THE GEOLOGY OF NORTH-WESTERN SOUTH GEORGIA: III. PETROLOGY OF THE CUMBERLAND BAY FORMATION

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Abstract. The petrography of the detrital components and secondary minerals of a sequence of volcaniclastic greywackes, the Cumberland Bay Formation, is described. Lapilli, glass shards and pumice are common, indicating contemporaneous volcanic activity during deposition of the Cumberland Bay Formation. Widespread albitization of plagioclase and the generally basaltic nature of volcanic fragments from active structural arcs suggests that the trachytic clasts represent soda-metasomatized andesites. Boron in vein axinite was probably leached from the surrounding greywackes by pore fluids. Prehnite, the most widespread metamorphic product in the Cumberland Bay Formation, is also the most important index mineral. The formation of prehnite in the absence of pumpellyite is probably due to the low-pressure high-temperature conditions of metamorphism and/or a calcite-rich environment. It is concluded that, during burial metamorphism of the Cumberland Bay Formation, transition through the zeolite facies into the quartz–prehnite field of the prehnite–pumpellyite facies was completed in the lower part of the succession.

The sub-Antarctic island of South Georgia lies approximately 2,000 km. east of Cape Horn (between lat. 54°–55°S. and long. 36°–38°W.) and it is the largest island on the north Scotia Ridge. The field geology of the volcaniclastic greywackes at the north-western end of the island was investigated during the austral summer seasons of 1972–73 and 1973–74, and thin-section examination of the collections was subsequently carried out at the University of Birmingham.

The Cumberland Bay Formation consists essentially of turbidites showing lithological variation from fine shale to cobble-conglomerate. The coarser sediments, consisting predominantly of lava clasts, are pale grey-green in colour whereas the more argillaceous rocks are dark grey to black. Textural immaturity is demonstrated by variation from rounded lava clasts to sub-angular detrital feldspars.

Detrital Components

The detrital components of the Cumberland Bay Formation are mainly rounded to sub-angular volcanic fragments and broken plagioclase phenocrysts.

Volcanic fragments

Two groups of volcanic clasts have been recognized in the Cumberland Bay Formation: a microlitic mass of feldspar laths surrounding occasional phenocrysts of albite, oligoclase and andesine; and felsitic clasts with feldspar phenocrysts set in a cryptocrystalline quartzo-feldspathic groundmass (Fig. 1a). The first group comprises the majority of clasts and these have been subdivided into three types of volcanic clast according to their textural variations:

i. Trachytic clasts with feldspar laths showing a strong flow alignment (Fig. 1b).
ii. Felted clasts with feldspar laths in random orientation.
iii. Hyalopilitic clasts with feldspar laths set in a groundmass of dirty brown devitrified volcanic glass (Fig. 1c). These clasts are generally much smaller than the trachytic or felted types and the contained feldspar laths are much smaller in size.

The plagioclase laths vary in length from 0·1 to 1 mm. and have an extinction angle $\gamma : c = 0$–21°. The majority have been albitized, giving them a characteristic cloudy appearance with indistinct twinning and a shadowy extinction. Albitization has also caused fusion of grain boundaries so that in the finer-grained lavas the crystal boundaries are very indistinct. Compositionally, the plagioclase laths range from albite to oligoclase and occasionally andesine. The matrix of

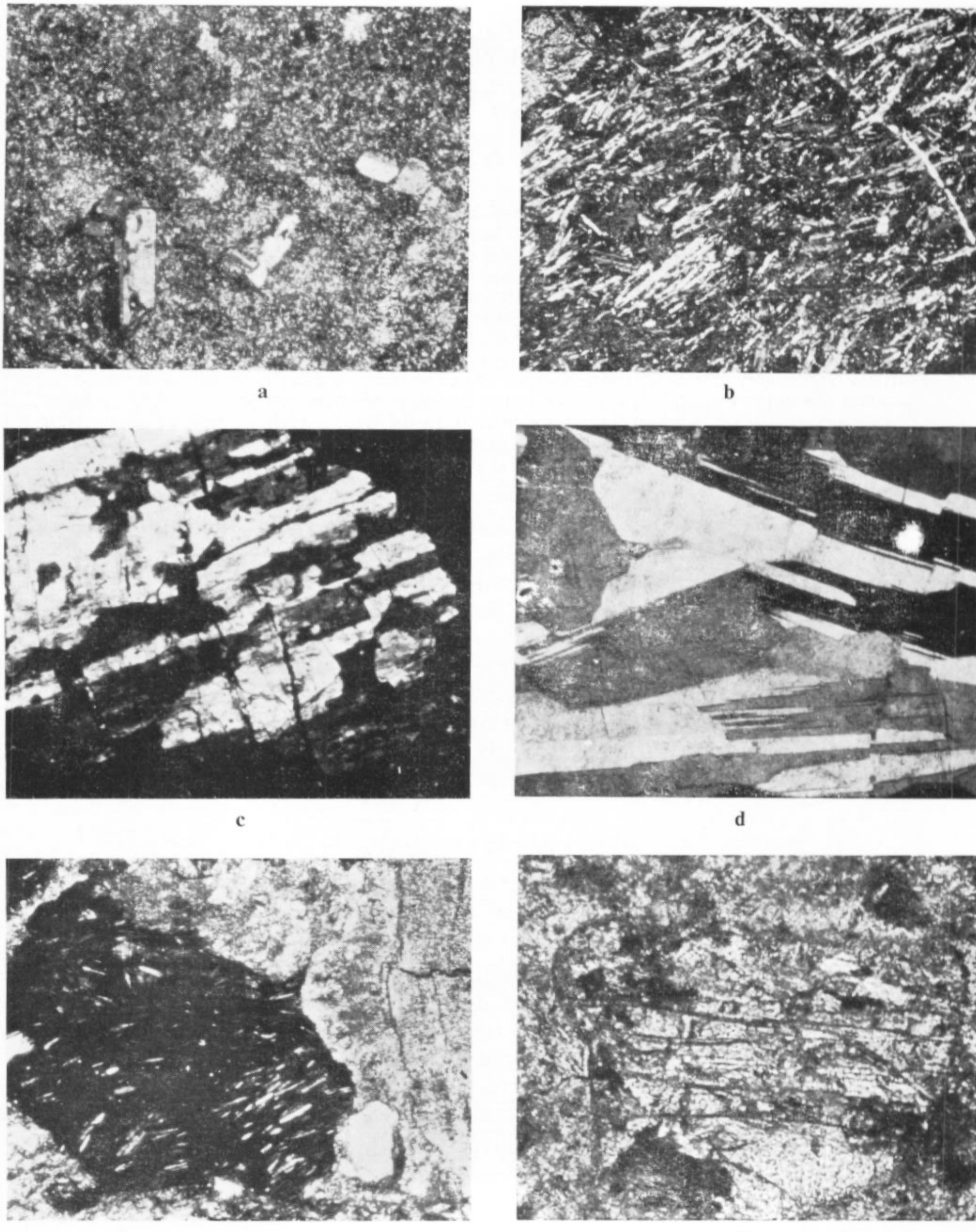

Fig. 1. a. Felsitic lava clast with feldspar phenocrysts set in a cryptocrystalline quartzo-feldspathic groundmass (M.1006.1; X-nicols; ×50).
b. Trachytic lava clast with feldspar laths showing strong flow alignment (M.1682.1; X-nicols; ×80).
c. Hyalopilitic lava clast with feldspar laths set in a groundmass of dirty brown volcanic glass; there is a bivalve shell on the right (M.1679.1; X-nicols; ×50).
d. Vein albite in a quartz vein (M.1695.3; X-nicols; ×50).
e. Preferential replacement of albite by penninite along twin lamellae (M.1638.8; X-nicols; ×80).
f. Well-cleaved augite phenocryst surrounded by the cryptocrystalline calcite of a calcareous nodule (M.1679.1; X-nicols; ×200).

most clasts consists essentially of devitrified volcanic glass which is altered either to chlorite or sericite. A few of the clasts accept sodium cobaltinitrite staining in the matrix, indicating that the groundmass is probably a mixture of quartz and potash feldspar which is common in andesites (Williams and others, 1954).

Tyrrell (1930) suggested that the trachytic clasts had been derived from a trachytic or keratophyric lava. However, volcanic fragments from active structural arcs are generally basaltic (Jakes and White, 1971) and therefore the volcanic clasts in the Cumberland Bay Formation may represent a more basic provenance than that implied by Tyrrell. Alternatively, if keratophyres are formed by the alkali metasomatism of original rhyolitic rocks, as suggested by Battey (1974), the trachytic clasts may represent soda-metasomatized andesites. The original andesine was probably albitized during low-grade metamorphism and any excess soda has appeared as vein albite (Fig. 1d).

Detrital feldspar

Detrital feldspars are generally more angular than the volcanic clasts from which they have probably been derived (Skidmore, 1972) and they form approximately 10–20 per cent of the Cumberland Bay Formation. Treatment of several thin sections with sodium cobaltinitrite solution showed that potash feldspar is present as perthitic intergrowths in the plagioclase phenocrysts. Replacement is generally irregular but in a few phenocrysts the potash feldspar is present as regular "vein-like" bands. The orientation of these bands bears no clear relationship to the twin or cleavage planes. The plagioclase phenocrysts, which are mainly of albite and oligoclase, are characterized by fine polysynthetic twinning but individual twin planes are generally indistinct. The majority of the phenocrysts have been albitized and many have suffered subsequent prehnitization; sericitization and replacement by calcite have also been observed. Unlike the uniform clouding effect which characterizes alteration to albite, subsequent prehnitization often develops preferentially along twin planes. Similarly, albite has been preferentially replaced along twin lamellae by pale green penninite (Fig. 1e). Secondary chlorite occurs more frequently as radiating clusters, presumably replacing original glassy inclusions in the feldspar.

Sedimentary rock fragments

Sedimentary rock fragments form a very small proportion of the greywackes examined and they consist largely of fine-grained angular slate clasts and rounded grains of polycrystalline quartz.

Accessory minerals

Detrital ores, predominantly steel-blue magnetite and reddish haematite, are the most important accessory minerals. Rarer pyrite is often oxidized whereas ilmenite generally shows some alteration to leucoxene. In the coarser greywackes the ore minerals are present as irregular aggregates scattered randomly throughout the matrix. The primary ore minerals in the volcanic clasts are generally lath-shaped and, like the adjacent feldspars, they sometimes show flow alignment.

Rare pyroxene, sometimes showing alteration to chlorite and a brownish epidote, is present in a few of the coarser volcaniclastic rocks. Fig. 1f shows a well-cleaved augite phenocryst surrounded by the cryptocrystalline calcite of a calcareous nodule.

Rare detrital sphene and granules of yellow epidote have also been identified.

Pyroclastic fragments

Lapilli, glass shards and pumice commonly occur in the coarser greywackes, clearly indicating contemporaneous volcanic activity during sedimentation of the Cumberland Bay Forma-

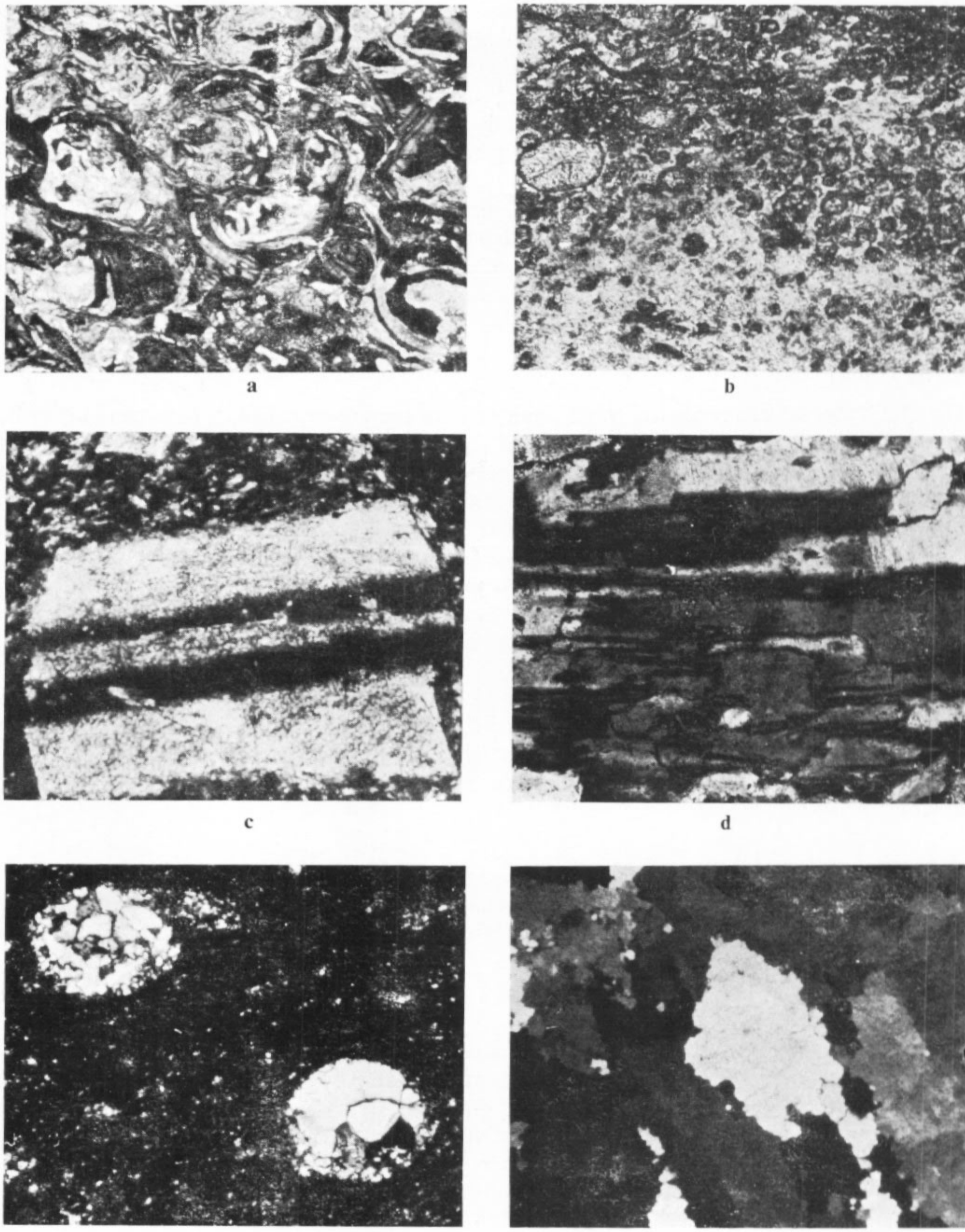

Fig. 2. a. Perlitic texture with alteration of devitrified volcanic glass to chlorite along concentric cooling cracks in one of the lapilli (M.1679.1; X-nicols; ×80).
b. Spherulitic clusters of chlorite infilling the gas vesicles of pumice fragments (M.1679.1; ordinary light; ×80).
c. Albitized plagioclase with broad diffuse twin lamellae (M.1679.1; X-nicols; ×80).
d. Albitization of plagioclase with replacement as discrete patches related to twin lamellae (M.1193.2; X-nicols; ×200).
e. Secondary quartz pseudomorphing Radiolaria (M.1191.2; X-nicols; ×200).
f. Sutured grain boundaries in vein quartz (M.1695.3; X-nicols; ×50).

tion. The shards, with concave facets and central vesicles, are scattered throughout the matrix which wraps around the fragments of pumice and volcanic glass. Rapid chilling of lapilli has resulted in the development of a perlitic texture, generally followed by devitrification and alteration to chlorite along concentric cooling cracks (Fig. 2a). Chlorite is also commonly found as spherulitic clusters (Fig. 2b) infilling the gas vesicles of pumice fragments.

Although Trendall (1953) described the Cumberland Bay Formation as "tuffaceous greywackes", thin-section analysis by Skidmore (1972) indicated a virtual absence of pyroclastic material and prompted him to describe these rocks as "volcanic greywackes". The present author has found abundant pyroclastic debris in the coarse greywackes of north-western South Georgia and so suggests that the term "volcaniclastic greywacke" be adopted.

Matrix

The matrix of the greywackes consists essentially of clay minerals and devitrified volcanic glass, altered to chlorite, sericite and a considerable amount of indeterminate material. Contained within this groundmass are fragments of volcanic rocks, broken feldspars and a variety of accessory minerals.

Secondary Minerals

The metamorphic products in the Cumberland Bay Formation are albite, quartz, calcite, chlorite, epidote, prehnite and a variety of opaque minerals. In thin section, the coarser volcanic greywackes show extensive mineralogical re-adjustments but, in the field, apart from the extensive development of prehnite, these rocks appear to be unaltered with their original sedimentary structures and textures preserved. In addition to the metamorphic minerals, the vein minerals such as quartz, calcite, prehnite, clinozoisite and axinite are present in various associations.

Albite

The plagioclases are cloudy with an undulose extinction and broad, diffuse twin lamellae indicating that albitization is widespread (Fig. 2c). Sometimes the original more calcic feldspars are partially replaced by albite as discrete patches, generally related to the twin planes but with "finger-like" terminations (Fig. 2d). Vein quartz with an undulose extinction is the host to clear subhedral albite with fine polysynthetic twinning and an extinction angle $\gamma:c=0–16°$ (Fig. 1d). This occurrence of secondary albite is unusual and indicates a marked excess of soda.

Quartz

Secondary quartz occurs in polycrystalline amygdales in the volcanic clasts and more commonly as pseudomorphs after Radiolaria (Fig. 2e). As a vein mineral, quartz is generally clear and the extinction is undulose, indicating pre- or syn-tectonic growth. It is occasionally biaxial positive with a very low 2V and occurs in association with calcite, prehnite, albite, axinite and clinozoisite. The grain boundaries are often highly sutured (Fig. 2f) indicating slight post-crystalline deformation (Spry, 1969). Comb structure is well developed in some narrow veins, with columnar quartz crystals nucleated at the fissure walls, whereas in a few of the wider veins a growth-mosaic sub-structure has been observed (Fig. 3a).

Calcite

Although the occurrence of calcite is common as a vein mineral, it is not a principal constituent of the Cumberland Bay Formation except in those beds where nodules have formed. It is occasionally found as well-formed crystals but more often as discrete interstitial flakes in

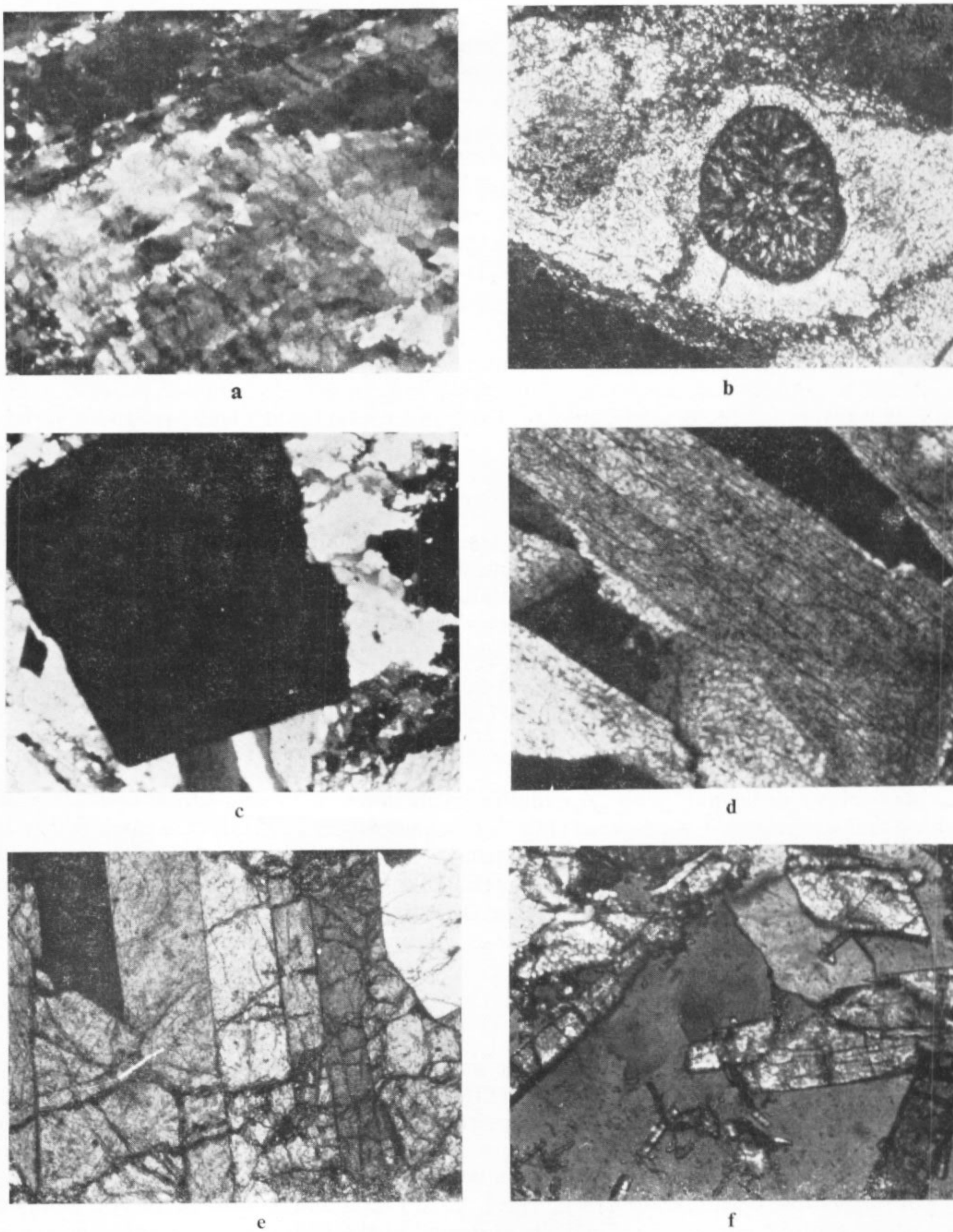

Fig. 3 a. Growth-mosaic sub-structure in vein quartz (M.1653.2; X-nicols; ×50).
b. Penninite amygdale in a prehnitized plagioclase phenocryst (M.1197.5; X-nicols; ×80).
c. Magnetite with characteristic square and rhombohedral sections in vein quartz (M.1112.5; ordinary light; ×80).
d. Massive columnar prehnite in association with vein quartz (M.1190.5; X-nicols; ×200).
e. Subhedral axinite in a quartz vein (M.981.1; X-nicols; ×80).
f. Colourless prismatic crystals of clinozoisite in association with vein quartz (M.1695.1; X-nicols; ×200).

the matrix. Secondary calcite has been identified as a replacement product of volcanic glass and albitized plagioclase.

The greatest concentration of calcite has taken place during diagenesis with nucleation around decaying organic material (Weeks, 1957). Fig. 1c shows a bivalve shell at the centre of a calcareous concretion; this represents the skeletal remains of an invertebrate which on decaying may have increased the pH of the immediately adjacent sediments sufficiently to precipitate calcite. Concretionary calcite is generally subhedral and modal analysis shows that it may form at least 50 per cent of a nodule.

Chlorite

As the main alteration product of volcanic glass, chlorite minerals constitute a large proportion of the matrix of the Cumberland Bay Formation. Pale green penninite, identified by its anomalous Berlin blue birefringence, is present as an amygdaloidal mineral in both prehnitized plagioclase phenocrysts (Fig. 3b) and fragments of pumice. Penninite is the principal constituent of the matrix of trachytic and felted volcanic clasts but it also occurs most abundantly along the margins of quartz veins.

Epidote

Authigenic epidote has developed in the matrix of the coarser greywackes as minute cryptocrystalline aggregates of pale yellow material. Where it is associated with magnetite, it occurs as randomly orientated orange-yellow fibrous growths.

Opaque minerals

Secondary ore minerals are commonly present in association with vein quartz or in the matrix of the coarse volcanic greywackes.

Magnetite sometimes occurs in unusually high concentrations in quartz veins as lustreless, black euhedral crystals with characteristic square and rhombohedral sections (Fig. 3c). Fossil wood replaced by magnetite is recognized in the hand specimen by a characteristic metallic blue sheen. In some cases, the development of secondary magnetite in the groundmass of trachytic and felted volcanic clasts has almost totally obscured the matrix.

Secondary haematite is rare but occasionally it forms a translucent red-brown veneer to joints or cavities as a product of recent surface weathering.

Authigenic pyrite, formed during diagenesis, is common in the finer lithologies as discrete needle-like laths lying parallel to the first cleavage and often crenulated by F2.

Anhedral ilmenite is distinguished from magnetite by its frequent alteration to creamy white leucoxene.

Prehnite

Prehnite, the most ubiquitous mineral in the Cumberland Bay Formation, has developed in a variety of forms, each reflecting a different mode of origin. The different forms of prehnite exhibit a characteristic birefringence which may be dependent on the amount of available calcium, either in the replaced plagioclase or in solution as a percolating hydrothermal fluid (Skidmore, 1972).

i. Prehnite pseudomorphs after albitized plagioclase are common in the coarse greywackes. The prehnite frequently develops parallel to twin or cleavage planes and generally exhibits upper first-order birefringence. In the argillaceous rocks, prehnite replaces the cryptocrystalline silica of Radiolaria, occasionally as a peripheral development leaving the central quartz intact.

ii. Massive columnar prehnite is found in association with vein quartz. The birefringence varies from first to low second order but it is uniform in any one section (Fig. 3d).

iii. Patchy areas of prehnitization, "spreading like a disease through the affected rock" (Tyrrell, 1930), are common in the finer-grained lithologies. The margins of the prehnitized areas are often indefinite and the birefringence is low second or first order. This type of prehnitization, identified by the spotted appearance of the hand specimen, is widespread in the pelitic divisions of the distal turbidites. Prehnitization also occurs in bleached aureoles surrounding discrete pelitic fragments. This diffuse development of prehnite, in association with calcite, lightens the colour of the surrounding greywacke producing a bleached appearance on weathered surfaces. Skidmore (1972) suggested that the presence of graphite or authigenic pyrite is indicative of an alkaline reducing environment within the pelitic fragment and he concluded that aureole development may take place by a similar process to the nucleation of calcite during nodule formation (Weeks, 1957).

Axinite

The sea cliffs on the south side of Sunset Fjord are cut by numerous quartz veins, one of which was found to contain a high proportion of a creamy pink mineral. Petrological and X-ray diffraction studies have shown that this is axinite.

The axinite, occurring in patches between quartz veinlets, is associated with clinozoisite and all three mineral phases appear to have crystallized simultaneously. The axinite is generally subhedral with acute-angled sections and first-order grey interference colours (Fig. 3e). It is slightly pleochroic and optically negative with a large 2V. The associated clinozoisite forms colourless prismatic grains of high relief and has anomalous blue-grey interference colours (Fig. 3f).

Axinite usually occurs in one of the following environments (Mason, 1958):

i. Contact metamorphic rocks.
ii. Cavities in granites.
iii. Hydrothermal veins.

Axinite ($(Ca\ Mn\ Fe)_3Al_2(B_3)SiO_4(OH)$) is rich in boron, which is generally derived from a magmatic source. Granitic intrusions have not been found cutting the Cumberland Bay Formation in north-western South Georgia but several are exposed at the south-eastern end of the island. If these intrusive bodies extend north-westward beneath the island, they could have been a possible source for the boron in the axinite. Alternatively, the chemical constituents of the axinite, including the boron, were possibly not derived from an undetected magmatic source, but were leached from the surrounding greywackes by circulating pore fluids. Mason (1958) has shown that, in an area of axinite-bearing quartz veins in New Zealand, the boron content of the country-rock greywackes ranges from 100 to 800 p.p.m., which is far higher than the average crustal abundance of boron (3 p.p.m.).

Metamorphic Grade

The abundance of prehnite and the marked absence of zeolites in the Cumberland Bay Formation of north-western South Georgia suggests that metamorphic recrystallization occurred at higher temperatures than diagenesis. The transition between the zeolite and the greenschist facies is marked by the formation of prehnite, pumpellyite, chlorite and albite in the absence of zeolite. Coombs (1960) named this transition stage the prehnite–pumpellyite metagreywacke facies. The prehnite–pumpellyite association has been reported in clastic rocks which have been buried to a minimum depth of about 3 km. (Otalora, 1964) and the quartz-prehnite-chlorite assemblage appears to be stable down to a depth of 16 km. (Hay, 1966). The depth range would be equivalent to a pressure of about 1–4 kbar. Skidmore (1972) suggested that the development of prehnite in the Cumberland Bay Formation was achieved by burial metamorphism to a depth of about 10 km. Recent experimental data (Liou, 1971) shows that the prehnite–pumpellyite facies is stable in the temperature range 250–380°C at pressures exceeding 2 kbar.

Contrasting with the widespread occurrence of prehnite, pumpellyite has not been found in the greywackes of north-western South Georgia and, apart from a single occurrence reported by Dalziel and others (1975), it has not been found elsewhere in the Cumberland Bay Formation. The almost total absence of pumpellyite may reflect the low-pressure conditions of metamorphism and/or the ratio of the partial pressures of CO_2 and H_2O. Surdam (1973) attributed the absence of pumpellyite in rocks of the Karmutsen Group, British Columbia, to an abundance of calcium carbonate, suggesting that the formation of epidote is preferential over pumpellyite in a high $\mu CO_2/\mu H_2O$ environment. The widespread occurrence of calcite in the Cumberland Bay Formation could therefore be responsible for the suppression of pumpellyite crystallization.

At low pressures of 1 kbar and less, Nitsch (1971) has shown that the chlorite-epidote-prehnite-quartz assemblage is stable in the temperature range 320–360°C but pumpellyite appears at higher pressures. This high-temperature low-pressure zone of the prehnite-pumpellyite facies has a relatively restricted stability field requiring a geothermal gradient in excess of 40°C/km. To explain the formation of a prehnite association without pumpellyite, Skidmore (1972) proposed a geothermal gradient of between 40° and 50°C/km. This unusually high rate of heat flow is typical of a marginal basin (Packham and Falvey, 1971), the depositional environment proposed by Dalziel and others (1975) for the sediments of the Cumberland Bay Formation. Skidmore (1972) also suggested that the Cumberland Bay Formation volcaniclastic sediments were not sufficiently basic to allow the development of pumpellyite which is generally described from more basic greywackes, basaltic flows or pillow lavas. It is therefore possible that all three factors may have contributed to some extent in limiting the development of pumpellyite in the Cumberland Bay Formation.

Although zeolites have been reported from the Annenkov Island Formation, possibly a lateral facies variant of the upper parts of the Cumberland Bay Formation (Pettigrew, 1981), they have not been found in the volcaniclastic sediments of north-western South Georgia. Transition through the zeolite facies into the quartz–prehnite field of the prehnite–pumpellyite facies was therefore only completed in the lower part of the succession. In a restricted stability field of the prehnite–pumpellyite facies, prehnite development took place throughout all lithologies in north-western South Georgia. The absence of pumpellyite in this association is attributed to a combination of low pressure and/or calcite-rich environment.

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