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The age of cleavage development in the Ross orogen, northern Victoria Land, Antarctica: evidence from $^{40}Ar/^{39}Ar$ whole-rock slate ages

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Abstract—Metamorphic conditions accompanying regional S_1 cleavage development and whole-rock slate $^{40}Ar/^{39}Ar$ age spectra indicate that the Ross orogeny occurred at *ca* 500 Ma. Subsequent deformation associated with development of a major thrust overprinted the regional cleavage. Existing cleavage micas were not thermally reset and syntectonic mica did not crystallize during thrusting. A regional, low-grade thermal event of Middle Jurassic age may be suggested by the variably discordant age spectra.

INTRODUCTION

DATING of individual deformational events is fundamental in evaluating the tectonothermal evolution of orogens. Although relative ages may be defined by cross-cutting relationships, this typically results in a relatively broad range of permissible ages. Isotopic dating of fabric elements directly associated with tectonic episodes offers the potential to bracket more closely individual deformational events. Fabrics may be dated if: (1) there was synkinematic growth of minerals suitable for isotopic analysis; and/or (2) if another time-dependent measurable parameter forms or is reset during a fabric-forming event (e.g. fission tracks). Progress has been made in dating fabrics formed at relatively high metamorphic grades (e.g. mylonites) where datable minerals crystallize during deformation (e.g. Etheridge & Cooper 1981, Sinha *et al.* 1986). At lower metamorphic grades, direct dating of deformation fabrics is more difficult because of: (1) an increased possibility of incomplete rejuvenation of pre-existing isotopic systems; (2) synkinematic minerals which crystallize during a deformational episode and may have diffusive characteristics similar to those which existed prior to deformation (see review in Reuter & Dallmeyer 1989); and (3) difficulties of mineral separation and analytical problems due to the small grain sizes involved. Hunziker *et al.* (1986) traced the evolution of illite to muscovite and evaluated the conditions at which reliable age dates may be obtained from fine-grained slates. Reuter & Dallmeyer (1989) extended this analysis, concluding that cleavages formed under uppermost anchizone and higher metamorphic conditions may be successfully dated by K/Ar and/or $^{40}Ar/^{39}Ar$ techniques. The $^{40}Ar/^{39}Ar$ incremental-heating technique offers the additional possibility of detecting extraneous argon and partial thermal resetting. However, it also presents additional methodological difficulties because of the potential for ^{39}Ar recoil during neutron irradiation.

This paper provides an example where the age brackets for a significant regional deformation event have been considerably narrowed by using whole-rock $^{40}Ar/^{39}Ar$ incremental-release dating and consideration of the conditions under which cleavage micas crystallized. It also demonstrates why the technique fails to date a prominent superimposed, low-grade deformational event.

GEOLOGIC SETTING

Tectonic elements comprising the geology of northern Victoria Land, Antarctica, are illustrated in Fig. 1. Detailed descriptions of the geology of this area are available in GANOVEX (1987); therefore, only a brief summary is presented here. The Wilson Terrane is the westernmost tectonic element. It is characterized by medium- to high-grade schists and gneisses which host syn- to post-tectonic, *ca* 500–460 Ma granitic plutons of the Granite Harbor intrusive suite (GANOVEX 1987). The Wilson Terrane has been generally interpreted to represent part of the Antarctic craton (Gibson & Wright 1985, Borg *et al.* 1987). The outboard Bowers and Robertson Bay terranes appear to have accreted to the craton margin during the early Paleozoic, Ross orogeny (Weaver *et al.* 1984, Findlay 1987), or during the Devonian (Borg & Stump 1987). The Bowers Terrane is in tectonic contact with the Wilson Terrane. It is represented by a sequence of variably metamorphosed mafic volcanic rocks and proximal marine volcaniclastic sedimentary rocks of Middle Cambrian age. These are conformably overlain by a Middle to Late Cambrian regressive marine sequence and a non-marine quartzose conglomerate. The Robertson Bay Terrane structurally underlies the Bowers Terrane and is characterized by a thick and laterally homogeneous sequence of distal turbidite and slate. Upper portions of this sequence range into the uppermost Cambrian or lowermost Ordovician (Wright 1981, Burrett & Findlay 1984, Wright *et al.* 1984, Wright & Brodie 1986).

The three terranes which comprise northern Victoria Land are separated by regional, polyphase faults (Fig. 1). These include the Lanterman and Leap Year faults. The Bowers and Robertson Bay terranes (and possibly the Wilson Terrane) host post-tectonic granites of the *ca* 370–350 Ma Admiralty Intrusive Suite (Borg & Stump 1987).

Units within both the Bowers and Robertson Bay terranes are deformed into upright, shallow plunging folds with NW-trending axes (GANNOVEX Team 1987). These metasedimentary rocks exhibit an associated regionally penetrative slaty cleavage (S_1). Except in the vicinity of contacts with Devonian granitic plutons (Admiralty Intrusive Suite), metamorphic grade is uniformly low (lowest greenschist) in the Robertson Bay Terrane. This is also the case throughout most of the Bowers Terrane (Kleinschmidt 1981).

Previously reported geochronology from northern Victoria Land has been summarized by Kreuzer *et al.* (1987). Most work is represented by Rb/Sr (mineral and whole-rock) and K/Ar (mineral) dating of granitoids; however, Adams *et al.* (1982) and Adams & Kreuzer (1984) reported K/Ar whole-rock slate ages. These display considerable variation in the Bowers Terrane (510–270 Ma). In the Robertson Bay Terrane, most whole-rock K/Ar ages range between 510 and 450 Ma. Wodzicky & Robert (1986) interpreted whole-rock slate ages from the Bowers Terrane to date two distinct tectonic events: (1) a 490–430 Ma collision between the Wilson and Bowers terranes; and (2) refolding events at *ca* 420–384 Ma. By contrast, Adams & Kreuzer (1984) suggested that the scatter in K/Ar whole-rock ages recorded in the Bowers Terrane reflects partial resetting during burial and subsequent uplift; however, Kreuzer

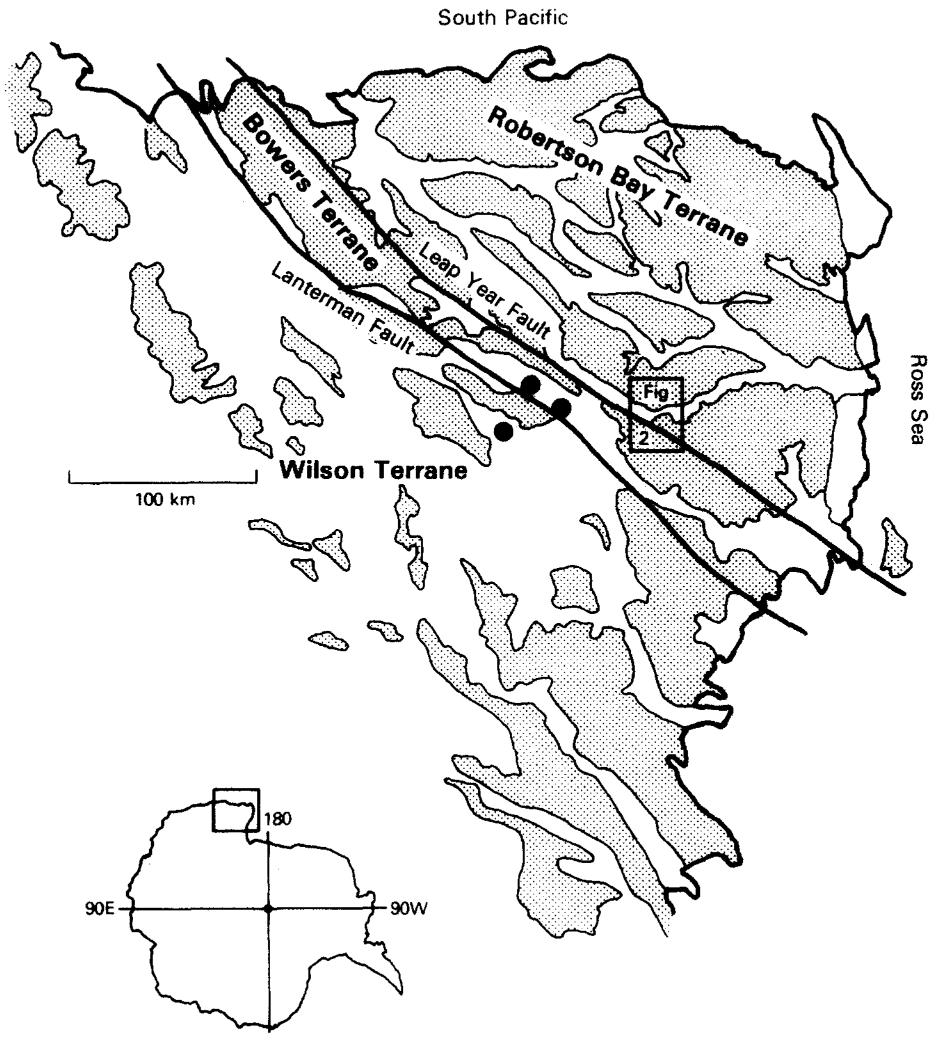

Fig. 1. Generalized tectonic map of northern Victoria Land, Antarctica, with bedrock exposure patterned. Adapted from map accompanying GANOVEX Report (1987). Ferrar dolerite exposures most proximal to the present study area shown by solid circles. Area of Fig. 2 is outlined.

et al. (1987) also discussed the possibility of partial rejuvenation during a Cretaceous thermal event. Additionally, there is a possibility of detrital contribution to the whole-rock slate ages. Thus, interpretation of radiometric controls bracketing the age of cleavage formation associated with folding during the Ross orogeny has been uncertain.

GEOLOGY OF THE STUDY AREA

The present study was focused in western parts of the Robertson Bay Terrane (adjacent to the Leap Year fault in the vicinity of Handler Ridge; Fig. 2). Wright & Brodie (1986) described the stratigraphy of the upper part of the Robertson Bay Group (Handler Formation) in this area. The Handler Formation is deformed into upright folds with an approximately axial-planar cleavage (S_1) that is typical of that developed throughout the Robertson Bay Group. Conodont Alteration Index values of material collected at Handler Ridge are *ca* 4. These indicate metamorphic temperatures of *ca* 190–300°C (J. Repetski written communication 3 June 1987). The E-vergent Millen thrust fault separates the Bowers Supergroup and structurally underlying Handler Formation. A variably penetrative cleavage (S_2) developed in association with this thrust and overprinted the pre-existing S_1 cleavage. The intensity of the overprinting S_2 cleavage and other thrust-related deformational features (steeply-plunging folds, disrupted bedding and extensive quartz veining) systematically decreases with distance from the thrust plane; however, they may be detected locally up to distances of several kilometers. Because the high-angle Leap Year normal fault truncates the Millen thrust, only small tectonic elements of the thrust plane and upper plate remain to the east.

Paleontologic controls, cross-cutting relationships and available geochronology establish that folding and associated regional cleavage in the Bowers and Robertson Bay terranes must have developed after the Late Cambrian and prior to emplacement of Late Devonian granites. Assuming that the folding and cleavage were

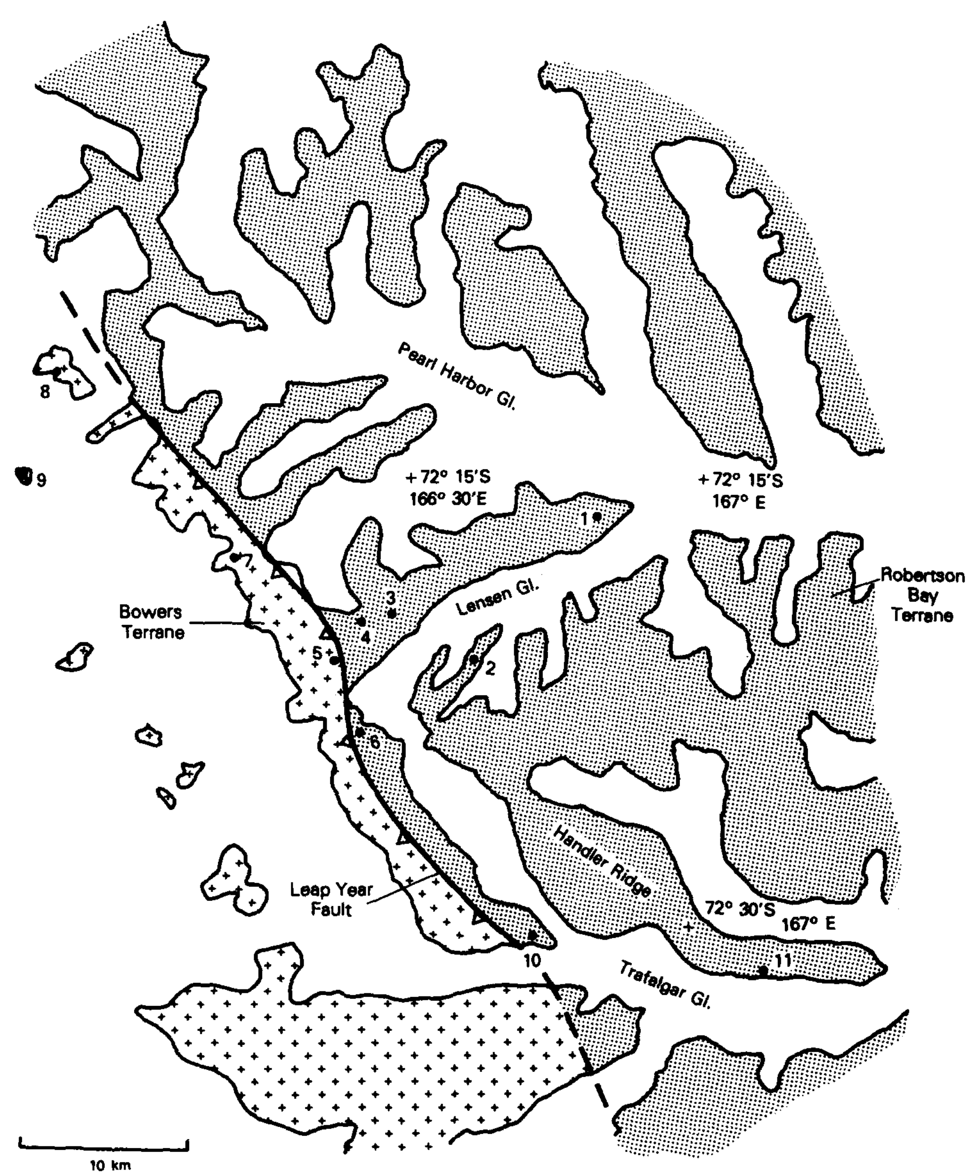

Fig. 2. $^{40}Ar/^{39}Ar$ sample locations (1–11) within the western Robertson Bay Terrane and eastern Bowers Terrane.

related to terrane assembly during the Ross orogeny, an Ordovician age is suggested for the Ross orogeny. The Millen thrust is clearly younger than the regional S_1 cleavage. This study was undertaken to improve the chronologic constraints for these tectonic events and to better interpret existing whole-rock slate radiometric ages.

ANALYTICAL METHODS

Introduction

A suite of slate samples was collected in conjunction with a collaborative 1984 mapping program conducted by New Zealand, West German and U.S. investigators in the vicinity of Handler Ridge (Fig. 2). Thin sections of each sample were examined for mineralogy and grain size, and a subset was selected for further analysis. Samples with low percentages of chlorite, and of very fine-grain size were chosen to reduce complexity of mineralogy while maintaining maximum geographic distribution. After wire brush removal of weathered surfaces and washing, the samples were gently crushed and sieved.

X-ray diffraction

Splits of selected samples were prepared for determination of illite crystallinity by disaggregation in a shatter box for 20 s. A bulk $<2\,\mu m$ size-fraction was isolated by differential settling in Atterberg cylinders and centrifugation (following techniques listed in Reuter 1985). Illite crystallinity of $<2\,\mu m$ size fractions was determined from oriented sedimentation slides by comparison of the (001) illite and (100) quartz (internal standard) reflections following the methods of Weber (1972). Cross-calibration of 28 samples (correlation coefficient = 0.97) from Reuter (1985) suggests the following boundary values are appropriate for the equipment setting employed at the University of Georgia (compared with the calibrations of Teichmüller *et al.* (1979): greenschist–anchizone = 85; anchizone–digenesis = 290–495. In the present study boundaries between the upper anchizone–middle anchizone and middle anchizone–upper anchizone are defined by crystallinity values of 150 and 220, respectively. According to Kubler (1967) and Dunoyer de Segonzac (1969) minimum illite crystallinity values are reached within the epizone whereas Teichmüller *et al.* (1979) defined the greenschist–anchizone boundary by the first appearance of minimum crystallinity values. As a result, rocks suggested to reflect epizonal metamorphism according to Kubler (1967) and/or Dunoyer de Segonzac (1969) are classified as upper anchizone by Teichmüller *et al.* (1979).

$^{40}Ar/^{39}Ar$

The techniques used during $^{40}Ar/^{39}Ar$ analyses of the northern Victoria Land samples generally followed those described in detail by Dallmeyer & Keppie (1987). Whole-rock powders were wrapped in aluminum-foil packets, encapsulated in sealed quartz vials, and irradiated for 40 h at 1000 kW in the central thimble position of the U.S. Geological Survey TRIGA reactor in Denver, Colorado. Variations in the flux of neutrons along the length of the irradiation assembly were monitored with several mineral standards, including MMhb-1 (Alexander *et al.* 1978). The samples were incrementally heated until fused with an RF generator. Each heating step was maintained for 30 min. Measured isotopic ratios were corrected for mass discrimination and the effects of interfering isotopes produced during irradiation using factors reported by Dalrymple *et al.* (1981) for the reactor used in the present study. Apparent $^{40}Ar/^{39}Ar$ ages were calculated from the corrected isotopic ratios using the decay constants and isotopic abundance ratios listed by Steiger & Jäger (1977).

Intralaboratory uncertainties are reported and have been calculated by statistical propagation of uncertainties associated with measurement of each isotopic ratio (at two standard deviations of the mean) through the age equation. Interlaboratory uncertainties are *ca* 1.25–1.5% of the quoted age. Total-gas ages have been computed for each sample by appropriate weighing of the age and percent ^{39}Ar released within each temperature increment. A 'plateau' is considered to be defined if the ages recorded by two or more contiguous gas fractions (with similar apparent K/Ca ratios) each representing >4% of the total ^{39}Ar evolved (and together constituting >50% of the total quantity of ^{39}Ar evolved) are mutually similar within a ±1% intralaboratory uncertainty. Analysis of the MMhb-1 monitor indicates that apparent K/Ca ratios may be calculated through the relationship of 0.518 (±0.0005) × $^{39}Ar/^{37}Ar$ corrected.

RESULTS

Sample characteristics

Twelve whole-rock slate samples were prepared from specimens collected within the Robertson Bay and Bowers terranes exposed in northern Victoria Land, Antarctica. Sample locations are shown in Fig. 2 and coordinates are provided in Table A1 (Appendix). Thin section and SEM images (Fig. 3) indicate that samples 1, 3, 7, 8A, 9 and 11 consist of uniformly shaped, strongly oriented (along S_1) white mica and chlorite. Sample 10 contains significantly more fine quartz silt than the other samples. Sample 2 displays a slight crenulation cleavage (S_2), and sample 16 is characterized by a penetrative S_2 crenulation cleavage.

Illite crystallinity

Quartz normalized illite crystallinity values range between 110 and 121 for the samples analyzed (Appendix, Table A2). There is no significant change as a function and distance from the Millen thrust. All samples, there-

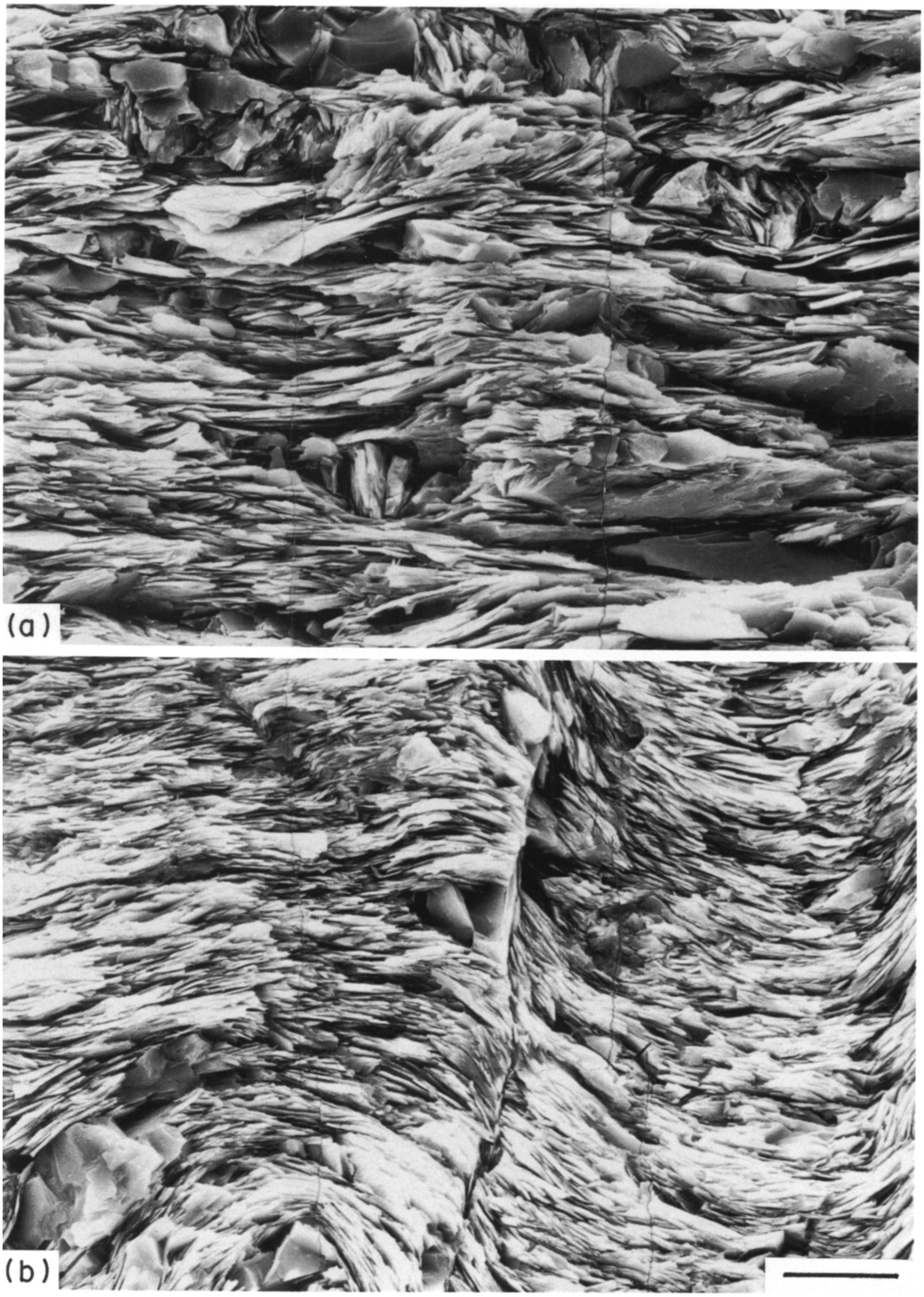

Fig. 3. *In situ* SEM photomosaics (bar = 10 μm) of slate from the Robertson Bay Group, northern Victoria Land, Antarctica. (a) Sample 1 with penetrative S_1 foliation; (b) sample 4 with S_2 crenulation of S_1 foliation.

fore, record greenschist facies metamorphic conditions. Conodont CAI valves from Handler Ridge (CAI = 4) are in general agreement with these data and suggest metamorphic temperatures of *ca* 190–300°C.

$^{40}Ar/^{39}Ar$ *ages*

The $^{40}Ar/^{39}Ar$ analytical data are listed in Table A3 (Appendix) and are presented as incremental age spectra in Figs. 4 and 5. Seven whole-rock slate samples were collected within the Robertson Bay Terrane. These record total-gas ages ranging between 475.1 ± 1.8 Ma (location 11) and 507.9 ± 2.2 Ma (10), and display variably discordant $^{40}Ar/^{39}Ar$ age spectra with generally similar characteristics (Fig. 4 and Table A3). Variable and relatively young apparent ages (*ca* 200–300 Ma) are recorded in the small-volume increments evolved from the samples at low experimental temperatures (*ca* 400–450°C). These increments are marked by relatively small and fluctuating apparent K/Ca ratios. Markedly older ages (*ca* 490–530 Ma) and higher apparent K/Ca ratios characterize the intermediate-temperature increments. For sample 11 the 480–750°C increments record mutually similar apparent ages ranging between 498.5 ± 1.1 and 510 ± 0.8 Ma. For sample 3 the 480–600°C increments yield dates between 519.5 ± 1.6 and 531.8 ± 2.9 Ma. The remaining five samples from the Robertson Bay Terrane are characterized by slightly more variation in the apparent ages (*ca* 5–15%) defined by intermediate-temperature increments. These generally display an age minimum in the *ca* 550–660°C increments. Apparent K/Ca ratios generally decrease systematically throughout higher-temperature portions of each analysis. In samples 3, 6, 2, 4 and 10 these are matched by increases in apparent ages (up to *ca* 585–590 Ma).

Five whole-rock slate samples were collected within the Bowers Terrane. These yield total-gas ages ranging between 369.1 ± 1.8 (9) and 499.2 ± 1.4 Ma (7). The five samples display variably discordant age spectra (Fig. 4 and Table A2) within characteristics similar to those described for samples from the Robertson Bay Terrane. The 475–600°C increments evolved from sample 7 record mutually similar apparent ages which range between 503.1 ± 1.4 and 514.8 ± 1.2 Ma. The 500–600°C increments evolved from sample 8B yield between 490.2 ± 1.2 and 499.3 ± 1.8 Ma. Slightly more age variation is displayed in intermediate-temperature portions of the analyses of samples 5, 8A and 9.

Interpretation

The 12 whole-rock slate samples display variably discordant $^{40}Ar/^{39}Ar$ age spectra which are difficult to interpret. Although the samples are composed primarily of very fine-grained white-mica, systematic intrasample variations in apparent K/Ca ratios suggest that several other phases probably contributed gas at various stages in the whole-rock analyses. Relative to white-mica these appear to have included: (1) a more non-retentive phase present in variable modal abundance and with a relatively low apparent K/Ca ratio; and (2) a more refractory phase with a relatively low apparent K/Ca ratio and present in minor but variable modal abundance. Mineralogical characteristics and observed modal variations suggest that these phases are chlorite and detrital plagioclase feldspar, respectively. It is proposed that most of the observed spectra discordance is related to differences in the modal abundance of these phases relative to white-mica in the whole-rock samples analyzed.

Apparent ages defined by intermediate-temperature gas fractions evolved from the whole-rock samples display variable intrasample fluctuations. Many show slight, but systematic trends to define low-age minima. Lo & Onstott (1989) described similar patterns of discordance for variably chloritized biotite from Taiwan. These age variations were accompanied by marked fluctuations in apparent K/Ca ratios. Lo & Onstott (1989) interpreted their results to reflect effects of recoil of ^{39}Ar and ^{37}Ar during irradiation. It is uncertain the extent to which similar patterns of recoil are recorded in the northern Victoria Land whole-rock samples. The intermediate-temperature minima observed are not accompanied by any marked fluctuations in apparent K/Ca ratios as would be expected if recoil had been significant. In addition, it is probably inappropriate to compare the effects of recoil in whole-rock slate samples dominated by white mica with those observed in the much finer grained material represented by variably chloritized biotite grains. We therefore conclude that irradiation-induced recoil was probably not significant in the northern Victoria Land whole-rock samples, and the ages defined by intermediate-temperature gas fractions evolved from the samples are considered to date the last cooling through temperatures required for intracrystalline retention of argon with constituent, fine-grained white-mica. The slightly older apparent ages recorded in the highest-temperature increments evolved from some of the samples are interpreted to correlate with gas evolved from detrital feldspar. The source terrane does not appear to have been significantly older than the regional metamorphism associated with the Ross orogeny. The variable apparent age recorded in the lower-temperature gas fractions are interpreted to relate to gas evolved from relatively non-retentive chlorite.

GEOLOGIC SIGNIFICANCE

Based on the illite crystallinity and CAI data it appears that the regional cleavage developed during maintenance of lowermost greenschist facies metamorphic conditions. Associated temperatures would probably have been sufficient to totally rejuvenate intracrystalline argon systems within fine-grained detrital white micas (e.g. Hunziker *et al.* 1986, Reuter & Dallmeyer 1989, Dallmeyer 1990, 1991) and the $^{40}Ar/^{39}Ar$ ages are therefore interpreted to closely date S_1 cleavage

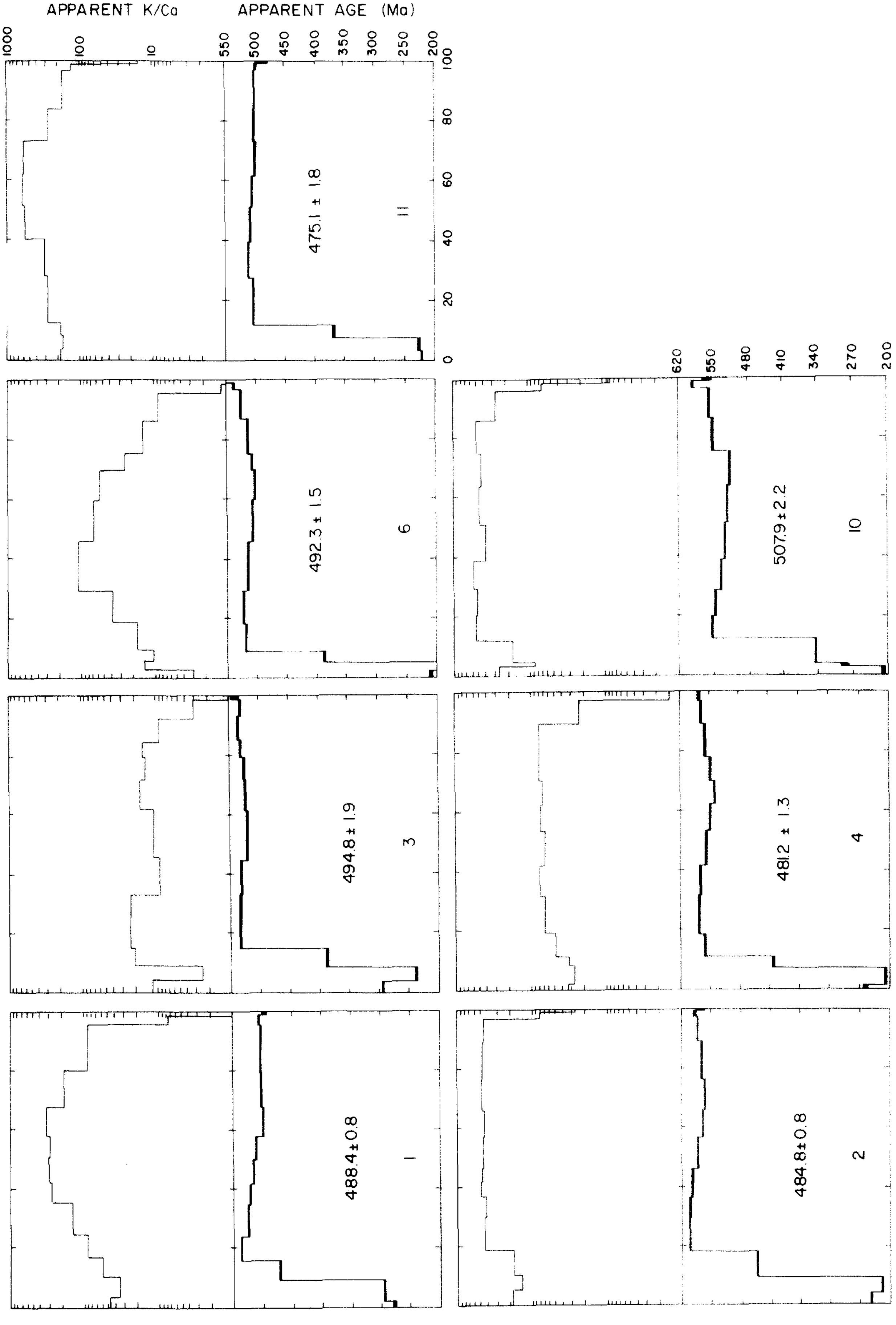

Fig. 4. $^{40}Ar/^{39}Ar$ incremental-release age and apparent K/Ca spectra of whole-rock slate samples from western portions of the Robertson Bay Terrane, northern Victoria Land, Antarctica (locations shown in Fig. 2). Except for sample 10, all spectra have co-ordinates shown for sample 11. Uncertainties in age (two sigma, intralaboratory) indicated by vertical width of bars. Experimental temperatures increase from left to right. Total-gas ages shown on each spectrum.

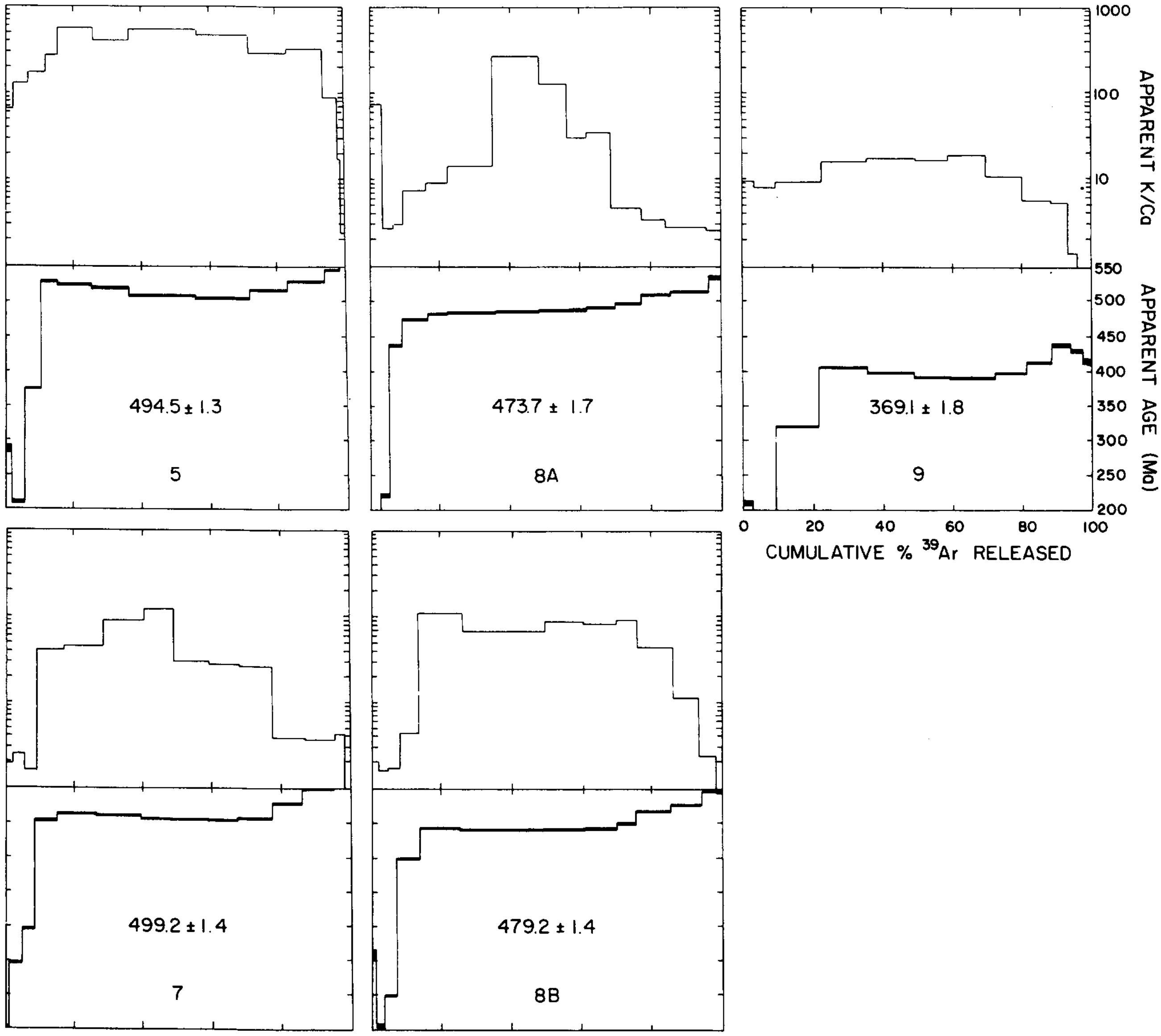

Fig. 5. $^{40}Ar/^{39}Ar$ incremental-release age and apparent K/Ca spectra of whole-rock slate samples from eastern portions of the Bowers Terrane, northern Victoria Land, Antarctica (locations shown in Fig. 2). Data plotted as in Fig. 4. All spectra have co-ordinates shown for sample 9.

formation during the Ross orogeny. The younger ages recorded in low-temperature increments are best explained by partial gas loss during a younger thermal event. Because the apparent gas loss was not significant, it is difficult to determine the age of the disturbance accurately; however, an average of *ca* 160–200 Ma may be estimated. These estimates are similar to crystallization ages reported for early to middle Jurassic mafic sills and flows of the Farrar Group (Kyle *et al.* 1980, Elliot & Foland 1986). However, the most proximal exposures of Farrar Group rocks are >*ca* 30 km NW of the present study area (Fig. 1); therefore, we consider it unlikely that the observed resetting is due to the emplacement of the sills and flows directly, but more likely, it reflects an associated regional perturbation. No thermal effects associated with emplacement of the Admiralty Intrusive Suite (at *ca* 360 Ma) are evident in the $^{40}Ar/^{39}Ar$ results.

In all samples, increments containing *ca* >20% of the total gas released range in age from 580 to 500 Ma and do not exhibit a simple plateau pattern. However, samples 1, 2 and 11 each have three or more adjacent increments in the *ca* 60–90% of total gas released range that closely share a 500 Ma age. Adjacent increments having discordant ages consistently have older ages. The interpretation of these older ages is significantly constrained by consideration of the Cambrian–Ordovician fossils in limestone clasts exposed on Handler Ridge (Burrett & Findlay 1984, Wright *et al.* 1984). The depositional age of the slate enclosing the fossils must be no older than the Cambrian–Ordovician boundary (*ca* 505 Ma: Palmer 1983, Menning 1989). Thus, ages older than *ca* 505 Ma must represent disturbances that have the effect of increasing the increment age past the depositional age.

As previously discussed, modal variations in chlorite may contribute to discordance in the low- to intermediate-temperature gas fractions. All samples show elevated ages in the increments comprising *ca* 20–

40% of total gas released, with maximum increment ages ranging from 550 to 506 Ma. These departures are greatest in samples 1, 2 and 10. Chlorite may have scavenged argon released from constituent white-micas during the Jurassic thermal event, with the excess argon held in sites of intermediate retentivity, resulting in anomalously old ages.

Gas increments released at high temperatures also show slightly elevated ages in several samples (e.g. samples 4, 6 and 10), ranging from 500 to 570 Ma. Argon released from detrital feldspars may account for these departures from a plateau. Plagioclase is a minor constituent in these rocks (Wright 1985), and decreases with decreasing grain size.

From the above considerations it is concluded that the S_1 cleavage formed between 500 and 505 Ma, and that this closely dates the Ross orogeny in this part of northern Victoria Land. In addition to regional diacronism (Wright & Dallmeyer 1986), the variations in whole-rock slate ages reported by Adams *et al.* (1982) and Adams & Kreuzer (1984) are interpreted as a result of variable degrees of thermal resetting, variable chlorite content and detrital feldspar content of the samples analyzed.

The Millen thrust exhibits deformation that cross-cuts the regional cleavage. Wright & Brodie (1987) reported plunging fold hinges, stratial disruption, well-developed stretching lineations and fold vergence changes spatially associated with the thrust plane. An S_2 crenulation cleavage is most intensely developed within *ca* 500 m of the thrust, but its effects are seen in thin section several kilometers away. SEM images (Fig. 3) indicate that regional S_1 cleavage micas were bent, and that considerable pressure-solution seams developed; however there is no evidence for new mica growth. The $^{40}Ar/^{39}Ar$ release spectra of sample 5 (within 10 m of the fault) and samples 6, 7 and 10 (within 500 m of the fault) are indistinguishable from the spectra of samples unaffected by the fault. Because no new micas grew during the thrusting event and there was apparently no significant modification of intracrystalline argon systems of the existing regional S_1 cleavage micas, the method was unable to date the fault movement.

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APPENDIX

Table A1. Sample locations

Sample	Latitude	Longitude
1	72°17′S	166°45′E
2	72°21.6′S	166°37′E
3	72°20′S	166°27′E
4	72°20.8′S	166°24′E
5	72°21.2′S	166°22′E
6	72°23.1′E	166°23′E
7	72°17.7′E	166°10′E
8A	72°12.2′E	165°53′E
8B	72°12.2′E	165°53′E
9	72°17.5′E	165°43′E
10	72°30.2′S	166°43′E
11	72°31.4′S	167°09′E

Table A2. Quartz-normalized illite crystallinity* of <2 μm size fractions within representative whole-rock slate samples from the Robertson Bay and Bowers terranes, northern Victoria Land, Antarctica

Sample	Crystallinity
Robertson Bay Terrane	
1	121
2	115
4	110
10	116
Bowers Terrane	
9	134

*Comparison of (001) reflection in illite and (100) reflection in external quartz standard (after Weber 1972).

Table A3. $^{40}Ar/^{39}Ar$ analytical data for incremental heating experiments on whole-rock slate samples from the Bowers and Robertson Bay terranes, northern Victoria Land, Antarctica

Release temp. (°C)	$(^{40}Ar/^{39}Ar)$*	$(^{36}Ar/^{39}Ar)$*	$(^{37}Ar/^{39}Ar)$†	^{39}Ar % of total	% ^{40}Ar non-atmos.‡	$^{36}Ar_{Ca}$ (%)	Apparent age§ (Ma)
Robertson Bay Terrane							
Sample 1: J = 0.007225							
425	26.05	0.01011	0.012	2.35	88.51	0.03	277.9 ± 2.4
450	24.98	0.00151	0.016	7.03	98.19	0.29	294.4 ± 1.4
475	42.14	0.00242	0.010	6.68	98.29	0.11	472.3 ± 0.7
500	48.41	0.00172	0.006	8.07	98.94	0.09	536.2 ± 0.5
525	47.09	0.00136	0.005	10.80	99.14	0.09	524.3 ± 0.8
550	46.79	0.00146	0.002	6.89	99.07	0.05	521.1 ± 1.1
575	46.09	0.00148	0.002	8.04	99.04	0.04	514.2 ± 0.8
600	45.53	0.00110	0.002	7.87	99.27	0.11	509.8 ± 0.7
650	44.42	0.00111	0.002	9.97	99.25	0.09	498.8 ± 0.7
700	44.91	0.00113	0.003	12.86	99.25	0.07	503.6 ± 0.6
750	44.88	0.00107	0.006	14.89	99.28	0.16	503.5 ± 0.7
800	46.24	0.00488	0.074	3.89	96.88	0.42	505.9 ± 1.1
Fusion	52.68	0.03019	0.698	0.67	83.16	0.63	496.2 ± 3.3
Total	43.72	0.00190	0.013	100.00	98.60	0.12	488.4 ± 0.8

Continued

Table A3. *Continued*

Release temp. (°C)	($^{40}Ar/^{39}Ar$)*	($^{36}Ar/^{39}Ar$)*	($^{37}Ar/^{39}Ar$)†	^{39}Ar % of total	% ^{40}Ar non-atmos.‡	$^{36}Ar_{Ca}$ (%)	Apparent age§ (Ma)
Sample 2: J = 007601							
425	23.95	0.02044	0.002	4.29	74.76	0.00	230.2 ± 0.9
450	17.51	0.00373	0.003	5.22	93.67	0.02	211.9 ± 0.4
475	35.32	0.00163	0.002	8.82	98.62	0.04	423.6 ± 0.4
500	45.74	0.00076	0.001	11.30	99.50	0.02	535.8 ± 0.4
525	45.75	0.00120	0.001	6.78	99.21	0.01	534.6 ± 1.4
550	45.52	0.00150	0.001	5.01	99.01	0.02	531.4 ± 1.7
575	45.63	0.00216	0.001	4.57	98.59	0.01	530.5 ± 2.2
600	44.42	0.00108	0.001	10.60	99.27	0.01	521.4 ± 0.7
650	43.59	0.00104	0.001	9.36	99.28	0.01	513.0 ± 0.7
700	43.19	0.00084	0.001	10.33	99.41	0.01	509.5 ± 0.6
750	43.74	0.00091	0.001	13.01	99.37	0.04	514.9 ± 0.7
800	44.60	0.00152	0.001	8.17	98.98	0.01	521.9 ± 0.6
875	46.15	0.00526	0.007	1.91	96.62	0.04	526.5 ± 2.5
Fusion	116.44	0.24674	0.020	0.63	37.38	0.01	515.6 ± 6.4
Total	41.89	0.00374	0.001	100.00	97.41	0.01	484.8 ± 0.8
Sample 3: J = 0.007522							
425	25.78	0.00809	0.044	4.07	90.69	0.15	292.2 ± 1.7
440	19.46	0.00296	0.245	4.82	95.58	2.25	236.2 ± 1.9
460	32.65	0.00293	0.026	6.27	97.33	0.24	386.5 ± 1.8
480	45.96	0.00124	0.024	18.00	99.19	0.53	531.8 ± 2.9
500	45.72	0.00101	0.058	11.50	99.33	1.56	530.0 ± 1.4
525	44.55	0.00055	0.049	16.99	99.61	2.42	519.5 ± 1.6
550	44.90	0.00072	0.047	10.44	99.51	0.28	522.5 ± 1.6
575	45.19	0.00133	0.039	7.26	99.12	0.80	523.8 ± 1.8
600	46.04	0.00197	0.037	5.77	98.71	0.52	530.3 ± 1.7
650	46.31	0.00166	0.060	7.66	98.94	0.99	534.1 ± 1.5
700	46.16	0.00241	0.147	5.97	98.47	1.66	530.4 ± 1.8
750	51.59	0.01791	1.129	0.85	89.91	1.72	540.1 ± 7.3
Fusion	57.37	0.04875	1.312	0.40	75.06	0.73	506.5 ± 14.9
Total	42.73	0.00199	0.027	100.00	98.40	0.41	494.8 ± 1.9
Sample 4: J = 0.007591							
425	38.05	0.06576	0.017	1.51	48.92	0.01	238.4 ± 2.2
450	19.62	0.01311	0.020	5.63	80.24	0.04	203.6 ± 0.5
475	35.43	0.01120	0.017	3.96	90.65	0.04	393.5 ± 1.4
500	43.62	0.00244	0.011	7.44	98.33	0.12	508.4 ± 1.8
525	44.28	0.00123	0.008	13.02	99.17	0.18	518.9 ± 2.3
550	43.74	0.00112	0.007	10.00	99.23	0.16	513.7 ± 0.9
575	42.99	0.00141	0.008	11.61	99.02	0.15	505.1 ± 0.8
600	42.50	0.00161	0.007	8.96	98.87	0.12	499.4 ± 1.4
650	41.57	0.00188	0.008	7.98	98.65	0.11	488.8 ± 0.9
700	42.44	0.00214	0.007	7.87	98.50	0.09	497.1 ± 1.1
750	43.26	0.00160	0.007	10.99	98.89	0.13	507.3 ± 0.9
800	44.00	0.00219	0.023	7.80	98.52	0.29	513.1 ± 1.0
875	45.46	0.00612	0.384	2.90	96.08	1.71	516.7 ± 1.3
Fusion	72.00	0.10718	3.393	0.33	56.38	0.86	485.5 ± 17.1
Total	41.67	0.00413	0.032	100.00	96.50	0.19	481.2 ± 1.3
Sample 6: J = 0.007051							
425	23.20	0.01977	0.181	2.49	74.85	0.25	208.4 ± 3.7
440	17.34	0.00453	0.039	2.95	92.23	0.23	192.7 ± 2.5
460	35.32	0.00474	0.048	3.63	96.03	0.27	386.8 ± 1.6
475	47.53	0.00111	0.030	9.24	99.30	0.74	518.2 ± 1.1
500	47.83	0.00082	0.014	10.95	99.48	0.46	521.8 ± 1.4
525	46.88	0.00050	0.005	16.37	99.66	0.07	513.6 ± 1.5
550	46.17	0.00062	0.008	14.29	99.57	0.06	506.4 ± 1.0
575	45.71	0.00075	0.010	9.87	99.50	0.04	501.7 ± 1.6
600	46.25	0.00121	0.022	5.54	99.22	0.50	505.6 ± 1.6
650	46.88	0.00086	0.040	11.61	99.41	0.05	512.5 ± 1.5
700	48.30	0.00156	0.067	9.75	99.02	0.16	524.2 ± 1.8
750	51.24	0.00757	0.454	2.54	95.70	1.63	535.8 ± 2.7
Fusion	58.96	0.02881	3.765	0.77	86.06	3.55	552.8 ± 5.0
Total	45.25	0.00197	0.065	100.00	98.29	0.45	492.3 ± 1.5

Continued

Table A3. *Continued*

Release temp. (°C)	$(^{40}Ar/^{39}Ar)$*	$(^{36}Ar/^{39}Ar)$*	$(^{37}Ar/^{39}Ar)$†	^{39}Ar % of total	% ^{40}Ar non-atmos.‡	$^{36}Ar_{Ca}$ (%)	Apparent age§ (Ma)
Sample 10: J = 0.007395							
425	94.71	0.26445	0.002	3.27	17.48	0.00	208.4 ± 5.5
450	32.02	0.02928	0.006	1.07	72.97	0.01	287.5 ± 8.4
475	30.01	0.00546	0.003	8.44	94.61	0.01	343.8 ± 1.6
500	49.27	0.00241	0.001	7.63	98.54	0.01	553.5 ± 1.1
525	48.45	0.00208	0.001	8.88	98.72	0.01	546.3 ± 1.8
550	47.14	0.00188	0.001	10.01	98.81	0.01	533.9 ± 1.2
575	46.42	0.00162	0.002	12.62	98.95	0.07	527.5 ± 1.1
600	45.83	0.00164	0.001	12.20	98.93	0.01	521.6 ± 0.9
650	45.02	0.00122	0.003	11.65	99.18	0.07	514.8 ± 2.5
700	48.42	0.00124	0.001	11.04	99.23	0.02	548.5 ± 4.4
750	49.36	0.00172	0.002	10.05	98.96	0.02	556.3 ± 3.3
800	53.84	0.00597	0.008	2.40	96.71	0.04	587.7 ± 2.3
Fusion	87.82	0.13022	0.067	0.73	56.18	0.01	561.2 ± 7.4
Total	47.69	0.01193	0.002	100.00	95.27	0.03	507.9 ± 2.2
Sample 11: J = 0.009071							
425	15.84	0.00498	0.003	3.39	90.68	0.01	221.0 ± 1.1
440	15.05	0.00155	0.003	4.43	96.92	0.05	224.1 ± 1.7
460	25.42	0.00151	0.003	4.33	98.22	0.05	368.3 ± 2.4
480	35.56	0.00043	0.002	15.64	99.62	0.05	502.7 ± 0.7
500	36.15	0.00038	0.002	11.91	99.67	0.03	510.1 ± 0.8
525	35.90	0.00030	0.001	11.54	99.74	0.01	507.3 ± 0.8
550	35.59	0.00029	0.001	10.42	99.75	0.01	503.6 ± 1.1
575	35.26	0.00055	0.001	6.56	99.52	0.01	498.5 ± 1.1
600	35.22	0.00057	0.001	4.97	99.50	0.02	497.9 ± 1.6
650	35.43	0.00055	0.002	10.76	99.53	0.03	500.6 ± 1.4
700	35.48	0.00060	0.003	13.11	99.48	0.04	501.0 ± 0.6
750	35.53	0.00171	0.004	2.22	98.56	0.06	497.6 ± 1.8
Fusion	34.52	0.00635	0.032	0.71	94.56	0.14	467.9 ± 4.3
Total	33.59	0.00076	0.002	100.00	99.07	0.08	475.1 ± 1.0
Bowers Terrane							
Sample 5: J = 0.007623							
425	46.53	0.08129	0.008	1.87	48.36	0.00	285.6 ± 2.3
450	18.36	0.00719	0.004	3.79	88.40	0.02	210.4 ± 1.2
475	32.47	0.00756	0.003	4.93	93.10	0.01	374.4 ± 0.5
500	45.32	0.00255	0.002	4.91	98.32	0.02	527.5 ± 1.1
525	44.59	0.00164	0.001	9.99	98.90	0.01	522.9 ± 0.8
550	44.00	0.00078	0.002	10.87	99.46	0.07	519.4 ± 1.3
575	42.91	0.00069	0.001	19.42	99.51	0.01	508.3 ± 1.6
600	42.37	0.00067	0.001	16.31	99.52	0.01	502.8 ± 1.1
650	43.59	0.00095	0.002	11.27	99.34	0.05	514.6 ± 1.1
700	44.86	0.00112	0.001	10.45	99.25	0.03	527.2 ± 1.2
750	47.07	0.00318	0.006	4.34	97.99	0.06	543.6 ± 1.4
800	52.61	0.00759	0.030	1.56	95.73	0.11	586.2 ± 2.4
Fusion	124.06	0.25891	0.227	0.28	38.34	0.02	558.2 ± 14.7
Total	42.69	0.00399	0.003	100.00	97.35	0.03	494.5 ± 1.3
Sample 7: J = 0.007603							
425	25.69	0.03390	0.263	1.33	60.91	0.21	202.7 ± 4.4
440	24.50	0.00406	0.207	3.74	95.15	1.39	294.4 ± 3.0
460	29.48	0.00664	0.313	3.78	93.41	1.28	343.0 ± 2.2
475	42.86	0.00169	0.013	6.81	98.82	0.21	503.6 ± 1.5
500	43.69	0.00085	0.012	11.27	99.41	0.37	514.8 ± 1.2
525	43.47	0.00081	0.006	12.86	99.43	0.07	512.6 ± 1.4
550	42.96	0.00096	0.005	8.24	99.31	0.04	506.8 ± 0.9
575	42.83	0.00077	0.018	11.27	99.46	0.63	506.2 ± 0.7
600	42.67	0.00119	0.019	8.42	99.16	0.54	503.1 ± 1.4
650	43.14	0.00125	0.019	9.89	99.13	0.40	507.9 ± 1.5
700	45.70	0.00159	0.140	8.92	98.98	2.39	533.3 ± 1.4
750	47.37	0.00185	0.139	9.00	98.84	2.57	549.4 ± 1.0
800	51.38	0.00488	0.125	3.72	97.20	0.70	580.7 ± 2.9
Fusion	66.87	0.05870	1.634	0.75	74.25	0.76	578.3 ± 8.0
Total	42.79	0.00249	0.038	100.00	98.06	0.08	499.2 ± 1.4

Continued

Table A3. *Continued*

Release temp. (°C)	($^{40}Ar/^{39}Ar$)*	($^{36}Ar/^{39}Ar$)*	($^{37}Ar/^{39}Ar$)†	^{39}Ar % of total	% ^{40}Ar non-atmos.‡	$^{36}Ar_{Ca}$ (%)	Apparent age§ (Ma)
Sample 8A: J = 0.007320							
425	30.91	0.05314	0.007	3.06	49.19	0.01	190.4 ± 4.1
440	19.58	0.00659	0.202	2.49	89.94	0.83	218.8 ± 3.0
460	38.31	0.00428	0.173	3.62	96.72	1.10	433.0 ± 3.0
475	41.53	0.00252	0.072	7.22	98.18	0.78	471.2 ± 1.6
500	41.98	0.00162	0.058	5.72	98.86	0.57	478.6 ± 1.8
525	42.04	0.00078	0.037	13.71	99.43	0.31	481.6 ± 1.4
550	42.34	0.00113	0.002	12.37	99.19	0.04	483.6 ± 1.3
575	42.60	0.00127	0.004	8.90	99.10	0.10	485.8 ± 1.6
600	43.25	0.00328	0.020	4.58	97.75	0.16	486.4 ± 2.4
650	43.00	0.00151	0.013	8.14	98.95	0.24	489.2 ± 2.2
700	43.81	0.00188	0.114	7.29	98.74	1.65	496.3 ± 1.3
750	45.18	0.00204	0.157	8.24	98.64	1.77	509.3 ± 1.7
800	45.59	0.00199	0.192	10.59	98.68	1.25	513.5 ± 1.2
Fusion	69.63	0.07632	0.204	4.08	67.60	2.31	534.1 ± 3.5
Total	43.07	0.00649	0.016	100.00	95.76	0.37	473.7 ± 1.7
Sample 8B: J = 0.007452							
425	90.91	0.22281	0.264	1.43	27.54	0.03	308.5 ± 9.7
440	17.69	0.00590	0.418	2.30	90.31	1.93	202.9 ± 4.8
460	21.38	0.00561	0.375	3.75	92.36	1.82	247.7 ± 1.5
475	38.49	0.00221	0.120	6.59	98.32	1.48	448.0 ± 1.5
500	42.55	0.00133	0.004	11.35	99.06	0.09	492.7 ± 1.0
525	42.09	0.00054	0.008	24.07	99.59	0.09	490.2 ± 1.1
550	42.23	0.00086	0.007	11.78	99.39	0.01	490.9 ± 1.3
575	42.51	0.00140	0.007	9.04	99.01	0.03	492.0 ± 1.2
600	43.58	0.00261	0.006	5.38	98.22	0.08	499.3 ± 1.8
650	45.05	0.00182	0.012	9.78	98.80	0.04	516.6 ± 1.0
700	46.19	0.00243	0.044	8.69	98.43	0.19	526.2 ± 1.2
750	48.64	0.00372	0.215	5.04	97.76	1.57	547.2 ± 1.6
Fusion	55.47	0.02556	1.932	0.81	86.65	2.06	552.7 ± 8.4
Total	42.49	0.00511	0.039	100.00	97.41	0.45	479.2 ± 1.4
Sample 9: J = 0.007619							
425	22.21	0.01804	0.052	2.94	76.00	0.08	218.3 ± 3.4
450	13.95	0.00345	0.064	6.62	92.69	0.51	169.6 ± 1.3
475	24.87	0.00285	0.054	12.19	96.60	0.51	302.2 ± 0.6
500	33.36	0.00115	0.031	13.85	98.97	0.74	404.9 ± 1.4
525	32.57	0.00121	0.029	13.54	98.89	0.66	396.0 ± 0.9
550	31.93	0.00139	0.030	9.30	98.70	0.59	388.3 ± 0.8
575	31.78	0.00119	0.028	13.94	98.88	0.63	387.3 ± 1.9
600	32.52	0.00129	0.026	8.99	98.82	0.56	395.1 ± 2.0
650	34.11	0.00120	0.049	7.26	98.96	1.11	413.0 ± 2.8
700	37.00	0.00179	0.087	5.33	98.57	1.33	442.4 ± 3.7
750	36.58	0.00322	0.404	3.40	97.47	3.42	433.6 ± 5.1
800	36.62	0.00900	0.910	1.57	92.93	2.75	416.2 ± 6.2
Fusion	54.12	0.06892	1.417	1.07	62.57	0.56	414.4 ± 5.4
Total	30.81	0.00301	0.081	100.00	96.97	0.80	369.1 ± 1.8

*Measured
†Corrected for post-irradiation decay of ^{37}Ar (35.1 day half-life).
‡[$^{40}Ar_{tot.}$ − ($^{36}Ar_{atmos.}$)(295.5)]/$^{40}Ar_{tot.}$.
§Calculated using correction factors of Dalrymple *et al.* (1981); two sigma, intralaboratory errors.