

THE SCOTIA METAMORPHIC COMPLEX AT CAPE BOWLES, CLARENCE ISLAND, SOUTH SHETLAND ISLANDS, WESTERN ANTARCTICA

F. HERVÉ

*Departamento de Geología, Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile,
Casilla 13512 - Correo 21, Santiago, Chile*

and

R. J. PANKHURST

*British Antarctic Survey, Natural Environment Research Council, High Cross,
Madingley Road, Cambridge CB30ET, UK*

ABSTRACT. Phyllite and schist samples from Cape Bowles, Clarence Island, have a relatively simple structure related to F_2 isoclinal folding with an axial S_2 cleavage. Greenschist facies metamorphic mineralogy was developed during or shortly after production of S_1 ; some mineral analyses are reported. Relict mineralogy and total rock chemistry suggest a pre-metamorphic lithology of arenaceous sediments derived from an acid igneous terrane. Rb/Sr geochronological data show that metamorphism occurred during the same late Cretaceous (70–100 Ma) event recorded elsewhere in the Scotia metamorphic complex and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are consistent with a Mesozoic rather than Precambrian source area.

INTRODUCTION

The Elephant Island group, to which Clarence Island belongs, constitutes the north-eastern extremity of the South Shetland Islands (Fig. 1), and is composed mainly of metamorphic rocks of the Scotia metamorphic complex (Tanner and others, 1982).

Two rock series of different characteristics have been distinguished in the Elephant Island group (Fig. 2): lower grade blueschist-to-greenschist facies rocks occupy the whole of Clarence Island and the northern part of Elephant Island, whereas albite-epidote-amphibolite facies rocks crop out on south-western Elephant Island (Dalziel, 1982; Tanner and others, 1982, fig. 2). The age of the metamorphic complex is still a matter of discussion (Tanner and others, 1982), and the petrographical and mineralogical characteristics of the rocks are not known in detail.

A brief landing at Cape Bowles (Fig. 1) during the XXXV Chilean Antarctic Expedition allowed structural observations and sampling of a small area around the cape. The purpose of this paper is to present structural, petrological, geochemical and geochronological data on the metamorphic rocks at Cape Bowles, which may add to the understanding of the Scotia metamorphic complex. Brief comparison is made with other parts of the metamorphic complex, including new petrographical and mineralogical data from Cape Lookout, Elephant Island.

STRUCTURE

Cape Bowles ($61^\circ 19' \text{ S}$, $54^\circ 06' \text{ W}$) is an outcrop of grey and black phyllites and schists, with conspicuous folded quartz bands and veins.

The structure is dominated by a subhorizontal main crenulation cleavage S_2 , also apparent along the entire east coast of the island. S_2 is axial planar to

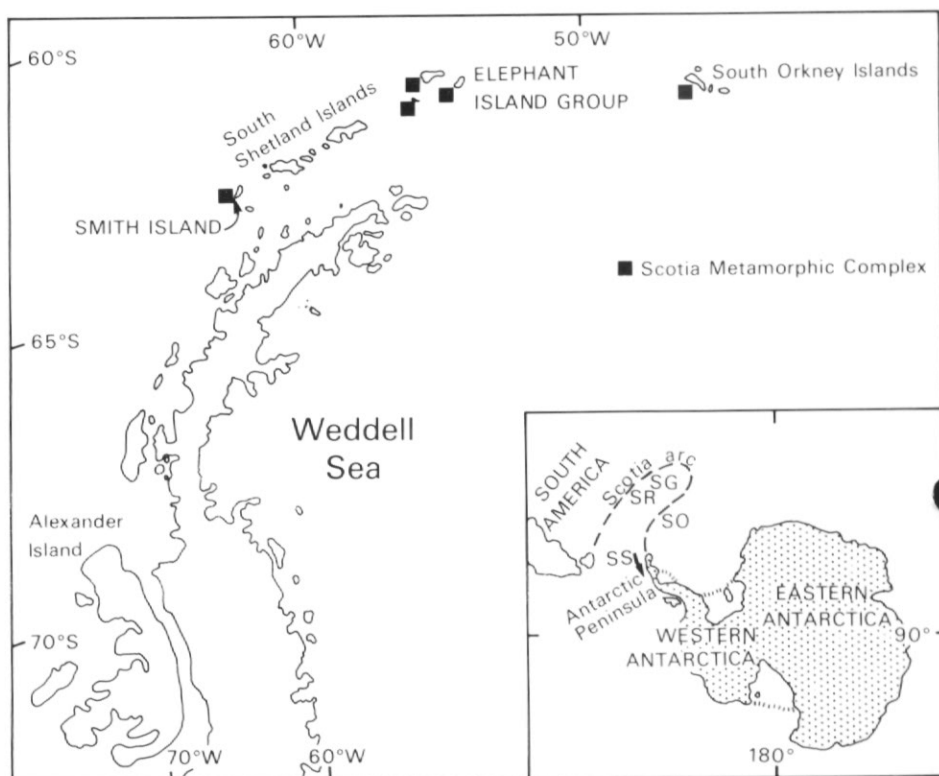


Fig. 1. Sketch map showing the location of the Elephant and Smith Island groups (South Shetland islands) relative to South America and the Antarctic Peninsula (after Tanner and others, 1982). SR = Shag Rocks; SG = South Georgia; SO = South Orkney Islands; SS = South Shetland Islands.

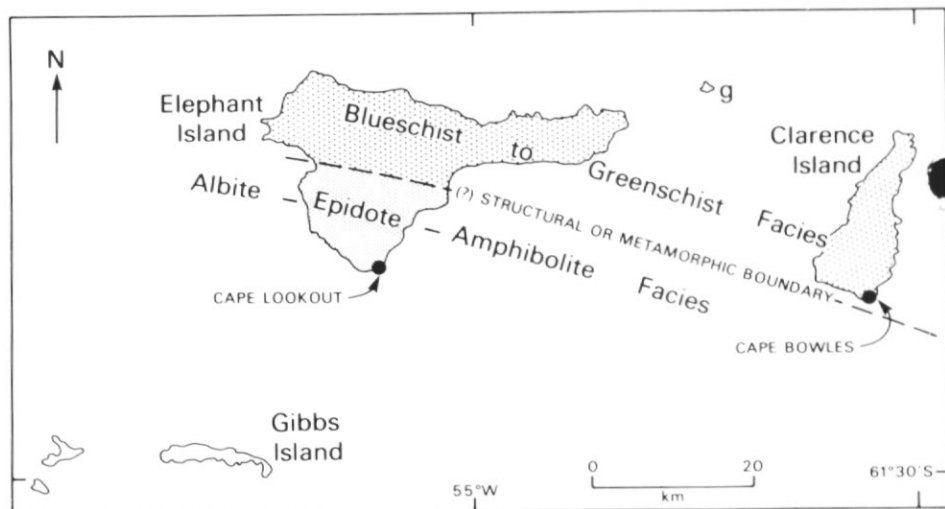


Fig. 2. Sketch map of the Elephant Island group showing sample localities and the distribution of metamorphic facies (after Tanner and others, 1982).

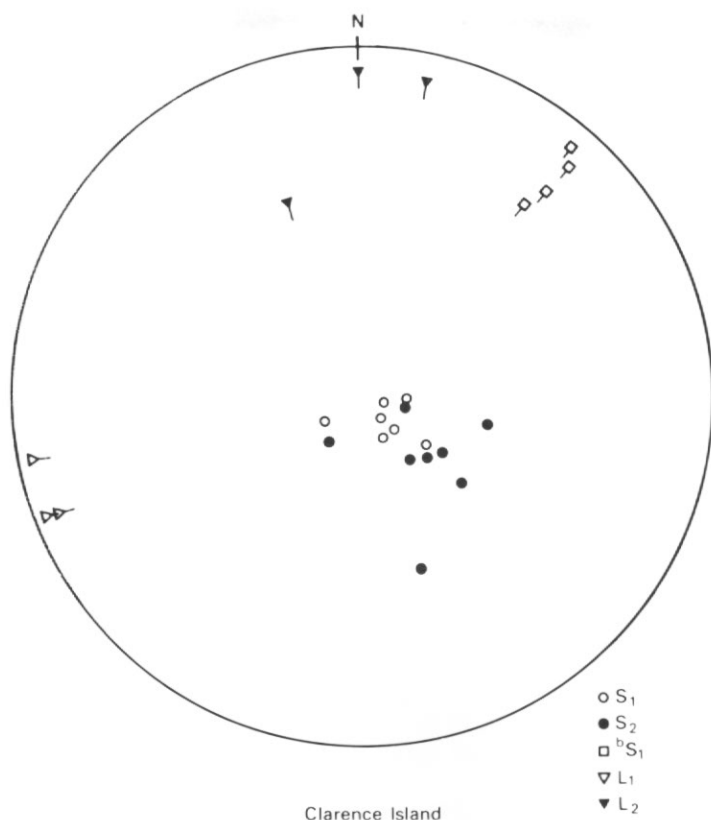


Fig. 3. Stereographic plot (Schmidt, lower hemisphere) of structural measurements at Cape Bowles, Clarence Island: S₁ = poles to first foliation; S₂ = poles to crenulation cleavage; ^bS₁ = F₂ fold hinges of S₁ fabric; L₁ and L₂ are observed lineations in S₂ surfaces.

tight-to-isoclinal F₂ folds of S₁ which have amplitudes of the order of 0.1–1 m. The S₁ fabric, which is only preserved in the microlithons between S₂ cleavage planes, is defined by mineral banding and rough alignment of platy minerals. Near sea level S₂ is present macroscopically as discrete surfaces 5–10 cm apart, and is more penetrative in the higher levels (up to 50 m above sea level) where tight chevron folds of S₁ are observed. F₂ fold hinges of S₁ surfaces have a north-east trend and gentle north-east plunge (Fig. 3). An early west-north-west subhorizontal lineation (L₁) and a later north-south one (L₂) were observed on the S₂ planes, but their geometry does not relate to F₂ fold hinges so that they may indicate a further, unidentified, phase of deformation. Since, in this outcrop, S₂ dips more steeply than S₁, the observed structural features may be interpreted as representing the upper limb of a tight-to-isoclinal antiformal structure of unknown dimensions.

LITHOLOGY

The rocks are a sequence of monotonous grey, fine-grained phyllites with only a few bands of spotted albite schists and some black phyllite. No traces of original bedding were identified in the field.

The grey phyllites consist of quartz- and albite-rich S_1 bands interlayered with discontinuous white mica-bearing layers with an S_1 fabric, which are folded in the microlithons generated by S_2 . Epidote grains with epitaxial outgrowths are always present, as well as minor amounts of chlorite, calcite, sphene and apatite. Quartz and albite predominate (60%); some albite is present as pre- S_2 microporphyroblasts with well-developed twinning, which extends from a cloudy core to a limpid rim. Except for some pale green amphibole automorphs and perhaps the epitaxial clinozoisite outgrowths on epidote, the bulk of the minerals appear to have crystallized prior to the development of the S_2 crenulation cleavage, represented by discrete planes with dusty opaque mineral concentrations 1–2 mm apart.

Some grey-green phyllites contain no white mica, but have abundant actinolite needles apparently replacing chlorite in thin layers. Epidote-rich bands and opaque-mineral-rich laminae are folded into isoclinal folds, whereas stilpnomelane crystals appear randomly in the quartz-rich bands. The black phyllites consist of graphite(?) rich micaceous laminae alternating with coarser chlorite-apatite-rich bands. However, none of these rocks contains glaucophane or lawsonite, which characterize the blueschists of Smith Island (Fig. 1), at the south-western extremity of the South Shetland Islands (Smellie and Clarkson 1975; Rivano and Cortes 1975, 1979; Hervé and others, 1983).

Coarser grains of quartz and albite, especially those albite crystals whose cores have randomly orientated sericite flakes, may be considered to be relict detrital grains. The grey phyllites are thus believed to be metamorphosed quartz-rich arkosic sediments, an interpretation that is consistent with the chemical characteristics shown below. They appear to have a very different provenance to the metamorphically comparable rocks of Smith Island which are derived from oceanic igneous and sedimentary assemblages.

GEOCHEMISTRY

The available chemical data on rocks from Cape Bowles are presented in Table I.

These rocks have a rather uniform chemical composition, which differs from 'average' metapelitic rocks in having lower Al_2O_3 and FeO^* contents, and a K_2O/Na_2O ratio less than 1. The trace element analyses are few, but also differ from 'typical' pelites.

Probably, the protolith of the metamorphic rocks of Cape Bowles was an arenaceous sequence derived from a granitic or acid volcanic source terrane, as is suggested by the chemical similarity of these rocks with the representative average analyses of Tobifera acid volcanics or the more acid facies of the Patagonian batholith (Bruhn and others, 1978).

MINERALOGY (MINERAL CHEMISTRY)

Electron probe analyses of minerals from the metamorphic rocks of Clarence Island are shown in Table II.

The albite is unzoned and almost pure, with minor contents of K_2O and negligible amounts of CaO . Epidote is fairly Fe-rich (average 8.5% FeO^*) in the pleochroic varieties, and was followed in time by uncoloured clinozoisite, presumed to be poor in Fe (which was not determined). The MnO content is significant in some of the analysed grains. The white mica is celadonite-rich and fairly homogeneous in all the samples; no Na-rich varieties were detected. Chlorites are Fe-rich (average 29% FeO^*) with anomalous blue interference colours.

Table I. Chemical analyses by XRF at Liverpool University

	Cape Bowles							Tobifera (1)	Patagonian Batholith (2)	Low grade metapelites (3)
	CL2	CL3	CL4	CL5	CL6	CL8	CL12			
SiO ₂	62.91	74.91	73.73	76.98	73.21	73.45	76.66	77.40	73.22	59.93
Al ₂ O ₃	16.36	12.55	12.83	11.84	13.36	12.81	11.83	12.13	13.43	16.62
FeO*	7.24	2.99	3.53	2.80	3.36	3.57	2.46	1.37	2.23	6.21
MgO	2.84	1.21	1.48	1.11	1.38	1.31	0.90	1.12	0.44	2.63
CaO	2.28	2.11	1.99	1.54	1.89	2.28	1.75	0.67	2.07	2.18
Na ₂ O	2.80	2.82	2.65	2.60	3.01	2.71	3.57	2.69	3.75	1.73
K ₂ O	2.66	2.19	2.34	2.11	2.32	2.40	1.72	3.53	3.38	3.54
TiO ₂	0.63	0.36	0.41	0.39	0.41	0.41	0.37	0.13	0.24	0.85
MnO	0.08	0.05	0.05	0.03	0.05	0.05	0.03	0.03	0.06	-
P ₂ O ₅	0.33	0.09	0.11	0.09	0.12	0.13	0.17	0.03	0.06	-
Total	98.13	99.28	99.13	99.49	99.11	99.12	99.46	99.10	98.88	
K ₂ O/Na ₂ O	0.95	0.78	0.88	0.81	0.77	0.89	0.48	1.31	0.90	2.05
Ce	33		37			39	35			
Co	13		13			11	6			
La	22		22			20	16			
Nd	20		23			24	23			
Ni	9		11			10	8			
Rb	80	66	69	61	69	76	55	117	123	
Sr	372	356	288	229	277	281	290	126	193	
V	114					65	51			
Y	25					22	21			
Zr	133		197			197	199	159	146	
K/Rb	276	275	281	287	279	262	260	250	229	

(1), (2) Bruhn and others (1978).

(3) Shaw (1956).

FeO* = total iron as FeO.

Table II. Chemical composition of minerals from Cape Bowles, Clarence Island

<i>WHITE MICA</i>				
	<i>CL3</i>	<i>CL6</i>	<i>CL9</i>	<i>CL13</i>
Na ₂ O	—	—	—	—
MgO	4.40	3.71	3.79	3.69
Al ₂ O ₃	25.94	27.59	25.95	27.69
SiO ₂	48.09	48.77	49.03	49.05
K ₂ O	10.13	10.99	11.07	10.81
FeO*	6.10	4.58	4.34	3.85
CaO	—	0.29	0.10	0.12
TiO ₂	—	0.20	—	0.12
Total	94.66	96.13	94.28	95.33
<i>EPIDOTE</i>				
	<i>CL4</i>	<i>CL9</i>	<i>CL13</i>	
Al ₂ O ₃	26.35	25.75	27.48	
SiO ₂	40.35	37.93	39.54	
CaO	21.28	23.15	23.22	
TiO ₂	tr	1.73	—	
FeO*	8.49	7.64	9.20	
MnO	0.91	0.64	0.12	
Total	97.38	96.84	99.56	
<i>CHLORITE</i>				
	<i>CL6</i>	<i>CL13</i>		
Al ₂ O ₃	22.71	22.11		
SiO ₂	26.92	27.73		
CaO	11.91	13.28		
TiO ₂	—	0.06		
FeO*	29.89	29.92		
MnO	0.69	0.54		
Total	92.12	93.64		
<i>ALBITE</i>				
	<i>CL4</i>	<i>CL6</i>	<i>CL9</i>	<i>CL13</i>
Na ₂ O	11.78	11.65	11.37	10.67
Al ₂ O ₃	19.36	18.67	18.77	20.63
SiO ₂	69.56	69.33	68.32	68.18
K ₂ O	0.07	0.06	0.63	0.95
CaO	0.02	0.01	—	—
FeO*	—	—	0.46	0.73
Total	100.79	99.72	99.55	101.16

All the rocks are grey phyllites as described in the lithology section.
FeO* = total iron as FeO.

The mineralogy contrasts sharply with that of the amphibolite facies metamorphic rocks of Cape Lookout, Elephant Island (Fig. 2), where coarse-grained garnet amphibolites, grey-spotted mica-schists and impure marbles have been described (Araya and Hervé, 1965). Those rocks contain zoned plagioclase porphyroblasts with An₃₀ centres and An₅ rims (Table III), almandine garnet, biotite, Mg-rich

Table III. Chemical composition of minerals from Cape Lookout, Elephant Island

	<i>Garnet</i>		<i>Plagioclase</i>	
	<i>E5</i>	<i>E10</i>	<i>E5</i>	
	<i>Av. of 4</i>	<i>Av. of 2</i>	<i>Centre</i>	<i>Rim</i>
Na ₂ O	—	—	9.77	11.56
MgO	1.44	0.91	—	—
Al ₂ O ₃	21.62	22.06	21.22	19.23
SiO ₂	38.69	38.49	64.68	68.58
CaO	9.92	7.79	3.03	0.52
TiO ₂	0.13	—	—	—
K ₂ O	—	—	0.08	0.08
MnO	0.72	7.20	—	—
FeO*	28.47	25.71	—	—
Total	100.99	102.16	98.78	99.97

	<i>Epidote</i>	<i>Biotite</i>	<i>Chlorite</i>	<i>Amphibole</i>
	<i>E2</i>	<i>E2</i>	<i>E5</i>	<i>E10</i>
				<i>Av. of 2</i>
Na ₂ O	—	—	—	2.01
MgO	—	14.20	16.28	8.19
Al ₂ O ₃	20.67	14.20	22.97	12.46
SiO ₂	36.71	38.99	27.41	43.05
CaO	24.01	—	0.01	10.32
TiO ₂	—	—	—	0.51
K ₂ O	—	10.23	—	0.64
MnO	0.24	0.71	—	0.40
FeO*	15.10	17.50	22.32	20.60
Total	96.73	95.83	88.99	98.18

chlorite, edenitic hornblende, Mg- and Fe-bearing calcium carbonate, pyrite, titanomagnetite and Fe-rich epidote. This contrast is in accordance with the distribution of metamorphic grade in the rocks of the Elephant Island group as shown in Fig. 2.

GEOCHRONOLOGY

A selection of the samples from Cape Bowles was analysed by the Rb–Sr whole-rock method at the Institute of Geological Sciences, London, using identical techniques to those employed by Tanner and others, 1982. The results are listed in Table IV and plotted in an isochron diagram (Fig. 4). As a whole, the data form a scattered group with one point (CL7) having a much higher Rb/Sr ratio than the rest. If two of the samples with the lowest Rb/Sr ratios (CL10 and CL12) are ignored, the remainder lie on a reasonable errorchron (MSWD = 8.4). The scatter may be assigned to initial ⁸⁷Sr/⁸⁶Sr heterogeneity inherited from the provenance area and not completely homogenized during greenschist facies metamorphism. If the scatter about the errorchron is taken into account, an estimated age of 71 ± 40 Ma is obtained. This clearly corresponds with the late Cretaceous metamorphism known from a Rb–Sr whole-rock isochron of 75 ± 16 Ma and mineral ages of up to 100 Ma for the blueschist–greenschist facies rocks of northern Elephant Island and Smith Island (Tanner and others, 1982, and references therein). This Rb–Sr isochron is also indicated in Fig. 4, where it is clear that it has a much lower initial ⁸⁷Sr/⁸⁶Sr ratio (0.704) than the Clarence Island errorchron (0.709). The former low value was used

Table IV. Rb–Sr data for rocks from Cape Bowles, Clarence Island

Sample No.	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$
CL2	79	353	0.642	0.70980
CL3	66	342	0.561	0.71000
CL4	69	275	0.723	0.70999
CL5	62	230	0.784	0.71012
CL6	72	285	0.734	0.71041
CL7	207	412	1.458	0.71084
CL8	72	265	0.787	0.71042
CL10	41	220	0.533	0.70868
CL12	54	274	0.566	0.71116

Rb and Sr determined by X-ray fluorescence spectrometry (Rb/Sr ratio $\pm 0.5\%$).
 $^{87}\text{Sr}/^{86}\text{Sr}$ determined on VG Micromass 30 mass spectrometer to $\pm 0.01\%$.
 $\text{Rb} = 1.42 \times 10^{-11} \text{ a}^{-1}$.

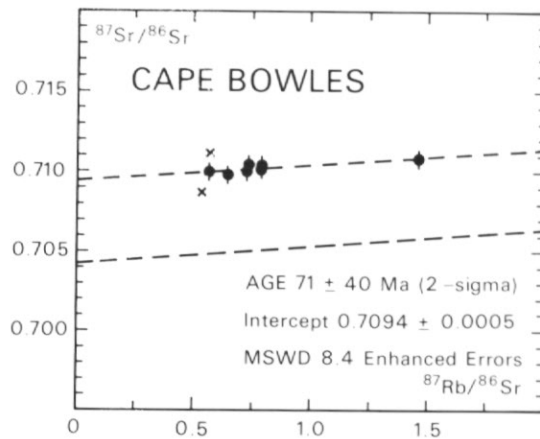


Fig. 4. Rb–Sr isochron plot for Cape Bowles samples. The upper line is a best-fit errorchron through seven of the nine data points. The lower line is the 75 Ma isochron for blueschist–greenschist facies rocks from northern Elephant Island (Tanner and others, 1982).

by Tanner and others (1982) to constrain a limited crustal residence time (50–100 Ma at the most) for the protolith of these rocks, an argument which clearly cannot be extended to the Cape Bowles samples. However, although individual samples have model ages (assuming a minimum initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.704) of 300–800 Ma, the data are also consistent with the hypothesis suggested above that these rocks were sediments derived from a (?) Jurassic acid igneous terrane. On the Antarctic Peninsula, acid volcanic rocks have initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios ranging from 0.704 up to 0.710 (Hamer, 1983). The deposition of the sediments could have occurred at any time between the age of the provenance area and the late Cretaceous metamorphism. On this basis, there are no grounds for requiring the involvement of pre-Mesozoic material in the blueschist–greenschist terrane of the Scotia metamorphic complex, although the protolith of the amphibolite facies terrane could be as old as Permian (Rex, 1976; Tanner and others, 1982).

CONCLUSIONS

The metamorphic rocks at Cape Bowles are possibly derived from an arkosic sedimentary pile of early Mesozoic age, as suggested by their major element geochemistry and initial Sr isotopic characteristics.

They have experienced a polyphase deformation in which a flat lying crenulation cleavage S_2 related to isoclinal folds was produced with little recrystallization of the S_1 fabric and mineralogy.

The very low grade (in the sense of Winkler, 1976) mineral assemblage developed during S_1 (quartz–albite–phengite–chlorite–Fe-rich epidote \pm stilpnomelane) was partially replaced by clinozoisite–actinolite-bearing low grade assemblages during or slightly after the generation of S_2 . There are no typical 'high P' mineral phases such as are found in other outcrop areas of the Scotia metamorphic complex.

The geochronological data suggest that, as elsewhere in the Scotia metamorphic complex, this metamorphic event was of late Cretaceous age.

ACKNOWLEDGEMENTS

Instituto Antártico Chileno (INACH) supported the field work which was carried out by F. H. with J. Davidson and C. Mpodozis. Grants from the J. S. Guggenheim Foundation and the Royal Society of London allowed F. Hervé to work on the electron probe analysis of minerals at the Geology Department, Colorado University, USA, the XRF whole rock chemistry at the Geology Department, University of Liverpool, and the Rb–Sr geochronology at IGS, London.

Professor Charles Stern (Colorado), Dr Michael P. Atherton and D. Stewart (Liverpool) helped and guided the analytical work. Dr Bryan Storey made useful suggestions.

Received 5 August 1983; accepted 6 October 1983

REFERENCES

- ARAYA, R. and HERVÉ, F. 1965. Studio geomorfológico y geológico en las Islas Shetland del Sur, Antártica. *Publicaciones del Instituto Antártico Chileno*, No. 8, 76 pp.
- BRUHN, B. L., STERN, C. R. and DE WIT, M. J. 1978. Field and geochemical data bearing on the development of a Mesozoic volcano-tectonic rift zone and back-arc basin in southernmost South America. *Earth and Planetary Science Letters*, **41**, 32–46.
- DALZIEL, I. W. D. 1982. The early (pre-Middle Jurassic) history of the Scotia Arc region: a review and progress report. (In CRADDOCK, C., ed. *Antarctic geoscience*. Madison, University of Wisconsin Press, 111–26.)
- HAMER, R. D. 1983. Petrogenetic aspects of the Jurassic-early Cretaceous volcanism, northernmost Antarctic Peninsula. (In OLIVER, R. L., JAGO, J. B. and JAMES, P. R. eds. *Antarctic earth science*, Cambridge University Press and Canberra, Australian Academy of Science, 338–42.)
- HERVÉ, F., GODOY, E., and DAVIDSON, J. 1983. Relic clinopyroxenes from blueschists of Smith Island, South Shetland Islands: their composition, origin and some tectonic implications. (In OLIVER, R. L., JAGO, J. B. and JAMES, P. R. eds. *Antarctic earth science*. Cambridge University Press and Canberra, Australian Academy of Science, 363–6.)
- REX, D. C. 1976. Geochronology in relation to the stratigraphy of the Antarctic Peninsula. *British Antarctic Survey Bulletin*, No. 43, 49–58.
- RIVANO, S. and CORTES, R. 1975. Nota preliminar sobre el hallazgo de rocas metamórficas en la Isla Smith (Shetland del Sur, Antártica). *Serie Científica del Instituto Antártico Chileno*, **3**, No. 1, 9–14.
- RIVANO, S. and CORTES, R. 1976. Note on the presence of the lawsonite–sodic amphibole association on Smith Island, South Shetland Islands, Antarctica. *Earth and Planetary Science Letters*, **29**, 34–6.

- SHAW, D. M. 1956. Geochemistry of pelitic rocks. Part III. Major elements and general geochemistry. *Bulletin of the Geological Society of America*, **67**, 919-34.
- SMELLIE, J. L. and CLARKSON, P. D. 1975. Evidence for pre-Jurassic subduction in western Antarctica. *Nature, London*, **258**, 701-2.
- TANNER, P. W. G., PANKHURST, R. J. and HYDEN, G. 1982. Radiometric evidence for the age of the subduction complex in the South Orkney Islands and South Shetland Islands, West Antarctica. *Journal of the Geological Society of London*, **139**, 683-90.