Journal of the Geological Society, London, Vol. **146**, 1989, pp. 207–210, 4 figs, 3 tables. Printed in Northern Ireland

Short paper: The significance of mid-Palaeozoic basement in Graham Land, Antarctic Peninsula

A. J. MILNE & I. L. MILLAR

British Antarctic Survey, NERC, High Cross, Madingley Road, Cambridge CB3 0ET, UK

A mid-Palaeozoic basement to the Antarctic Peninsula is confirmed by a geochronological study of the gneissose country rock of the Mesozoic magmatic arc of eastern Graham Land. Rb–Sr whole-rock ages of 410 ± 15 and 426 ± 12 Ma from samples of orthogneiss indicate a previously unrecognized episode of granitic magmatism in the Antarctic Peninsula during the Silurian. Sm–Nd data on garnet–whole-rock pairs indicate that subsequent amphibolite facies metamorphism occurred in late Carboniferous times, probably as a result of plutonism.

Although the exposed rocks of the Antarctic Peninsula are almost entirely Mesozoic or Cenozoic in age, the existence of a pre-Mesozoic basement has long been advocated. (Pankhurst 1982; Dalziel 1984; Storey & Garrett 1985). Most outcrops of gneissic rocks were initially assigned to the Archean (Adie 1954), but now have been shown to be Mesozoic (Gledhill *et al.* 1982). Nevertheless, a hypothical pre-Mesozoic basement has remained a critical component in constraining reconstructions of West Antarctica in Gondwana (Dalziel & Elliot 1982). We report here the first reliable radiometric age determinations on basement rocks from Graham Land. The equivalence of time rock units and absolute ages is based on the scheme of Harland *et al.* (1982).

The isotopic search for the basement has been hindered by the extensive Mesozoic magmatism and, in east Graham Land, by Triassic amphibolite grade metamorphism (Rex 1976; Pankhurst 1983) which thoroughly disturbed the isotopic systems of most of the pre-existing rocks. However, migmatitic gneisses from east Graham Land analysed by Pankhurst (1983) were found to contain much more radiogenic strontium ($\epsilon_{Sr}^{200} > 150$) than could be explained by an exclusively post-Palaeozoic history involving no older crustal material, although no pre-Mesozoic isochrons were obtained. Three whole rock samples from granitic sheets at Target Hill on the east coast of east Graham Land (Fig. 1), also analysed by Pankhurst, suggest a mid- to late Palaeozoic age. This area, which gives the strongest indications of a pre-Mesozoic history, was revisited to study the possible basement rocks.

The geology of the Target Hill area. The geology of central eastern Graham Land, in common with most of the Antarctic Peninsula, is dominated by magmatic arc rocks, which locally are of Middle Jurassic age (eight isochrons reported in Pankhurst 1982). The Middle Jurassic plutons intrude a complex of granitic orthogneiss, banded gneiss, and metasedimentary rocks (Milne 1987). The largest exposure of granitic orthogneiss is at Target Hill (Fig. 1) There, the granitic orthogneiss contains up to 30% of concordant amphibolite sheets. This banded complex is cross-cut by many dykes and veins, all Mesozoic.

The granitic orthogneiss at Target Hill has a mineralogy of quartz + plagioclase + K-feldspar + biotite ± garnet ± muscovite. The foliation is developed to varying degrees, and the samples may be subdivided on this basis. Those samples with the poorest fabric tend to be fine-grained or pegmatitic, and are of tonalitic or granodioritic composition. In the fine-grained samples the feldspar crystals are preserved as porphyroclasts while the quartz has been completely recrystallized and reduced in grain size. The pegmatite samples often contain large K-feldspar phenocrysts. The more strongly foliated orthogneiss contains more K-feldspar than plagioclase, and consists of a fine-grained granoblastic aggregate of quartz and feldspar surrounding some perthitic K-feldspar augen. The foliation is defined by biotite and coarser quartz segregations which show a strong preferred orientation. The concordant amphibolite sheets have a pronounced foliation parallel to that in the orthogneiss, although the amphibolite sometimes shows a crenulation not present in the orthogneiss.

All of the gneissose lithologies of Target Hill show evidence of amphibolite facies regional metamorphism accompanying deformation. Garnet, where present, is clearly of metamorphic origin, and contains abundant inclusions of quartz, feldspar and amphibole. The concordant amphibolite sheets contain hornblende + quartz + plagioclase + biotite + sphene ± garnet, and have been recrystallized under amphibolite facies conditions.

Sr and Nd isotope geochemistry. Six samples of weakly foliated orthogneiss from western Target Hill (Table 1a)

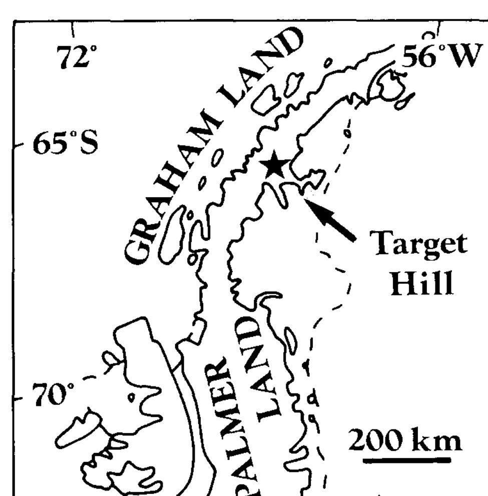

Fig. 1. Map of the Antarctic Peninsula showing the location of Target Hill.

Table 1. *New Rb–Sr data for Target Hill gneisses*

Sample no.	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
(a) Weakly foliated orthogneiss				
R.3434.2	63.0	171.0	1.0538	0.709096
R.3434.3	107.4	620.1	0.5012	0.705802
R.3434.4	59.9	912.4	0.1903	0.704150
R.3434.6	71.0	272.0	0.7551	0.707325
R.4016.1	76.0	360.0	0.6161	0.706670
R.4016.5	61.2	211.2	0.8382	0.708063
(b) Strongly foliated orthogneiss				
R.3434.1	118.4	228.9	1.4976	0.713111
R.3434.7	121.6	182.9	1.9257	0.715614
R.4016.11	110.8	212.2	1.5113	0.713127
R.4016.2	49.7	219.5	0.6553	0.707926

define an isochron (MSWD = 2.8), yielding an age of 410 ± 15 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7030 ± 0.0001 (Fig. 2a). Four samples of strongly foliated orthogneiss, collected from the same locality (Table 1b), define an isochron (MSWD = 0.3) giving an age of 426 ± 12 Ma, with an initial ratio of 0.7040 ± 0.0002 (Fig. 2b). The best estimate of the time of emplacement of the orthogneiss protolith is given by the weighted mean and standard deviation of the two obtained ages (420 ± 8 Ma).

In an attempt to constrain the age of the amphibolite facies metamorphism which affected the Target Hill gneisses, Sm–Nd isotopic analyses were carried out on several garnet–whole-rock pairs (Table 2).

Garnets from a pegmatitic segregation within the granitic orthogneiss ((a) in Table 2) have a considerably higher Sm/Nd ratio than their host whole rock, and define an age of 323 ± 11 Ma. A hand-picked fraction containing the brown cores of these garnets yielded an age of 331 ± 8 Ma. Garnets from a sample of the orthogneiss itself ((b) in Table 2) show a more limited enrichment of Sm relative to Nd, and define a less precise age of 292 ± 35 Ma. Garnets from a melanocratic banded orthogneiss ((c) in Table 2) show no significant fractionation of Sm and Nd.

With the exception of the analysis of the brown garnet cores, all of the data from the garnet–whole-rock pairs, plotted together, define an isochron (MSWD = 0.5) giving an age of 311 ± 8 Ma, with an initial $^{143}Nd/^{144}Nd$ ratio of 0.51225 ± 0.00003 (Fig. 3). The cores lie significantly above this line, and define a maximum age for the onset of amphibolite facies metamorphism. Pankhurst (1983) obtained a Rb–Sr whole-rock age of 336 ± 34 Ma from three samples taken from nearby garnet-bearing granitic sheets. The emplacement of these sheets may be related to the same amphibolite facies metamorphic event.

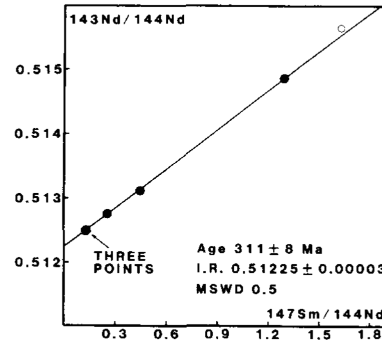

Fig. 3. Sm–Nd isochron for the garnet-whole-rock pairs from the granitic orthogneiss and banded gneiss of Target Hill. Errors are 0.2% on Sm/Nd and 0.005% on $^{143}Nd/^{144}Nd$ (1-sigma). Errors on age and initial ratio (I.R.) are quoted at the 2-sigma level. $^{143}Nd/^{144}Nd$ ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$. Analysis of dark coloured cores (open circle) not included in regression.

Discussion. The results presented here indicate that granitic plutons were emplaced in Graham Land during the Silurian Period. Their low $^{87}Sr/^{86}Sr$ ratios (ϵ^{420}_{Sr} from −17 to +3), and high $^{143}Nd/^{144}Nd$ ratios (ϵ^{420}_{Nd} from −0.3 to +1.3) at this time preclude any significant involvement of older crustal material in their genesis. All of the mid-Palaeozoic lithologies underwent amphibolite facies metamorphism during the Carboniferous.

Attempts at dating orthogneissic rocks from elsewhere in the Antarctic Peninsula have generally yielded only Mesozoic ages (e.g. Gledhill *et al.* 1982). However,

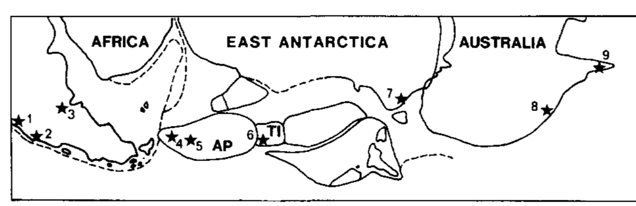

Fig. 4. Map of the Pacific margin of Gondwana showing occurrences of Carboniferous magmatic events (see Table 3 for details). AP, Antarctic Peninsula crustal block; TI, Thurston Island crustal block. Map based on Middle Jurassic reconstruction of Storey & Nell (1988).

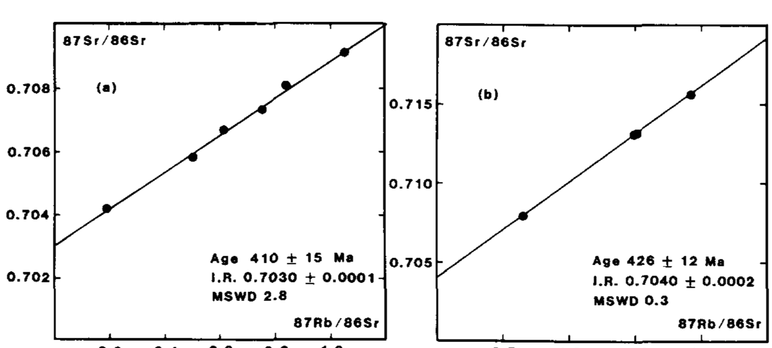

Fig. 2. Rb–Sr isochrons for orthogneiss from Target Hill: (a) weakly foliated; (b) strongly foliated. Errors are 0.5% on Rb/Sr, 0.01% on $^{87}Sr/^{86}Sr$ (1-sigma). Errors on ages and initial ratios (I.R.) are quoted at the 2-sigma level. $^{87}Sr/^{86}Sr$ ratio were normalized to $^{86}Sr/^{88}Sr = 0.1194$.

Table 2. *New Sm–Nd data for Target Hill gneisses*

Sample no.	Sm	Nd	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$
(a) R.3415.14 (whole rock)	1.46	3.53	0.2495	0.512770
R.3415.14 (garnet)	12.72	5.96	1.2909	0.514879
R.3415.14 (brown cores)	63.30	23.52	1.6278	0.515662
(b) R.3434.6 (whole rock)	3.97	18.61	0.1289	0.512519
R.3434.6 (garnet)	16.78	22.72	0.4466	0.513126
(c) R.4007.1 (whole rock)	5.39	26.27	0.1240	0.512495
R.4007.1 (garnet)	17.54	82.72	0.1282	0.512507

Table 3. *Radiometric evidence for Carboniferous magmatism on the Pacific margin of Gondwana*

No.	Date (Ma)	Method	Lithology	Reference
1	308 ± 15	Rb–Sr WR	San Domingo granitoid	Brook *et al.* 1987
	311 ± 10	Rb–Sr WR	Pichilemu metamorphics	Hervé *et al.* 1984
2	294 ± 24	Rb–Sr WR	Nahuelbuta granitoid	Brook *et al.* 1987
3	332 ± 15	Rb–Sr WR	Navarette granodiorite	Caminos & Parica 1985
4	322 + 7/−8	U–Pb zircon	Trinity Peninsula Group sandstone	Miller *et al.* 1987
5	323 ± 11	Sm–Nd garnet-WR	Pegmatite in Target Hill	this work
	336 ± 34	Rb–Sr WR	Granite sheets in Target Hill	Pankhurst 1983
6	306 ± 9	Rb–Sr WR	Morgan Inlet orthogneiss	Storey *et al.* 1987
7	319 ± 5	Rb–Sr mineral-WR	Salamander granite complex	Stump *et al.* 1987
8	288 ± 31	Rb–Sr WR	Urannah batholith	Webb 1974*
9	294 ± 5	K–Ar biotite	Cape York Peninsula granites	Richards & Willmott 1970*

* Date reported in Richards (1980); WR, whole-rock analyses.

Harrison & Piercy (1987) have reported Rb–Sr errorchrons of 399 ± 35 and 440 ± 57 Ma from north-western Palmer Land, and Harrison & Loske (1988) a 506 +7/−8 Ma upper intercept age for zircons from the same area. Furthermore, granophyric cobbles from within the Triassic Trinity Peninsula Group analysed by Pankhurst (1983) gave a Rb–Sr errochron of 386 ± 39 Ma. Thus, it is possible that Palaeozoic basement may underlie much of the Antarctic Peninsula.

Recent work on detrital zircons in Trinity Peninsula Group sandstones from northern Antarctic Peninsula by Miller *et al.* (1987) yielded a lower intercept age of 322 +7/−8 Ma, which they have interpreted as the date of emplacement of granitic plutons. We suggest that the Carboniferous metamorphic event identified here was the result of increased heat flow due to emplacement of plutons. Support for this hypothesis comes from the occurrence of a granitic pegmatite (this work) and granite sheets (Pankhurst 1983) within the metamorphic complex at Target Hill which are of Carboniferous age. Thus it is possible that Carboniferous plutonism occurred in the Antarctic Peninsula and that the source of the detrital zircons in the Trinity Peninsula Group was not southern South America but the Antarctic Peninsula. Today there is no known large exposure of these plutons on the Antarctic Peninsula but it is possible that they were emplaced to the east of the present-day peninsula and that the formation of the Larsen Basin (Macdonald *et al.* 1988) in the Jurassic after their uplift and erosion has resulted in their burial.

A broadly linear Carboniferous magmatic belt can now be recognized along much of the Pacific margin of Gondwana (Fig. 4). If this belt is taken as an indication of the palaeocontinental margin, it can be seen that certain portions of Gondwana, which are present in the Middle Jurassic reconstruction must have accreted in the late Palaeozoic or early Mesozoic; this is consistent with the observed geology. The recognition of this Carboniferous magmatic belt supports reconstructions which place the Antarctic Peninsula south of South America (Storey & Nell 1988) but is not easily reconcilable with a reconstruction which places the Antarctic Peninsula seaboard of Patagonia (Harrison *et al.* 1979).

Conclusions. Mid-Palaeozoic lithologies have been discovered in the Antarctic Peninsula and a hitherto unreported Carboniferous metamorphic event dated. These data confirm the widely held belief that the Antarctica Peninsula Mesozoic magmatic arc has a Palaeozoic basement, but give no indications of a pre-Silurian history in Graham Land.

We are grateful for the support provided by J. Hall and the personnel of Rothera base, especially the assistance during fieldwork given by A. Cain and C. Griffiths. Discussions with colleagues at BAS helped improve the manuscript. Isotopic analyses were carried out at the NERC Isotope Geology Centre, London.

References

Adie, R. J. 1954. *The petrology of Graham Land I. The basement complex: early Palaeozoic plutonic and volcanic rocks.* Falklands Islands Dependencies Survey Scientific Reports, No. 11.

Brook, M., Pankhurst, R. J., Shepherd, T. J. & Spiro, B. 1987. *ANDCHRON, Andean geochronology and metallogenesis. Report on BGS/ODA research and development project 1983–1986* (unpublished BGS open file report).

Caminos, R. & Parica, C. A. 1985. The significance of new Rb–Sr ages of igneous rocks from northern Patagonia. *Comunicaciones,* **35,** 41–43.

Dalziel, I. W. D. 1984. *Tectonic evolution of a forearc terrane, southern Scotia Ridge, Antarctica.* Geological Society of America, Special Paper, **200.**

—— & Elliot, D. H. 1982. West Antarctica: problem child of Gondwanaland. *Tectonics,* **1,** 3–19.

Gledhill, A., Rex, D. C. & Tanner, P. W. G. 1982. Rb–Sr and K–Ar geochronology of rocks from the Antarctica Peninsula between Anvers Island and Marguerite Bay. *In*: Craddock, C. (ed) *Antarctica Geoscience.* University of Wisconsin Press, 315–323.

Harland, W. B., Cox, A. V., Llewellyn, P. G., Pickton, C. A. G., Smith, A. G. & Walters, R. 1982. *A geologic timescale.* Cambridge University Press.

Harrison, C. G. A., Barron, E. J. & Hay, W. W. 1979. Mesozoic evolution of the Antarctic Peninsula and the southern Andes. *Geology,* **7,** 374–378.

Harrison, S. W. & Loske, W. P. 1988. Early Palaeozoic U–Pb isotopic age for an orthogneiss from northwestern Palmer Land, Antarctic Peninsula. *British Antarctic Survey Bulletin,* (in press).

—— & Piercy, B. A. 1987. Basement gneisses in north-western Palmer Land: further evidence for pre-Mesozoic rocks in Lesser Antarctica. *In*: *Abstracts, Fifth International Symposium on Antarctic Earth Sciences,* Cambridge, August 1987.

Hervé, F., Kawashita, K., Munizaga, F. & Bassei, M. 1984. Rb–Sr isotopic ages from late Palaeozoic metamorphic rocks of central Chile. *Journal of the Geological Society, London,* **141,** 877–884.

Macdonald, D. I. M., Barker, P. F., Garrett, S. W., Ineson, J. R., Pirrie, D., Storey, B. C., Whitham, A. G., Kinghorn, R. R. F. & Marshall, J. E. A. 1988. A preliminary assessment of the hydrocarbon potential of the Larsen Basin, Antarctica. *Marine and Petroleum Geology,* **5,** 34–53.

Miller, H., Loske, W. P. & Kramm, U. 1987. Zircon provenance and Gondwana reconstruction: U–Pb data of detrital zircons from Triassic Trinity Peninsula Formation metasandstones. *Polarforschung,* **57,** 59–69.

Milne, A. J. 1987. The geology of southern Oscar II Coast, Graham Land. *British Antarctic Survey Bulletin,* **75,** 73–81.

Pankhurst, R. J. 1982. Rb–Sr geochronology of Graham Land, Antarctica. *Journal of the Geological Society, London,* **139,** 701–711.

—— 1983. Rb–Sr constraints on the ages of basement rocks of the Antarctic Peninsula. *In*: Oliver, R. L., James, P. R. & Jago, J. B. (eds) *Antarctic Earth Science.* Australian Academy of Science and Cambridge University Press, 367–371.

Rex, D. C. 1976. Geochronology in relation to the stratigraphy of the Antarctic Peninsula. *British Antarctic Survey Bulletin,* **43,** 49–58.

Richards, D. N. G. 1980. Palaeozoic granitoids of northeastern Australia. *In*: Henderson, R. A. & Stephenson, P. J. (eds) *The geology and geophysics of northeastern Australia.* Geological Society of Australia, Queensland Division, 229–246.

Storey, B. C. & Garrett, S. W. 1985. Crustal growth of the Antarctica Peninsula by accretion, magmatism and extension. *Geological Magazine,* **122,** 5–14.

—— & Nell, P. A. R. 1988. Role of strike-slip faulting in the tectonic evolution of the Antarctic Peninsula. *Journal of the Geological Society, London,* **145,** 333–338.

——, Grunow, A. M., Dalziel, I. W. D., Pankhurst, R. J. & Millar, I. L. 1987. A new look at the geology of Thurston Island. *In*: *Abstracts, Fifth International Symposium on Antarctic Earth Sciences,* Cambridge, August 1987.

Stump, E., Borg, S. G. & Armstrong, R. L. 1987. Rb–Sr geochronology of granitic rocks, northern Victoria Land. *In*: *Abstracts, Fifth International Symposium on Antarctic Earth Sciences,* Cambridge, August 1987.

Received 19 August 1988; revised typescript accepted 6 October 1988.