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New K-Ar isotopic ages of schists from Nordenskjöld Coast, Antarctic Peninsula: oldest part of the Trinity Peninsula Group?

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Abstract: K-Ar whole-rock dating of five samples of quartz-mica schist from the Nordenskjöld Coast, eastern Graham Land, provides the first unequivocal evidence of pre-Triassic (> 249 ± 7 Ma) deposition of a sequence regarded as part of the Trinity Peninsula Group (TPG). A maximum age range of latest Carboniferous (< *c.* 300 Ma)–Permian for deposition of the Nordenskjöld Coast sequence is indicated, and a polymetamorphic, polydeformational history for the TPG in northern Graham Land. However, the possibility exists that the rocks dated here from the Nordenskjöld Coast are part of a hitherto-unrecognized metamorphic basement unrelated to and older than the mainly Triassic TPG outcrops farther north. The new ages confirm the existence of a previously poorly-defined regional metamorphic event in the Antarctic Peninsula at about 245–250 Ma ago.

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Introduction

Deformed, low-grade (mainly sub-greenschist facies) metasedimentary sequences of the Trinity Peninsula Group (TPG) and its correlatives (Miers Bluff Formation (MBF), Greywacke-Shale Formation (GSF)) are widespread in northern Graham Land and South Scotia Ridge, where they form the local basement to the largely undeformed Mesozoic–Tertiary Antarctic Peninsula magmatic arc and associated sedimentary sequences (Aitkenhead 1975, Hyden & Tanner 1981, Smellie 1981, 1991, Dalziel 1984).

The age and tectonic position of the TPG are poorly known and contentious. Subduction complex, trench slope and upper slope basins are the most commonly cited settings (Hyden & Tanner 1981, Smellie 1981, 1987, Dalziel 1984, Storey & Garrett 1985) although some of the existing evidence is hard to reconcile with a fore-arc position and eastward subduction (Tokarski 1989, Smellie 1991). Critical to all of these models is the assumed age of the TPG, which strongly influences our understanding of the make-up of the Pacific margin of Gondwana prior to its fragmentation and the subsequent dispersal of the component crustal blocks.

Exposures of metamorphic rocks along the Nordenskjöld Coast of eastern Graham Land (Fig. 1) were mapped as part of the TPG by Elliot (1966). They flank the axis of the Mesozoic-Cenozoic magmatic arc, the thermal resetting ("younging") effects of which have complicated previous attempts at isotopic dating of Graham Land basement (e.g. Pankhurst 1983). Furthermore, the rocks reached a higher grade (greenschist facies) than those of the TPG elsewhere in Graham Land (Elliot 1966, Smellie 1991). Unlike isotopic studies of lower-grade TPG outcrops, which may contain detrital minerals with unequilibrated isotopic systems (cf. Pankhurst 1983, Smellie 1991), the Nordenskjöld Coast schists are recrystallized *para*schists and rare greenschists, lacking original clastic or igneous textures. Potentially, therefore, they should be fully equilibrated, and isotopic ages should more closely reflect cooling following the final metamorphism responsible for the recrystallization, thus potentially yielding a reliable minimum age for deposition of the sedimentary protolith. In this paper, new whole-rock K-Ar ages obtained on Nordenskjöld Coast schists are reported and interpreted together with existing age evidence to assess the likely depositional age of these presumed-TPG correlatives in Graham Land.

Geological background

The TPG (including Nordenskjöld Coast outcrops) and its correlatives consist of monotonous, polydeformed siliciclastic turbidite strata and rare limestone, which crop out extensively in Graham Land, South Shetland Islands and South Orkney Islands (see Smellie 1981 and Dalziel 1984 for reviews). In the type area of northern Graham Land, the TPG can be described as a low-T (mainly < *c.* 300–350°C)/medium-P tectonite, with fairly rapid changes in deformation intensity across NE–E-trending structural zones (Hyden & Tanner 1981, Smellie 1991 and unpublished). The major structure consists of a large-scale set of SE-verging (present coordinates) asymmetric folds, which have a generally weakly developed axial plane cleavage; overturned fold limbs are commonly preserved (Dalziel 1984, Tokarski 1989, Muñoz *et al.* 1992). The general similarity between the dominant structural elements in the TPG and MBF suggests a common, or at least overlapping, structural history, although structures in the GSF are more heterogeneous.

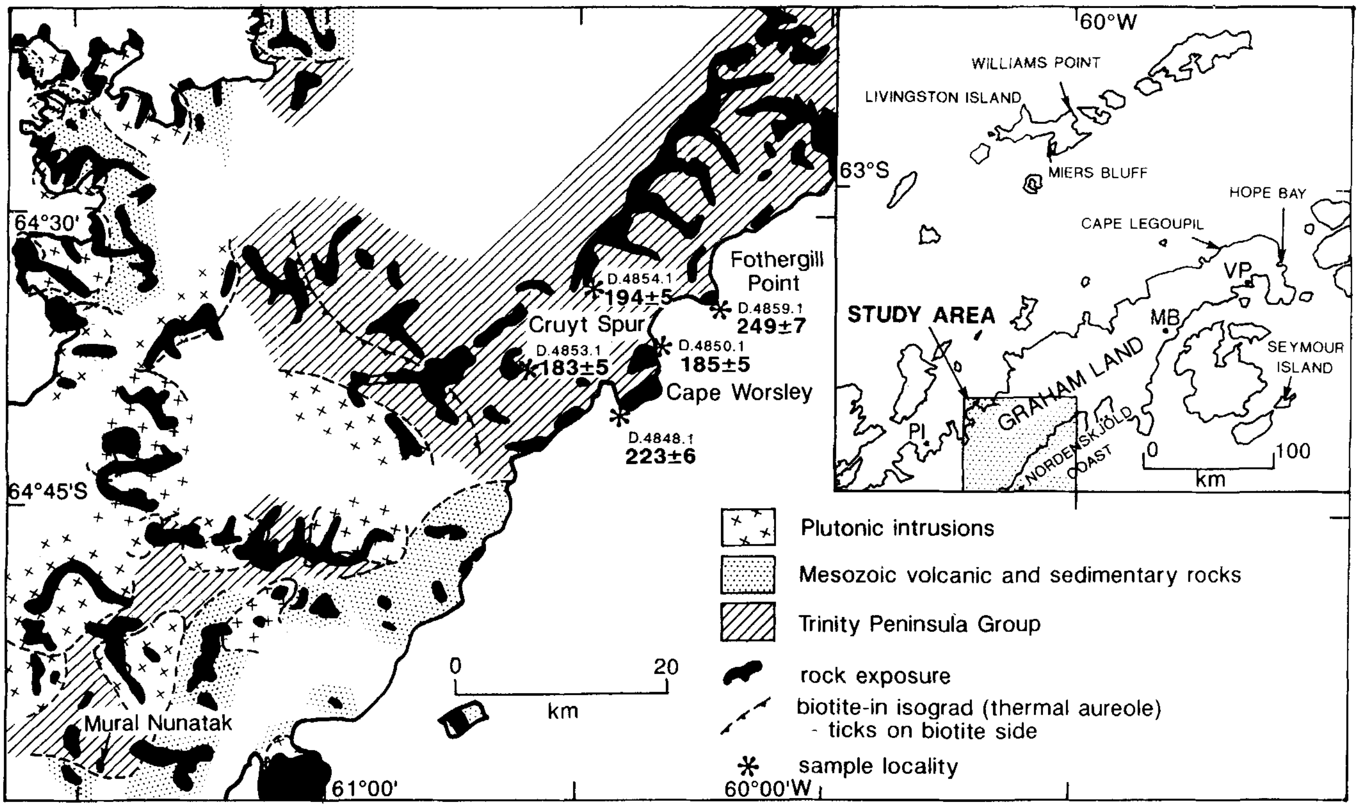

Fig. 1. Sketch map of part of the Nordenskjöld Coast showing its location in Graham Land (inset), the main geological features (based on Elliot 1966), locations of the samples analysed and their whole-rock K-Ar ages (in Ma). Precise locations of the samples are given by Elliot (1966). PI - Pelseneer Island; MB - Mount Bradley; VP - View Point.

Existing evidence for the age of the Trinity Peninsula Group

A maximum latest Carboniferous age (<*c*. 311 ± 8 Ma; Sm-Nd, garnet-whole rock age) for the TPG is constrained by a *high*-grade (amphibolite facies) regional metamorphism affecting Silurian plutons in eastern Graham Land (Milne & Millar 1989), and a possible Late Carboniferous (291 ± 25 Ma; U-Pb, zircon age) amphibolite/gneiss basement beneath the TPG in northern Graham Land (Loske *et al.* 1990). Provenance ages are indicated by Devono-Carboniferous (386 ± 39 Ma; Rb-Sr, whole-rock errorchron age) clasts in TPG conglomerate at View Point (Pankhurst 1983) and Carboniferous detrital zircons in TPG sandstones at Cape Legoupil (322 ± 7 Ma; U-Pb age: Loske *et al.* 1988). In addition, Sm-Nd analyses of detrital orange garnets from TPG sandstones at Pelseneer Island (Fig. 1) plot on the same isochron dating metamorphism of the Silurian plutons in eastern Graham Land (Milne & Millar 1989, and unpublished data of IL Millar) and also represent a provenance age. The TPG is overlain unconformably by the Lower Jurassic Botany Bay Group and younger volcanic strata (Farquharson 1984, Rees 1993) and is intruded by numerous undeformed Jurassic-Cretaceous plutons (174–92 Ma: Rex 1976, Pankhurst 1982). (?)Early or Middle Triassic bivalves are present at Cape Legoupil (TPG; Thomson 1975) and Late Triassic radiolaria in the South Orkney Islands (GSF; Dalziel *et al.* 1981). Elsewhere, only stratigraphically undiagnostic plant fragments and bivalves, jellyfish impressions and trace fossils are known (Dalziel *et al.* 1981, Smellie 1981, Birkenmajer 1992). The discovery of Carboniferous spores in the TPG sequence at Hope Bay (Grikurov & Dibner 1968) is unconfirmed and the spores could have been derived by reworking (cf. Askin & Elliot 1982).

Rb-Sr whole-rock dating of "grits" and mudstones at Hope Bay yielded an age of 281 ± 16 Ma (Pankhurst 1983). The age was regarded as the time at which Sr isotopes were homogenized during latest Carboniferous–Permian times, but it is difficult to interpret due to the presence of abundant detrital biotite (Pankhurst 1983, Smellie 1991). A Rb-Sr whole-rock age of 237 ± 67 Ma for TPG sandstones near Mount Bradley (Fig. 1) was interpreted as a metamorphic age by Hervé *et al.* (1990), but is subject to the same uncertainty as the Hope Bay age. Pankhurst (1983) and Hervé (1992) also reported Rb-Sr ages of 244 ± 27 Ma for biotite schists (TPG?) from Mural Nunatak and 204 ± 19 and 221 ± 34 Ma for MBF shales. The MBF mudstone ages have been variably attributed to diagenesis, metamorphism and/or deformation, but other studies have shown that Sr isotopes equilibrate in fine-grained metasedimentary rocks even at low metamorphic grades (Evans 1989) and we agree with Hervé (1992) that the ages reflect Late Triassic metamorphism, possibly accompanying deformation, rather than diagenesis. By contrast, a Rb-Sr whole-rock age of 243 ± 8 for MBF mudstones was interpreted by Willan *et al.* 1994 as representing early Triassic diagenesis.

Thus, the field relationships and sparse age evidence permit a possible maximum age range of latest Carboniferous (< *c.* 300 Ma)–Late Triassic for the TPG and related sequences in northern Graham Land and South Scotia Ridge, although there is no unequivocal evidence for pre-Triassic deposition.

K-Ar dating

Five samples of schists collected by D.H. Elliot on the Nordenskjöld Coast were selected from localities situated on the south-east flank of the present-day topographic axis of the Antarctic Peninsula (Fig. 1). They were analysed at the NERC Isotope Geosciences Laboratory, Nottingham, and the results are presented in Table I. The Antarctic Peninsula has been the locus of intense arc magmatism since at least Jurassic times (Pankhurst 1982), and the sample distribution was chosen to test for systematic, geographical age variations. All the samples were obtained from outcrops outside of the biotite-in isograd, which marks the *visible* limit of thermal aureoles related to plutonic intrusion (Fig. 1).

The samples are fine-grained, quartz-muscovite-chlorite (-albite-sphene-epidote) schists (metasediments) metamorphosed under greenschist facies conditions (quartz-albite-muscovite-chlorite sub-facies: Elliot 1966). White mica, the principal potassic phase, forms unaltered tabular to flaky crystals generally varying between 20 and 50 μm in length, rarely ranging up to 200 μm. The mica is commonly associated with chlorite(±quartz) and forms thin laminae or is disseminated within fine-grained (10–50 μm) polycrystalline quartz and rare albite. The laminae are folded, and cross-cut and locally disrupted by coarser quartz veins (crystals up to 400 mm). Some veins are offset by microfaults and they may contain traces of carbonate.

The samples yielded ages ranging from 183 ± 5 Ma at Cruyt Spur to 249 ± 7 Ma at Fothergill Point (Fig. 1). Samples from exposures situated between these two localities have intermediate ages, although there is no clear serial age progression. The distribution of sample ages does not closely mirror the shape of the mapped pluton outcrop to the south-west, although the pluton shape at depth is unknown and thermal effects of the intrusion could have affected the ages obtained. However, the two oldest ages were obtained on samples farthest away from the axis of the Antarctic Peninsula.

Whole-rock analyses of schists have to be interpreted with care. Each component mineral will close to argon diffusion at a different temperature (e.g. *c.* 350°C for muscovite, but possibly as low as 150°C for feldspars: Purdy & Jaeger 1976, Berger & York 1981). Only equilibrium parageneses will

Table I. New K-Ar ages of schists from Nordenskjöld Coast, Graham Land.

Sample	K(%)	Radiogenic ^{40}Ar (nl g^{-1})	Atmospheric ^{40}Ar (%)	Age (Ma)
D.4848.1	3.42	31.5117	11.55	223±6
D.4850.1	1.95	14.7467	10.16	185±5
D.4854.1	1.94	15.4458	15.60	194±5
D.4853.1	1.42	10.6213	19.14	183±5
D.4859.1	2.81	29.1015	7.29	249±7

Precision on the K analyses is better than 1% (1σ)
Constants taken from Steiger & Jaeger (1977).

yield chronometric information but isotopic disequilibrium is a possibility because of the slowness of reaction kinetics under the conditions of low-grade metamorphism, particularly if coarser, relict detrital grains are present (Hunziker 1987). Moreover, multiple generations of low temperature white micas in metamorphic rocks can crystallize at temperatures below the closure temperature for white mica and may be a common feature of mica schists. This can result in a range of isotopic ages being preserved in the mica population of a single sample and is often very hard to detect petrographically (Dempster 1992). Thus the apparent whole-rock age is the weighted mean of the individual mineral ages for a given modal composition.

Regional metamorphism of the TPG in its lower-grade type area (north-east of the Nordenskjöld Coast) took place mainly under prehnite-pumpellyite to pumpellyite-actinolite facies or anchizone to epizone conditions (Smellie 1991, Smellie, Roberts & Hirons unpublished data). These conditions correspond to alteration temperatures ranging mainly between 200 and 300°C, based on illite crystallinity measurements (J.L. Smellie, B. Roberts & S. Hirons unpublished data) and possibly up to 360–380°C, based on generally accepted temperatures for the upper boundary of the pumpellyite-actinolite facies (Kisch 1987). Thus, minimum temperatures in the Nordenskjöld Coast, where higher-grade, greenschist facies conditions were attained, probably exceeded 300–380°C.

The Nordenskjöld Coast samples are apparently entirely recrystallized schists, with a fine grain size (generally < 50 μm) and no relict clastic textures. The dominant planar mica fabric in the samples reflects strain during metamorphism, since micas are particularly susceptible to deformation-induced recrystallization (Dempster 1992). This allows the micas to equilibrate to the metamorphic conditions, and it is a process which is enhanced in the finer grain sizes, including those encountered in this study (Hunziker 1987). Thus, the predominant, finer-grained (< 50 μm) micas are probably fully equilibrated metamorphic phases. It is possible that some of the coarser-grained micas (>> 50 μm) are relict, detrital clasts containing radiogenic daughter products from a former metamorphic cycle, but their presence is unlikely to be a major problem in interpreting the K-Ar ages since their proportion is minor. Moreover, the alteration temperatures were close to or above the closure temperature for white mica and the possibility is increased that all of the micas are isotopically equilibrated.

The presence of coarse-grained, unequilibrated, detrital micas would act to increase the isotopic apparent age, whereas any micas formed at lower temperatures during retrogression and/or subsequent thermal events (e.g. related to the plutonic intrusions), would have the opposite effect. Because we believe that the net effect of any coarse, unequilibrated micas is likely to be small, the measured ages should be minimum ages mainly reflecting cooling following the latest metamorphism. The simplest interpretation of the results is that the quartz-mica schists in the Nordenskjöld Coast are no younger than about 250 Ma (latest Permian, using the time-scale of Harland *et al.* 1990). The spread of isotopic ages to lower values was probably caused by thermal resetting and variable Ar-loss during the emplacement of Mesozoic plutons in northern Graham Land.

Discussion

Interpretation of the new minimum ages for the Nordenskjöld Coast samples is complicated by uncertainty in the correlation of the schists with other tectono-stratigraphic units in the region. Although correlated by Elliot (1966) with the TPG, they could be a "basement" terrain hitherto unrecognized in Graham Land.

Other pre-Jurassic, basement units in Graham Land consist of high-grade, Palaeozoic metamorphic rocks (amphibolite facies gneisses; Milne & Millar 1989, Loske *et al.* 1990). At present, the TPG is the only low-grade metasedimentary basement identified in the region. Although the Nordenskjöld Coast schists are at a generally higher grade than in TPG metasedimentary rocks in their type area, a small part of the type area also attained greenschist facies conditions (Smellie 1991). Thus, although the possibility exists that the schists are part of a different basement terrain older than the TPG, the structural and metamorphic similarities with the TPG and the described progressive transition, from metasedimentary rocks to schists in the Nordenskjöld Coast, generally support a correlation with the TPG (Elliot 1966). The pervasive recrystallization of the rocks in the Nordenskjöld Coast precludes a closer comparison and correlation with specific parts of the less recrystallized outcrops of the TPG.

On the basis of this correlation, the Nordenskjöld Coast outcrops could represent the structurally deepest, potentially oldest part of the TPG outcrop in Graham Land. Because metamorphism and recrystallization were complete by latest Permian times, a Permian or older age for deposition is indicated. This would then be the first unequivocal evidence for pre-Triassic deposition of a presumed part of the TPG.

The new minimum age for the Nordenskjöld Coast schists is very close to the more poorly constrained ages obtained on metamorphosed TPG at Mural Nunatak and Mount Bradley (Fig. 1). Elsewhere in Graham Land, a granite gneiss and amphibolite inclusion at Gulliver Nunatak (*c.* 200 km south-west of Fothergill Point) also yielded Rb-Sr mineral ages of 240 ± 4 Ma and 246 ± 4 Ma, respectively (Pankhurst 1983), suggesting that all of the localities listed here may be recording the same, widespread metamorphic event, which reached its peak about 245–250 Ma ago (Permo-Triassic boundary). Moreover, different parts of the TPG may have experienced metamorphic episodes at different times, since TPG strata at Cape Legoupil and the MBF were deposited during the Triassic (*after* the Nordenskjöld Coast metamorphism) and subsequently metamorphosed to prehnite-pumpellyite and pumpellyite-actinolite facies (Smellie 1991). A polymetamorphic history (*sensu lato*) for the TPG is thus possible.

Because the schistosity in the Nordenskjöld Coast schists reflects strain-induced crystallization, the age of the metamorphism probably also provides a minimum age for a coeval deformation. By comparison with the Mesozoic–Cenozoic volcano-sedimentary sequences, which are generally only slightly deformed (although note Birkenmajer 1992), the deformation observed in the Nordenskjöld Coast schists and outcrops of the TPG in northern Graham Land is much more pronounced. The deformation of the entire TPG is generally ascribed to the Late Triassic-Early Jurassic, Peninsula orogeny (Miller 1983), defined by Storey *et al.* (1987) as the event responsible for deforming *Triassic and Early Jurassic* (*sic*) rocks below the unconformity with the Botany Bay Group and Mesozoic volcanic arc rocks. This remains true for TPG strata north of the Nordenskjöld Coast. Conversely, the new isotopic ages reported here indicate that deposition of the Nordenskjöld Coast sequence underwent *Permo-Triassic* metamorphism and coeval deformation, which correspond, in timing at least, to the Permo-Triassic Gondwanian orogeny. However, until the tectonic setting and relationships of the TPG and Nordenskjöld Coast sequences are much better known, it is meaningless to apply a chronology of discrete "orogenies" to these sequences.

The possibility that different parts of the TPG may have had separate, but possibly overlapping depositional, metamorphic and structural histories suggests that the TPG accumulated in more than one sedimentary basin (Hyden & Tanner 1981). Several basins may have existed, each with a distinctive evolution. The published and new information are consistent with a diachronous development, with sedimentation, metamorphism and deformation migrating north-westwards. This is broadly compatible with the accretionary prism hypothesis of Storey & Garrett (1985). However, the presence of older sialic crust beneath the TPG in Graham Land, postulated by Smellie (1981) and identified seismically and isotopically (Milne & Millar 1989, Birkenmajer *et al.* 1990, Loske *et al.* 1990, Grad *et al.* 1993), remains a problem for accretionary prism models.

Conclusions

K-Ar dating of quartz-mica schists from the Nordenskjöld Coast, Graham Land, has identified a metamorphic event of regional extent (at least 300 km), which probably reached a peak at *c.* 245–250 Ma. Thus, deposition of the Nordenskjöld Coast sequence could not have occurred later than Permian times. A maximum age is provided by the presence of amphibolite facies gneisses, which probably underlie the Nordenskjöld Coast schists and restrict deposition to younger than latest Carboniferous times (< *c.* 300 Ma). Although the schists were mapped as part of the TPG metasedimentary sequence, the exposures are discontinuous and the possibility exists that the schists are part of a hitherto unrecognized metamorphic basement in Graham Land. If they are part of the TPG, the Nordenskjöld Coast schists are the oldest known part of the group and the additional presence of Triassic TPG strata metamorphosed to prehnite-pumpellyite and pumpellyite-actinolite facies in northern Graham Land would indicate that the TPG is polymetamorphic as well as polydeformed.

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