out or by erosion of syngenetic tuffs is important in the quantitative interpretation of the provenance of the Alexander Island sandstones (Horne, 1968*b*).

The proportions of coarse anhedral quartz and potash feldspar (including orthoclase, perthite and microcline) in these mineralogically immature rocks are directly equivalent to a plutonic source rock of average adamellitic composition. The selective destruction of any significant proportion of the plagioclase from such a source under the prevailing conditions of rapid erosion and transport is improbable. That plagioclase and biotite from plutonic igneous and metamorphic rocks reached the trough in a fresh condition is shown by the presence of composite fragments of such rocks containing these minerals (Horne, 1968*b*).

Plagioclase and biotite crystals of anomalously large size enclosed in mudstones might be expected to have resulted from persistent crystal showers. The only examples of this are the mudstones containing other obvious volcanogenic material such as the axiolitic structures and devitrified lapilli, which appear to be rare in the succession. The plagioclase in these beds is in the form of fractured euhedral crystals which invariably show oscillatory zoning. In other rocks with mudstone matrices enclosing large plagioclase crystals together with quartz and "basement" composite fragments in a wide size range, the texture is attributable to mass flowage and slurrying of originally interlayered sands and muds (Horne, 1968*a*, p. 20).

The vast proportion of the plagioclase in the sandstones has a composition in the range An_{31-41}. Albite twinning is universal. Weak and normal zoning is quite common whereas oscillatory zoning is rare. These properties are consistent with the suggestion of a predominantly granodioritic to adamellitic source. There are two interesting exceptions to this. The first is the only sandstone sectioned (KG.74.1; Fig. 5e) which contains significant amounts of strongly oscillatory zoned fractured plagioclase similar to that in the volcanogenic blebs. It also proves to have a composition in the range An_{50-56} and is almost certainly of volcanic origin; it was probably derived from a subaerial crystal tuff of syndepositional origin. The second is an unusual sediment composed of plagioclase with a composition in the range An_{56-58}, biotite and green to greenish brown hornblende (Fig. 5f; Horne, 1968*b*, p. 81). Oscillatory zoning of the plagioclase in this rock is quite rare. The balance of the evidence suggests that this rock was derived from a meladiorite or hornblende-gabbro.

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