Prehnitization in the Yahgan Formation of Navarino Island, southernmost Chile

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Summary. Upper Mesozoic geosynclinal sedimentary rocks, mainly of volcanic (andesitic) derivation, show widespread prehnitization caused by very low grade metamorphism (burial metamorphism). The sediments, which include greywackes, argillites, cherty rocks, and occasional limestone concretions and thin beds, appear little altered in hand specimen and in the field despite the wide extent of recrystallization. Besides prehnite, secondary minerals include quartz, albite, chlorite, sericite, calcite, and sphene. The different modes of occurrence of the prehnite are described and briefly discussed. The alteration of the rocks is compared with similar widespread prehnitization recorded in probably correlative rocks on South Georgia.

The Yahgan Formation of southernmost Chile is a thick sequence of geosynclinal sediments exposed along the south-west and south margin of Tierra del Fuego and on some of the islands south of the Beagle Channel, notably Navarino Island (fig. 1). Much of it was described long ago by Charles Darwin (1846, pp. 151–156) as the 'clay-slate formation', while the present name Yahgan, constituting part of Darwin's original formation, was given by E. H. Kranck (1932). Its age is upper Mesozoic, and more probably Cretaceous; published information on it is summarized by R. Hoffstetter and G. Cecioni in the Chile volume of the International Stratigraphic Lexicon (1957, pp. 375–377). During the Royal Society Expedition to southern Chile in the 1958/59 season the author spent six weeks on Navarino Island with Dr. H. R. Katz of the Empresa Nacional del Petroleo (Magallanes). The present paper gives brief details of the alteration observed during petrographic study of the rocks collected during the field-work. More detailed stratigraphic and tectonic data are to be published separately (Katz and Watters).

Navarino Island covers about 900 square miles. Apart from superficial moraine and alluvium it consists mainly of folded sedimentary rocks of the Yahgan Formation, accompanied by penecontemporaneous altered basic igneous rocks and cut by several long conspicuous sills of partly-altered quartz dolerite. The Yahgan rocks are intruded by post-tectonic dioritic rock of the Andean Diorite Series. The distribution of the main formations is shown on the accompanying sketch-map (fig. 1).

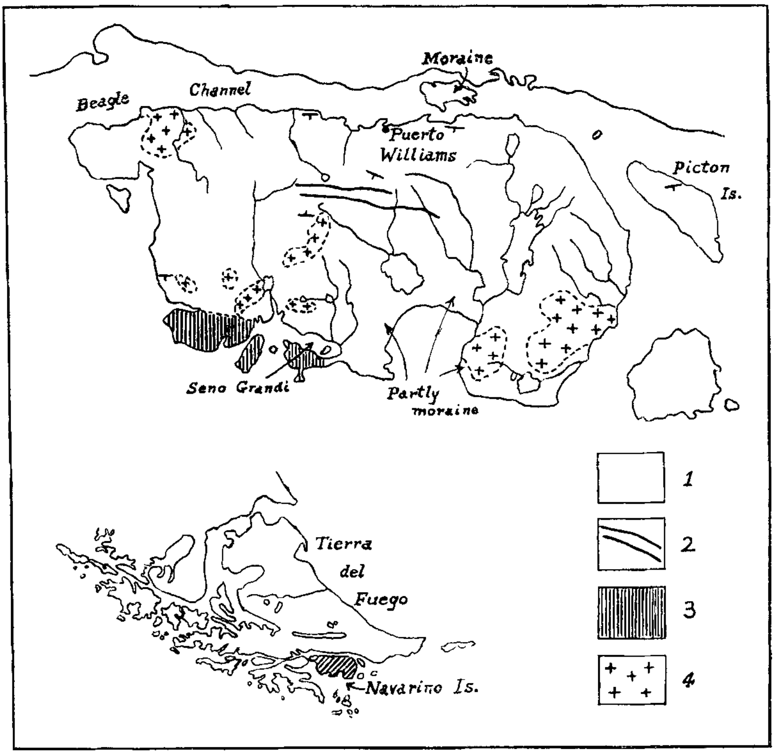

FIG. 1. Geological sketch-map of Navarino Island (scale 1:1,000,000). (1 = Yahgan Formation; 2 = quartz dolerite sills; 3 = altered basic igneous rocks penecontemporaneous with the Yahgan Formation; 4 = post-tectonic intrusive rocks (diorite, tonalite, monzonite) of the Andean Diorite Series.)

The principal rock-types are: volcanic greywacke; argillite, which in some places consists of alternating mudstone and siltstone beds; chert and cherty argillite; and comparatively rare limestone concretions and thin beds. Over the north part of the island the beds dip at moderate angles (up to 55°) to the south, but the succession is complicated by minor thrusting and asymmetric folding. The total thickness of the beds is unknown but is at least several thousand metres.

Lithology and petrography

(*a*) *Volcanic greywacke.* Typical volcanic greywacke (e.g. N2)[1] is a tough massive rock, grey to greenish-grey in hand specimen and averaging 0·5 to 1·0 mm in grain-size. In thin section the most abundant clastic mineral is plagioclase, accompanied by much smaller amounts of quartz, pale-greenish or almost colourless augite, and weakly pleochroic pale-green hornblende. Altered rock fragments rank with the clastic plagioclase in abundance and comprise volcanic rocks and generally much less abundant argillite; in a few rocks, however, small chips of argillite are much more widespread, and here and there the greywacke grades into intraformational breccia. Rarely (N60) small dioritic fragments made of plagioclase and pale-green hornblende are present.

The detrital plagioclase is uniformly albite (An_{0-6}), generally dusty in appearance or flecked with tiny sericite flakes. A few of the larger crystals contain irregular inclusions made up of very fine-grained pale chlorite; in appearance these crystals are similar to the plagioclase phenocrysts with glass inclusions present in some volcanic rocks. Much of the plagioclase is replaced by prehnite (see below), and there can be no doubt that this feldspar was formerly more calcic, and, from the composition of the rock (table I) and the nature of the volcanic rock fragments, probably approached andesine or even labradorite. In places, however, many detrital plagioclase grains show no trace of authigenic calcic minerals, and it is not known how many of these may be original detrital albite derived from rocks more acid or more sodic than the widespread andesitic fragments in the greywacke. Detrital augite and hornblende are mainly unaltered, although a few grains show minor replacement by sericite (N1, N60).

The volcanic rock grains are mainly fine-grained pilotaxitic types, here and there with well preserved idiomorphic augite phenocrysts. In some, excellent flow banding of tiny feldspar laths is present, while others have well preserved vesicles. In the more fine-grained types the groundmass may be replaced by finely divided pale chlorite. As far as could be seen none of the sedimentary rocks is tuffaceous in the strict sense, although the amount of volcanic debris in many of them is high.

Some variation in grain-size, degree of sorting, and in the relative proportions of the larger detrital fragments to the fine-grained matrix is present. In one place a thin band of light-coloured, coarse-grained rock

[1] Specimens are housed at the New Zealand Geological Survey, Lower Hutt, New Zealand. Duplicates are being sent to the British Museum of Natural History and to the Instituto de Geologia, Universidad de Chile, Santiago, Chile.

of arkosic appearance (N54) was found; this consists essentially of prehnitized plagioclase, quartz, minor hornblende, and a few ragged flakes of bleached biotite, and was probably derived from a tonalitic source.

TABLE I. Analyses of three sedimentary rocks from Navarino Island, with two others for comparison

	A	B	C	D	E
SiO_2	54·1	54·20	53·15	62·7	53·6
Al_2O_3	16·9	17·17	18·97	16·8	20·8
Fe_2O_3	1·4	3·48	1·59	0·65	0·75
FeO	6·85	5·49	8·09	3·75	3·95
MgO	5·0	4·36	2·85	1·35	2·05
CaO	5·70	7·92	3·83	5·60	11·55
Na_2O	3·70	3·67	4·64	1·75	0·25
K_2O	0·8	1·11	0·87	2·1	1·5
H_2O^+	3·76	0·86	4·30	2·96	4·08
H_2O^-	0·2	—	0·60	0·12	0·14
TiO_2	0·8	1·31	0·60	0·55	0·3
P_2O_5	0·13	0·28	0·27	0·08	0·05
MnO	0·17	0·15	0·21	0·12	0·37
CO_2	0·2	—	nil	0·52	$<$ 0·02
S	—	—	0·19	—	—
	99·71		100·16	99·05	99·41

A. Volcanic greywacke (N2), Navarino Island.
B. Average of 49 calc-alkali andesites (Nockolds, 1954).
C. Tuffaceous greywacke, Prince Olaf Harbour, South Georgia. Anal. W. H. and F. Herdsman (Tyrrell, 1930, p. 37).
D. Fine-grained greywacke (N74), Navarino Island.
E. Prehnitized fine-grained greywacke (N80), Navarino Island. (A, D, and E anal. by Mrs. M. Rundle, Dominion Laboratory, Lower Hutt, New Zealand.)

The analysis of a typical sample of the greywacke (N2) is set out in table I (A), together with the average analysis of forty-nine calc-alkali andesites given by Nockolds (1954) (B), and that of a tuffaceous greywacke from the Cumberland Bay Series of South Georgia (Tyrrell, 1930) (C).

(*b*) *Argillite.* In general the fine-grained rocks, though somewhat darker than the greywackes—partly because of the presence of very finely divided carbonaceous material—contain a higher proportion of detrital quartz, and the one rock analysed is appreciably higher in silica than the volcanic greywacke. Grain-size varies between mudstone and siltstone grades, which are both present in well-bedded rocks. As in the greywackes prehnitization is widespread and is further discussed below.

The analysis of a silty argillite (N74) is given in table I (D). In thin section this rock shows angular fragments, averaging about 0·1 mm, of quartz and considerably less abundant plagioclase set in a matrix containing much sericite, irregular areas of prehnite, and minor calcite. The banding visible on the hand specimen is due mainly to sub-parallel, somewhat wavy streaks of very fine-grained opaque (? carbonaceous) material.

(*c*) *Chert and cherty argillite.* These comprise tough light-coloured, very fine-grained siliceous rocks, well banded in places, with a thin weathered crust in various shades of white, grey, pinkish, and brown. Some detrital plagioclase can be seen optically, and the X-ray patterns also indicate appreciable amounts of feldspar.

Radiolarian skeletons, now replaced by secondary minerals (see below), are present not only in the finer-grained rocks (e.g. N53, N63, N65, N85) but also occasionally in a few of the more coarse-grained sediments (N35).

(*d*) *Limestone concretions.* A few limestone concretions or, rarely, thin limestone beds, as on the north coast of Picton Island (N87*a*), are found here and there. In some places the concretions are small, comparatively sharply bounded, spheroidal or lensoid bodies composed almost entirely of fine-grained calcite (N57, N76). Alternatively in several places volcanic greywacke grades into small irregularly bounded areas very similar to the surrounding rock in external appearance but with the normal clastic grains set in a calcareous cement (N3).

Besides prehnite (see below) secondary minerals are widespread, more particularly in the coarser-grained rocks: they are sericite, chlorite, and minor sphene, calcite and orthoclase. Identification of some of these is not always certain, but typical assemblages, together with quartz and albite, are:

quartz–prehnite–albite–chlorite–(sphene)
quartz–prehnite–albite–sericite–chlorite–(sphene, calcite)
quartz–prehnite–(sericite, calcite) [in veins]
quartz–(orthoclase)
quartz–(sericite) [replacing radiolaria]
prehnite *or* quartz–prehnite

Sericite forms aggregates of tiny flakes replacing feldspar, or, with prehnite and other secondary minerals, is scattered throughout the matrix, where it is abundant in some rocks.

Chlorite occurs as fine-grained pale-green or almost colourless flakes in the matrix of the rocks and replacing the groundmass of many volcanic rock fragments.

Several rocks (e.g. N1, N60, N62, N67, N82, N84) contain in addition to the above minerals numerous small irregular dark-greyish areas, either enclosed by plagioclase or scattered through the matrix. Many have a low patchy birefringence (d.r. up to 0·006) and undulose extinction, although others show no birefringence. At first they were thought to be finely granular iron-poor pumpellyite, but on examination of several crushed samples in oils the refractive index was found to be too low for pumpellyite and to be comparable with that of the adjacent prehnite. The writer considers that most of them are prehnite densely charged with minute opaque inclusions, possibly of carbonaceous material. Nevertheless a few tiny, highly refringent colourless grains in several of the rocks may be pumpellyite.

Prehnitization

This alteration has been observed over at least 60 square miles on Navarino Island (in the area south-west, south, and east of Puerto Williams) as well as on the north coast of Picton Island, and it is believed that further field-work would extend its known occurrence in this region. Prehnite is found in the following situations:

(*a*) Partial or almost complete replacement of detrital plagioclase (e.g. N2, N27, N54, N62, N67, N71, N77, N82). It forms shapeless or highly irregular skeletal areas (fig. 2A); here and there plagioclase grains are almost completely replaced by prehnite, which may extend across parts of the former feldspar boundary into the surrounding matrix. In general the partially replaced feldspar has uniform or near-uniform optic orientation, but in N27 one crystal is partly replaced by prehnite enclosing numerous small differently oriented crystals of albite (fig. 2C). The same rock contains a few feldspar crystals with small prehnite aggregates showing distinctive wedge-shaped forms (fig. 2B). Each of the small wedge-like portions is elongated negatively, and the whole aggregate shows undulose extinction and a highly irregular interference figure; the wedge-shaped parts are possibly comparable with the central portion of the composite crystal described by Dana (1904, p. 531). Another plagioclase crystal in the same rock contains—in addition to prehnite—a small area of calcite[1] showing the same distinctive wedge-like outline. The calcite here has probably replaced a prehnite aggregate similar to the one described above, although no textural evidence of pseudomorphing can be seen.

[1] Irregular areas of calcite replace plagioclase in a few rocks (e.g. N67) but it is quite subordinate to prehnite.

(*b*) Possible replacement of volcanic glass. In N35 a few small irregular areas with the typical shape of pumiceous or vitric fragments consist of prehnite and may result from replacement of volcanic glass.

(*c*) Replacement of radiolarian skeletons. In N33, N35, N53, N63, N65, and N85 radiolaria are still preserved, although in most of them no

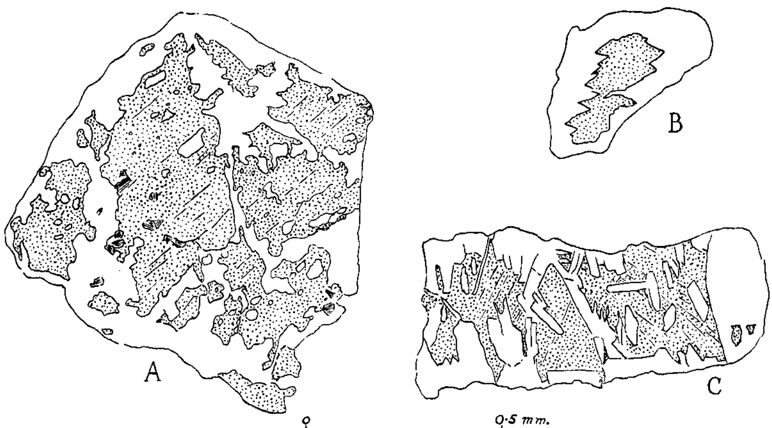

FIG. 2. Camera-lucida sketches of prehnite replacing plagioclase. A. The partially replaced feldspar has the same optic orientation throughout the crystal. Note minor sericite (N54). B. Aggregate of prehnite lamellae with wedge-shaped habit (N27). C. Original plagioclase partially replaced by prehnite with numerous small differently oriented crystals of albite (N27).

trace of the original skeletal structure can be seen, the tests now being shown in thin section by oval or circular areas composed of secondary minerals. Prehnite occasionally covers the whole area (e.g. N53) but in general it is accompanied by quartz. Many tests, however, are almost entirely made up of quartz, accompanied only by a little sericite (N53) or rarely dusty orthoclase (N85).

(*d*) Probably most widespread is the apparent replacement of the matrix by prehnite. This occurs mainly as shapeless crystals up to 5 mm across, many of which are riddled with tiny inclusions. Here and there radial aggregates of irregular prismatic crystals are seen, while in parts of N53 the prehnite forms long thin crystals with positive elongation (γ' 1·643) and prominent cross fractures.

In some rocks composed of alternating light-coloured silty beds and dark beds with much finely divided carbonaceous material the prehnite is mainly confined to the silty layers in which it forms up to half the total volume (e.g. N1, N62, N63, N64) and accentuates the colour difference between the beds. It is probable that differences in composition between the beds have favoured the crystallization of prehnite in the non-carbonaceous beds. The presence of sharply defined prehnite-rich layers up to 5 mm thick in otherwise prehnite-free rocks (N40, N46) is possibly due to selective replacement of thin beds originally rich in calcite. Coombs (1960) describes briefly the replacement of calcite by prehnite in some New Zealand greywackes, and although this has not been directly observed in the Navarino rocks the writer considers that it may have occurred locally.

The prehnitization is not generally apparent in hand specimen except for a few rocks (N80) where the prehnitized areas show on weathered surfaces as a whitish blotching (cf. Brown and Thayer, 1963, fig. 3, p. 418). The horizons unusually rich in prehnite point to a very considerable movement, especially of lime and alumina, during the alteration, even assuming some replacement of calcite. The analysis of a prehnitized fine-grained greywacke (N80) is given in table 1 (E): noteworthy is the very low value for Na_2O (0·25 %), suggesting that the rock may have formed from a bed originally rich in calcite or that much of the soda originally present in plagioclase has been expelled during the prehnitization.

The thin section shows numerous oval areas of dusty prehnite (β 1·625$\pm$0·003) up to 4 mm long. Many of these lie in sub-parallel alignment and are crossed by occasional thin veins composed mainly of quartz but carrying also a little prehnite. The only other recognizable minerals are small irregular grains of quartz and numerous tiny sericite flakes.

(*e*) The few veins observed in the rocks (e.g. N1, N66, N80) are formed mainly of quartz and prehnite. In N66 prehnite (α 1·613, β 1·622, γ 1·643, all $\pm$0·003) in fine prismatic crystals up to 1·5 mm long shows excellent intergrowth textures with quartz. They are accompanied by minor calcite and sericite; the latter is especially abundant throughout the enclosing greywacke, particularly as tiny sheaves replacing plagioclase.

(*f*) Finally, an unusual occurrence in N34 may be briefly mentioned. The thin section of this rock, a coarse-grained greywacke, contains a single fragment, 2 mm across, of a brown isotropic material with n 1·630 ($\pm$0·003). This contains numerous prismatic crystals of prehnite: some of the smaller prisms form a rectangular network, while others stand in parallel alignment at right angles to an indistinct prehnite-filled veinlet at one side of the fragment. The texture suggests possible replacement by prehnite of the brown material. The latter, which was first regarded by the writer as volcanic glass, has not been identified, although the possibility of its being collophane was suggested by Professor D. S. Coombs (personal communication).

Discussion

1. *Origin*

(*a*) *Metamorphism and metasomatism directly connected with igneous intrusion.* As far as is known the alteration described above is not directly related to igneous activity. Metasomatism connected with the injection of the doleritic sills and with the intrusion of the post-tectonic dioritic rocks appears to be limited to the following:

(i) Induration of fine-grained cherty and cherty-argillitic rocks near the sill contacts, with possible metasomatic introduction of soda and titanium, leading to the crystallization of albite and sphene. Probably related to this contact action is the formation of more or less spherical quartzo-feldspathic bodies up to 6 cm across in sedimentary rock near one of the doleritic sill contacts (Katz and Watters). These bodies, which are formed mainly of quartz, feldspar, and pale chlorite, are interpreted as metasomatites: the presence in them of minute grains of sphene concentrated in irregular streaks and of rare allanite suggests that some material may have been added to them during the intrusion of the nearby sill.

(ii) Contact effects, noticeable around some of the dioritic intrusions. In the field a pronounced reddening of the sedimentary rocks up to 100 metres from the intrusive contacts was noted in several places. Conspicuous pyrite veining of cherts at Seno Grandi, on the south side of the island, is probably related to the intrusion of adjacent tonalitic and monzonitic rocks (Kranck, 1932, pp. 169–175; Katz and Watters). At this locality the rocks are cut by a network of thin veins containing much pyrite and smaller amounts of quartz, epidote, hornblende, and chlorite.

(*b*) *Very low-grade regional metamorphism.* The available petrographic and chemical data suggest that much of the Yahgan Formation was derived from a basic to intermediate volcanic source, although rocks such as tonalite and diorite contributed in small amount. Most of the volcanic rock appears to be andesitic, but it is likely that some spilitic and trachytic debris is also present. In this connexion Tyrrell (1930, pp. 35–38) shows that the sedimentary rocks examined by him from probably correlative beds on South Georgia (see also table I, C) are composed of a mixture of keratophyric and spilitic debris.

The Yahgan Formation is comparable with other thick piles of geosynclinal sediments, of various ages, known from many parts of the circum-Pacific belt (e.g. Crook, 1960; Dickinson, 1962; Brown and Thayer, 1963). The widespread mineralogical alteration found within these sequences may be found to be closely related to depth of burial (see especially Coombs, 1954). At Navarino the top and bottom of the Yahgan sequence was not observed, and moreover the beds are somewhat folded and thrusted, so that no relationship of the mineralogical alteration found to stratigraphic position can be seen (cf. Brown and Thayer, 1963). There can be no doubt, however, that the alteration is due primarily to deep burial of the sediments before the main onset of folding. As in the other regions where such very low grade metamorphism (burial metamorphism of Coombs, 1961) has been reported the mineralogical alteration is accompanied by little change in the fabric of the rocks.

In the widespread development of prehnite the Navarino rocks are comparable with those described by Coombs (in Coombs *et al.*, pp. 65–67) from the so-called 'Alpine Facies' (mainly lower Mesozoic) of New Zealand. Here prehnite is developed on a regional scale in greywackes of predominantly acid composition, with SiO_2 averaging about 70 % (from analyses given by Reed, 1957). Some textural features noted by Coombs occur in the Navarino rocks, but the quartz–prehnite veining so widespread in the New Zealand greywackes is rare in the Yahgan Formation.

2. *Regional comparison*

The probable continuation of the fold-mountain belt of the Andes through the islands of the Scotia Arc (Southern Antilles) to the Antarctic Peninsula has long been suggested. Possible correlations were discussed by Wilckens (1933), while more recently comparisons have been given by Matthews (1959). Correlation of the Yahgan Formation with the Cumberland Bay Series of South Georgia, some 900 miles east of Navarino Island, is now reasonably well established on the basis of similar age and lithology, and from the descriptions given by Trendall (1953, 1959) there seems little doubt that the Yahgan Formation correlates closely with rocks of the Cumberland Bay Series. Tyrrell (1930), Barth and Holmsen (1939), and Trendall (1953, 1959) have all referred to widespread prehnitization of the Cumberland Bay Series. For example, Tyrrell (*loc cit.*, p. 38) writes: 'The prehnitization spreads like a disease through the affected rocks, and some of the specimens, as for example those from Prince Olaf Harbour, are practically prehnite-rocks. A curious feature about the replacement is that it has taken place without the slightest disturbance of the structures of the affected rocks.' This evidently refers to the same thoroughgoing replacement of the matrix of the rocks observed on Navarino Island. More details of the development of prehnite at South Georgia are given by Trendall (1959, pp. 12–14).

The prehnitization present at Navarino Island is thus matched by comparable alteration reported from South Georgia, and it seems likely that this very low grade metamorphism extends on a regional scale over this segment of the circum-Pacific fold-mountain belt.

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