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RUBIDIUM-STRONTIUM DATES & EXCESS ARGON IN THE ARLTUNGA NAPPE COMPLEX, NORTHERN TERRITORY

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(with 2 Tables and 8 Text-Figures)

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Abstract

Seven samples of metamorphic rocks from the Arunta basement of the Arltunga Nappe Complex gave a whole-rock Rb-Sr isochron date of 1723 ± 23 m.y. and a low initial ratio of 0.7051 (Rb decay constant = 1.39×10^{-11} yr^{-1}). Some of the rocks are retrogressively metamorphosed, and three micas from two gave Rb-Sr dates of 342 m.y. (whole rock-biotite isochron) and 320 m.y. (whole rock-muscovite-biotite isochron), compared to conventionally computed K-Ar dates of 889, 431, and 548 m.y., respectively, from the same micas. Thus, comparison of both Rb-Sr and K-Ar dates indicates the presence of considerable excess ^{40}Ar in the micas from the retrograded rocks. The dates show that initial differentiation or intense progressive regional metamorphism of the Arunta rocks occurred in Early Carpentarian time, and was followed by retrogressive metamorphism in Early to Middle Carboniferous time, during the Alice Springs Orogeny.

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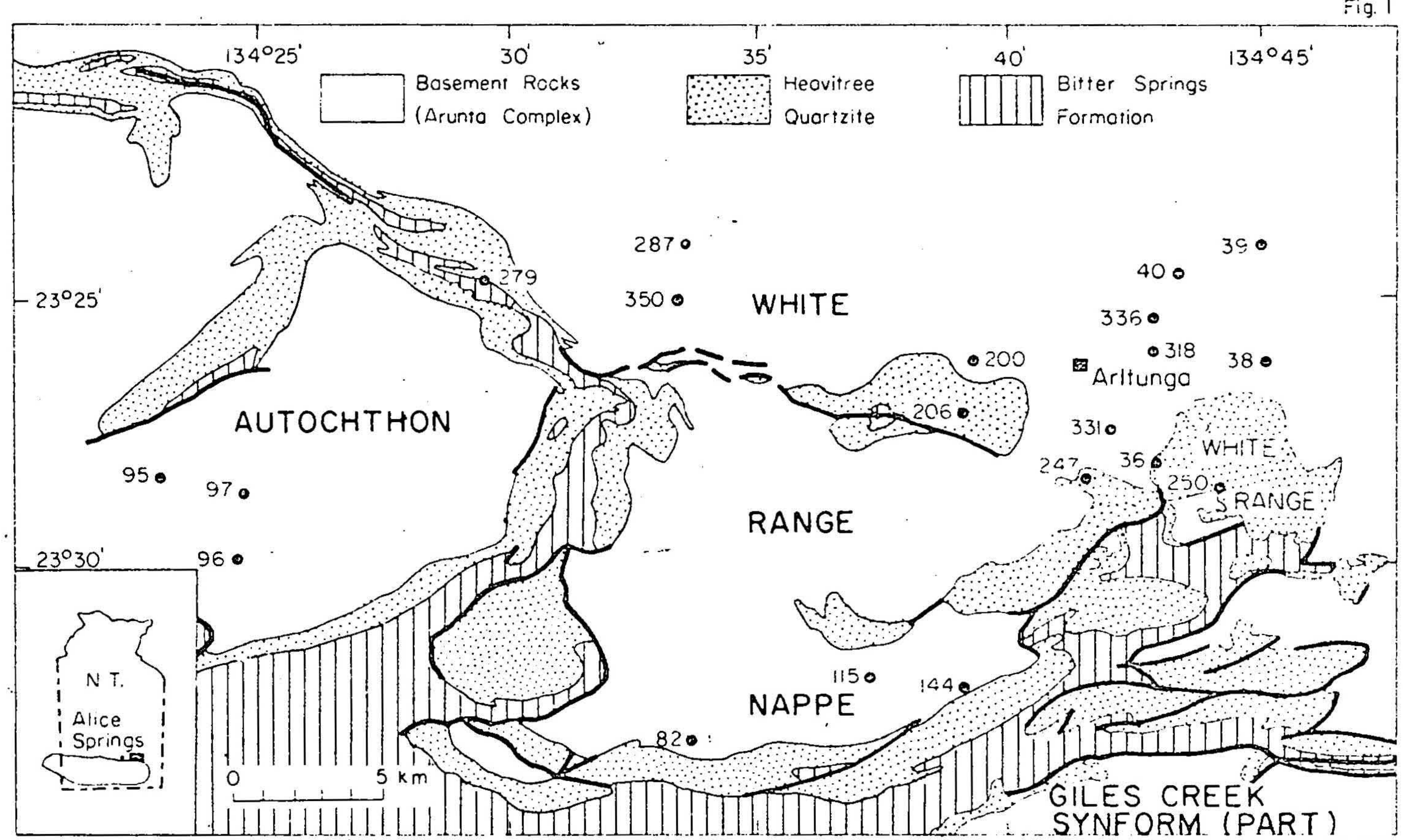
Introduction

The Arltunga Nappe Complex is situated in the southern part of the Northern Territory of Australia, on the northeastern margin of the Amadeus Basin (Fig. 1). Its general features were originally described by Forman, Milligan, & McCarthy (1967), and a later description and synthesis were presented by Forman (1971). Detailed studies of the nappe complex have been made by Shaw et al. (1971), Stewart (1971a, 1971b), Khan (1972), and Duff (1972). The nappe complex comprises several nappes of different sizes, the largest of which is known as the 'White Range Nappe'. The nappes consist of cores of crystalline basement rocks of the Precambrian Arunta Complex, and envelopes of Upper Proterozoic sedimentary cover rocks, the Heavitree Quartzite and Bitter Springs Formation, which are the two lowest units of the Amadeus Basin sedimentary sequence to the south of the Arunta Complex. All the nappes root to the north in a zone of retrogressively metamorphosed basement rocks, and front to the south against unmetamorphosed sediments of the Amadeus Basin.

The nappes were originally envisaged as giant recumbent folds with intact lower, middle, and upper limbs. However, later work has shown that they are essentially large thrust sheets with no inverted middle limbs. Inverted rocks do occur in places, but they appear to have formed mainly by drag adjacent to thrust faults, or by rotation at the fronts of the nappes. Penetrative deformation is also limited, and is important only in the root zone along the northern side of the nappe complex.

The tectonic movements that accompanied the formation of the Arltunga Nappe Complex have been called the 'Alice Springs Orogeny' (Forman et al., 1967), and the duration of the movements is bracketed on stratigraphic evidence between Late Devonian and Late Permian; thick synorogenic sandstone and conglomerate of the Pertnjara Group at the top of the Amadeus Basin

Fig. 1



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sequence are underlain by siltstone which contains Middle to Late Devonian fossils (Gilbert-Tomlinson, 1968; Hodgson, 1968), and the Arunta Complex is unconformably overlain by flat-lying Upper Permian sediments (Stage 5 of Evans, 1969; unpublished data of Evans, conclusions in Wells et al. 1970, p. 113). The younger stratigraphic time limit could possibly be put back to latest Carboniferous, as the Crown Point Formation, which unconformably overlies the Finke Group (equivalent to and interfingering with the Pertnjara Group) in the southeastern part of the Amadeus Basin, contains Late Carboniferous spores (Stage 1/2 of Evans, 1969) in its lower part, and Early Permian spores (Stages 2 and 3) in its upper part (Evans, 1964, and unpublished data in Amerada Petroleum Corp., 1965, summarized in Wells et al. 1970, p. 113), and thus straddles the Carboniferous-Permian boundary*.

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* The position of the Carboniferous-Permian boundary in Australia is still controversial (Black et al. 1972; Evans & White, 1972; Balme, 1973), and until this is settled we accept Evans' original determination (in Amerada Petroleum Corp., 1965) of the age of the Crown Point Formation as Carboniferous to Permian.

However, the nearest outcrop of Crown Point Formation to the Arltunga Nappe Complex is 140 km south-southeast of Arltunga.

The data presented in this report are complementary to the K-Ar study by Stewart (1971b), who determined 31 K-Ar dates on mica and hornblende from the basement and cover rocks of the Arltunga Nappe Complex. The mica dates fell into three groups:

1. Six micas from the basement rocks in the southern part of the White Range Nappe gave dates ranging from 1532 to 1368 m.y., and one hornblende gave 1660 m.y., indicating the time of metamorphism in these rocks as Late Carpentarian or earlier.

2. Twelve muscovites from basement and cover rocks in the northern part of the White Range Nappe gave dates ranging from 431 to 322 m.y., indicating an age older than Late Carboniferous for the Alice Springs Orogeny; one muscovite from a lens of basement quartzite gave 1077 m.y.

3. Seven biotites from basement rocks in the northern part of the White Range Nappe, and two biotites from the authochthonous basement west of the nappe, gave dates spread from 1775 to 370 m.y., with no particular concentration evident, and two possible explanations for the spread of dates were suggested, namely:

(i) Complete recrystallization of biotite during Devonian-Carboniferous time, accompanied by absorption of various amounts of excess argon, or

(ii) Partial recrystallization of biotite during Devonian-Carboniferous time, with concomitant retention of various amount of radiogenic argon originating from the earlier (Precambrian) time of crystallization.

4. Two hornblendes from the northern part of the White Range Nappe gave K-Ar dates of 2132 and 1639 m.y., and at least one, if not both, was suspected of containing excess argon.

This paper presents (1) the results of a graphical analysis of Stewart's 1971 K-Ar data, involving the computation and interpretation of K-Ar initial argon and isochron diagrams, and (2) new Rb-Sr dates (determined by Armstrong) on some of the rocks and minerals used in the K-Ar study. Both sets of results indicate the presence of excess argon in biotite from retrograded basement rocks in the northern part of the nappe complex, whereas in non-retrograded or only slightly retrograded basement rocks, partial argon loss has occurred.

GRAPHICAL ANALYSIS OF K-AR DATA

Two types of isochrons can be computed from the data gathered in the conventional determination of K-Ar dates. The first involves the plotting of percent K (or ^{40}K) against ^{40}Ar for each sample; a plot called the 'initial argon diagram' by Roddick & Farrar (1971). Data points in this diagram always lie on a straight line if it is simply a matter of mixing of two separate phases (e.g., Hayatsu & Carmichael, 1970; Roddick & Farrar, 1971; Harper *et al.*, 1973), but are scattered in other cases (e.g., McDougall et al., 1969; Wilson, 1972; this paper, Fig. 4). The second type of isochron is analogous to a Rb-Sr isochron, and involves the calculation and plotting of the total $^{40}Ar/^{36}Ar$ ratio and the $^{40}K/^{36}Ar$ ratio for each sample. This plot, called an 'isochron diagram' by Roddick & Farrar, may under rare circumstances give a straight line even where the data points are scattered on the initial argon diagram. This plot enables us to calculate a date and initial $^{40}Ar/^{36}Ar$ ratio, exactly as in the Rb-Sr method. The theory of both types of isochron plot is fully described by McDougall et al. (1969), Hayatsu & Carmichael (1970), and Roddick & Farrar (1971). In the present study, we have followed McDougall et al. in plotting duplicate analyses separately in both the initial argon and isochron diagrams, but have used only the means of these when regressing the isochrons. The isochrons were computed using the method of McIntyre et al. (1966); we have obtained only Model I isochrons, in which a value of more than unity for the mean square of weighted deviates (MSWD) indicates that the scatter is of geological origin, and not caused by experimental error.

The values of percent K and radiogenic ^{40}Ar in STP cm^3/g were taken directly from Stewart (1971b) and used in preparing the initial argon diagrams discussed below. The coefficients of variation used in the regressions for these diagrams were set at 1.5% for K, and 1.5% for ^{40}Ar. For the isochron diagrams, the total $^{40}Ar/^{36}Ar$ ratios and $^{40}K/^{36}Ar$ ratios were calculated from the same 1971 data, and the results are set out in Table 1; the coefficients of variation here were set at 2.0% for $^{40}K/^{36}Ar$, and 0.5% for $^{40}Ar/^{36}Ar$.

K-Ar isochrons for cover rocks

The four muscovite samples from the Heavitree Quartzite and the schist sample from the Bitter Springs Formation lie near isochrons in both the initial argon diagram (Fig. 2) and the isochron diagram (Fig. 3). In the initial argon diagram, the isochron passes close to the origin (y-intercept = $8.7 \pm 6.7 \times 10^{-6}$ STP cm^3/g), and its slope gives a date of

TABLE I

K-Ar data for isochron diagrams, western part of

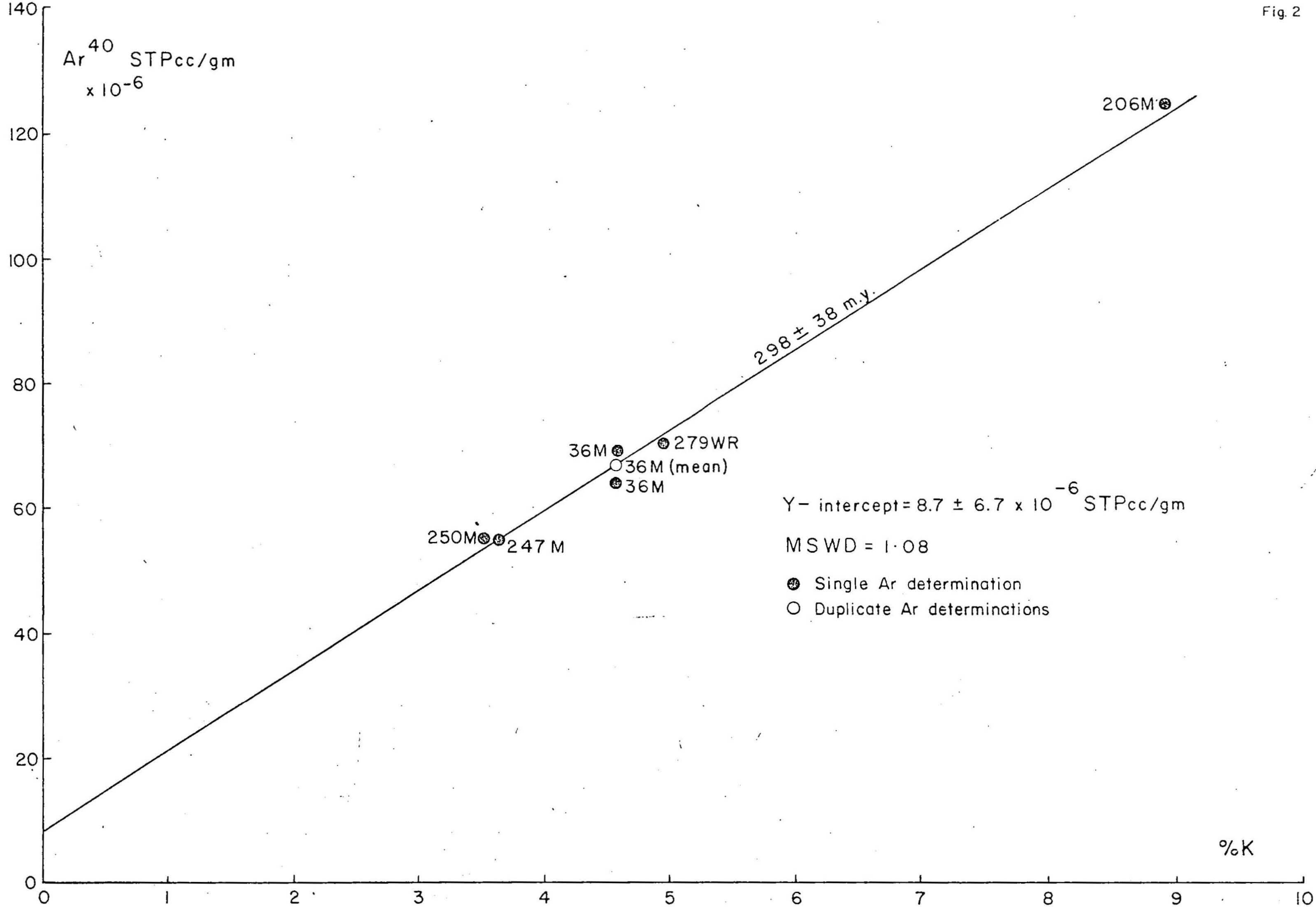
Arltunga Nappe Complex

nple No.*	$(^{40}Ar/^{36}Ar)_{total}$ x 10^3	$^{40}K/^{36}Ar$ x 10^4	K-Ar Date**	Sample No.*	$(^{40}Ar/^{36}Ar)_{total}$ x 10^3	$^{40}K/^{36}Ar$ x 10^4	K-Ar Date**
sement Rocks, northern part of nappe							
M(30)	0.985	2.795	380	336M(13)	2.273	7.608	399
B(17)	1.735	5.712	388	336B(10)	2.955	1.541	1775
M(5)	5.910	21.337	403	350B(4)	7.380	12.469	783
M(23)	1.285	3.802	399	350B(12)	2.463	3.855	776
B(8)	3.695	5.112	889				
M light(2)	14.771	51.099	431	Heavitree Quartzite			
M heavy(6)	4.929	20.481	352	36M(28)	1.056	3.631	327
B(14)	2.111	4.882	548	36M(7)	4.228	17.887	343
7M(19)	1.555	5.618	349	206M(2)	14.756	70.238	322
7M(7)	4.219	17.984	340	247M(15)	1.969	7.521	346
7B(4)	7.392	8.545	1058	250M(8)	3.688	14.695	358
8M(9)	3.284	3.514	1077				
8B(14)	2.109	7.574	370	Bitter Springs Formation			
1M(21)	1.407	4.464	384	279WR(33)	0.895	2.843	330
1M(19)	1.555	4.961	390				

With percent air correction in parentheses

Conventionally computed K-Ar date in m.y., from Stewart (1971b); means of duplicate dates not shown.

Fig. 2



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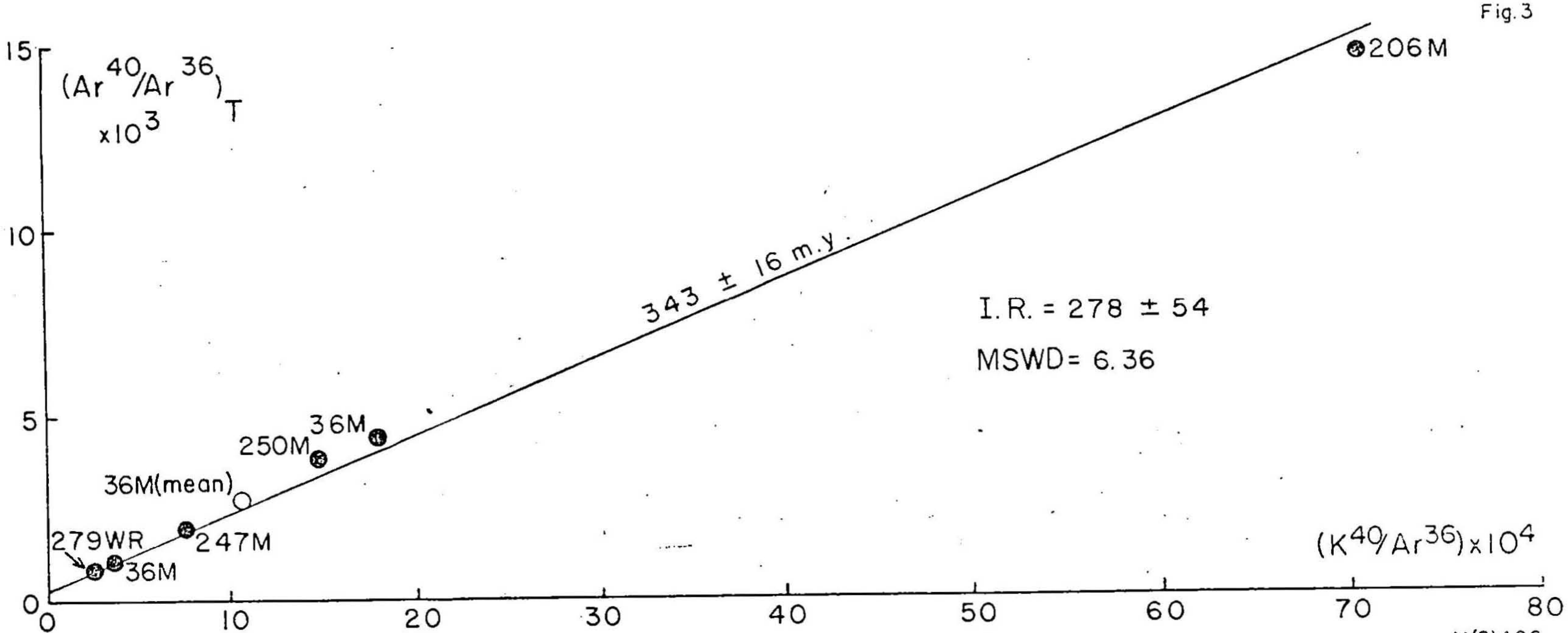
M(G)404

Fig. 3



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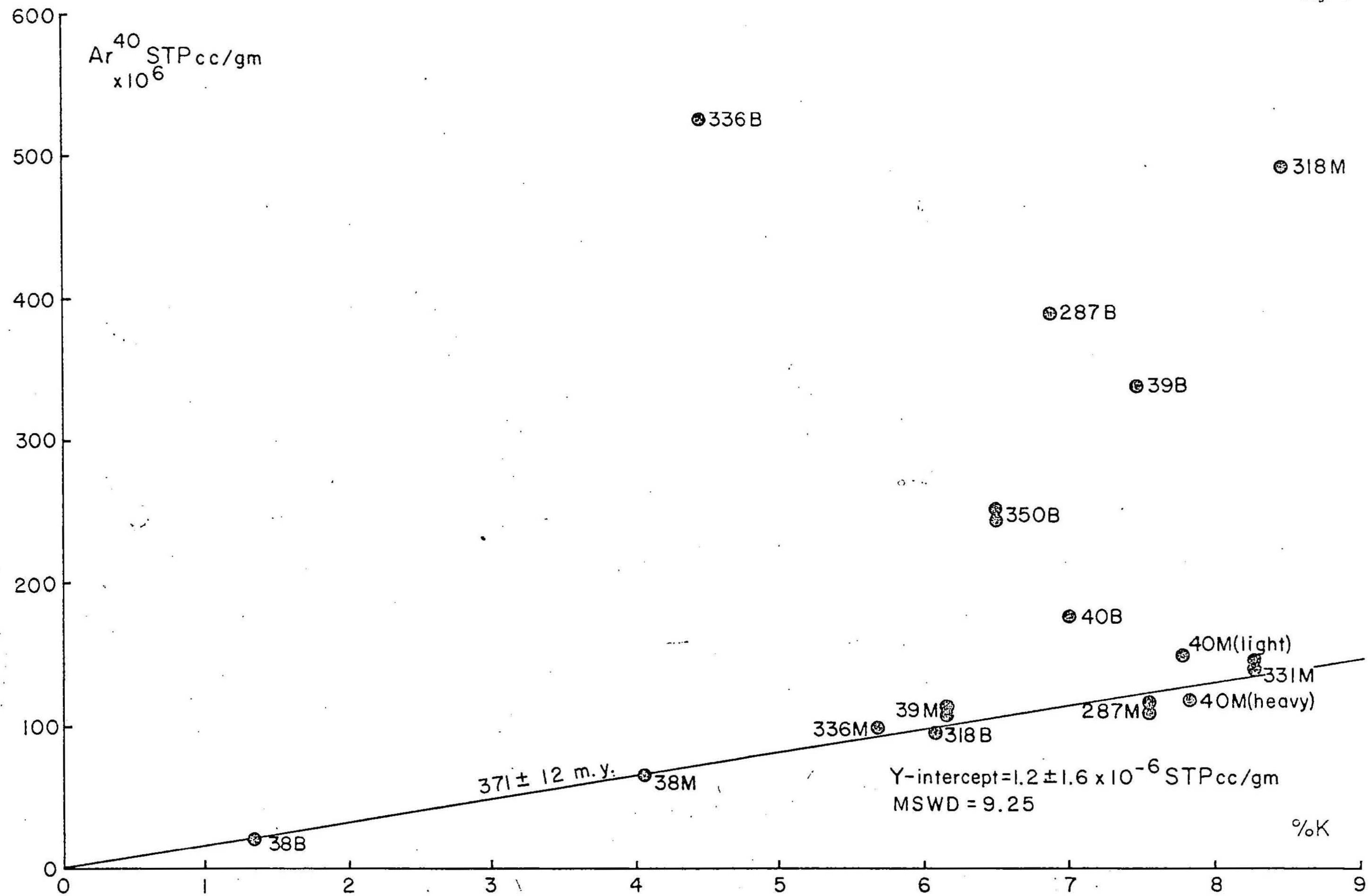
298 ± 38 m.y. The mean square of weighted deviated is 1.08. The result is strongly controlled by the single point 206M. In the isochron diagram (Fig. 3) the isochron gives a date of 343 ± 16 m.y., and has an initial $^{40}Ar/^{36}Ar$ ratio of 278 ± 54. The mean square of weighted deviates is 6.36, which indicates that the scatter of the points is too great to be explained by experimental error alone. The initial ratio coincides, within experimental error, with the present-day ratio of atmospheric argon. Hence, the individual K-Ar dates computed in the conventional manner for these five samples are as good as or better than the isochron dates, and nothing is gained by using the latter.

<u>K-Ar isochrons for basement rocks, northern part of nappe</u>.

The initial argon diagram for the seven biotite and eight muscovite samples from the basement rocks in the northern part of the nappe is shown in Figure 4. Seven of the muscovites plot near the bottom of the field of points, and an isochron regressed through six of them (38M, 39M, 40M (heavy), 287M, 331M, and 336M), plus two concordant biotites (18B and 318B), gives a date of 371 ± 12 m.y., with a y-intercept = 1.2 ± 1.6 x 10^{-6} STP cm^3/g, which is indistinguishable from zero; the mean square of weighted deviates is 9.25. The other five biotite and two muscovite points (40M (light), 431 m.y., and the basement muscovite (318M) that gave 1077 m.y.) are scattered about the diagram above the isochron in seemingly random fashion. In the isochron diagram for all 15 micas (Fig. 5), an isochron passing through the same six muscovites and two biotites gives a date of 372 ± 14 m.y. and an initial ratio of 326 ± 45. The mean square of weighted deviates is 11.06, indicating that the scatter is geological, not experimental. The initial ratio is not significantly higher than 295.5, indication virtually no anomalous initial $^{40}Ar/^{36}Ar$ in the samples. The poor fit of the samples to the isochron suggests slightly different ages or initial ratios. Thus the conventionally computer K-Ar dates on the eight micas on the isochron are just as meaningful as the isochron date; the isochron merely provides an unusual weighted-mean date for the suite of samples regressed.

Fig. 4



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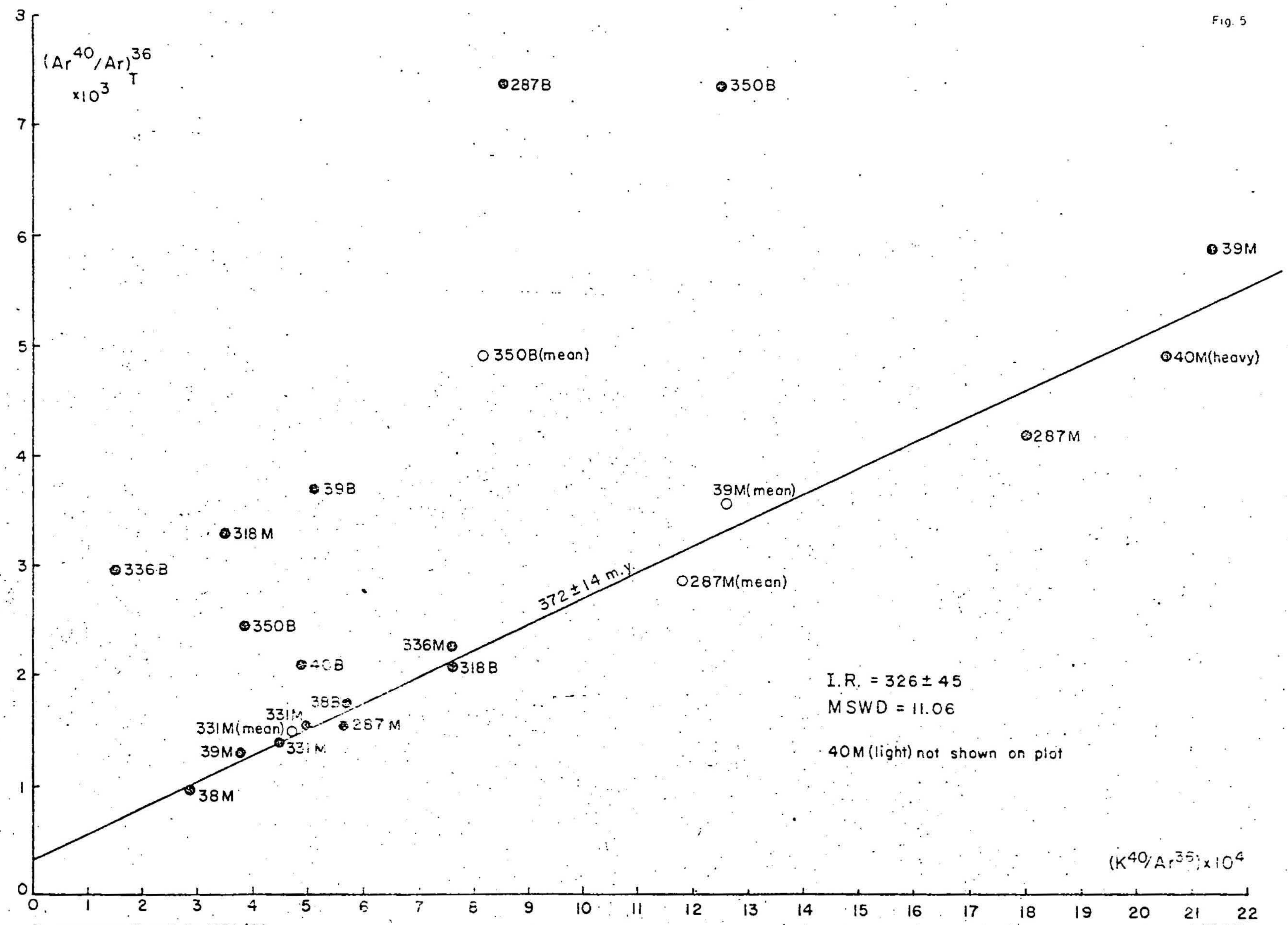

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RB-SR RESULTS

The locations of the samples used are shown in Figure 1, and the results of the rubidium and strontium analyses are set out in Table II. Five isochrons have been calculated from the data, and are discussed in turn.

Whole-rock isochron for Arunta basement rocks

Seven whole-rock samples, comprising four from the northern part of the White Range Nappe (samples 39, 40, 200, and 350) and three from the autochthon west of the White Range Nappe (samples 95, 96, and 97), define an isochron which gives a date of 1625 ± 22 (1723 ± 23) m.y. (Fig. 6). The initial ratio is low (0.7051), which suggests that the isochron has not been lowered by ^{87}Sr redistribution. Thus, 1723 m.y. appears to be the time of commencement of retention of radiogenic ^{87}Sr by the Arunta basement rocks in this area, and can probably be taken as the age of differentiation or of the first and only regional metamorphism of these rocks. The date agrees within experimental error with the whole rock isochron date of about 1710 m.y. given by four samples of basement rock from the Giles Creek Synform, in the southernmost part of the nappe complex, south and southeast of the area of the present study (R. Bennett, pers. comm. in Cooper et al., 1971).

All seven samples on the isochron have Rb/Sr ratios less than 3. In contrast, three mica-rich whole-rock samples from the southern part of the White Range Nappe have Rb-Sr ratios greater than 12, and lie below the isochron (Fig. 7), indicating that the ^{87}Sr in these samples has been remobilized on a modest scale, allowing Sr isotopic exchange or ^{87}Sr loss, or Sr loss, or, less likely, Rb enrichment of the already Rb-rich materials.

Rb-Sr mica dates from apparently unaltered to slightly retrograded Arunta basement rocks

Two of the sampes (nos. 96 and 350) gave whole-rock-biotite isochron dates that are comparable to, although slightly greater than, the K-Ar dates determined on the same biotite concentrates. Sample 96, from

Fig. 6

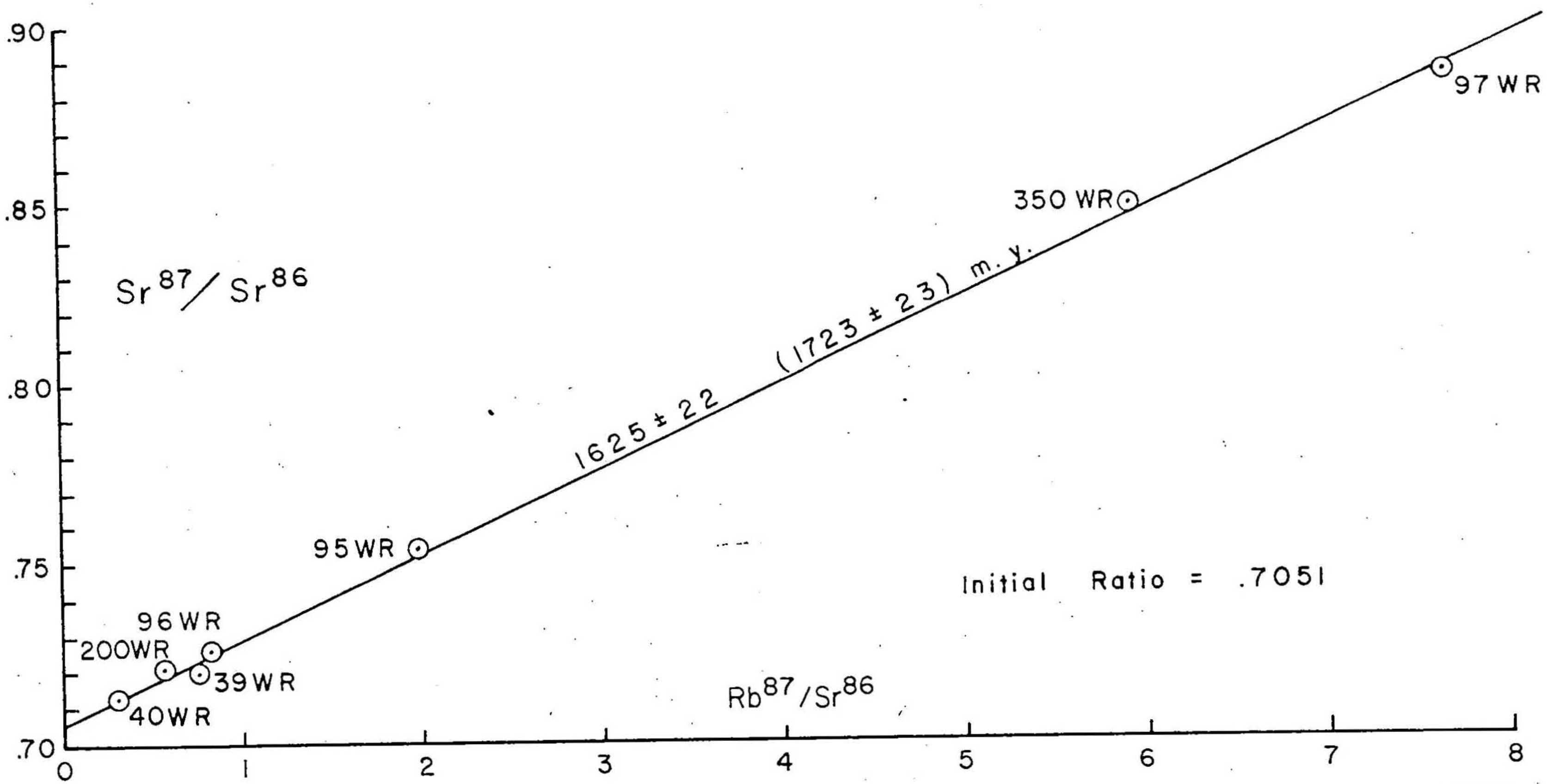

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TABLE II

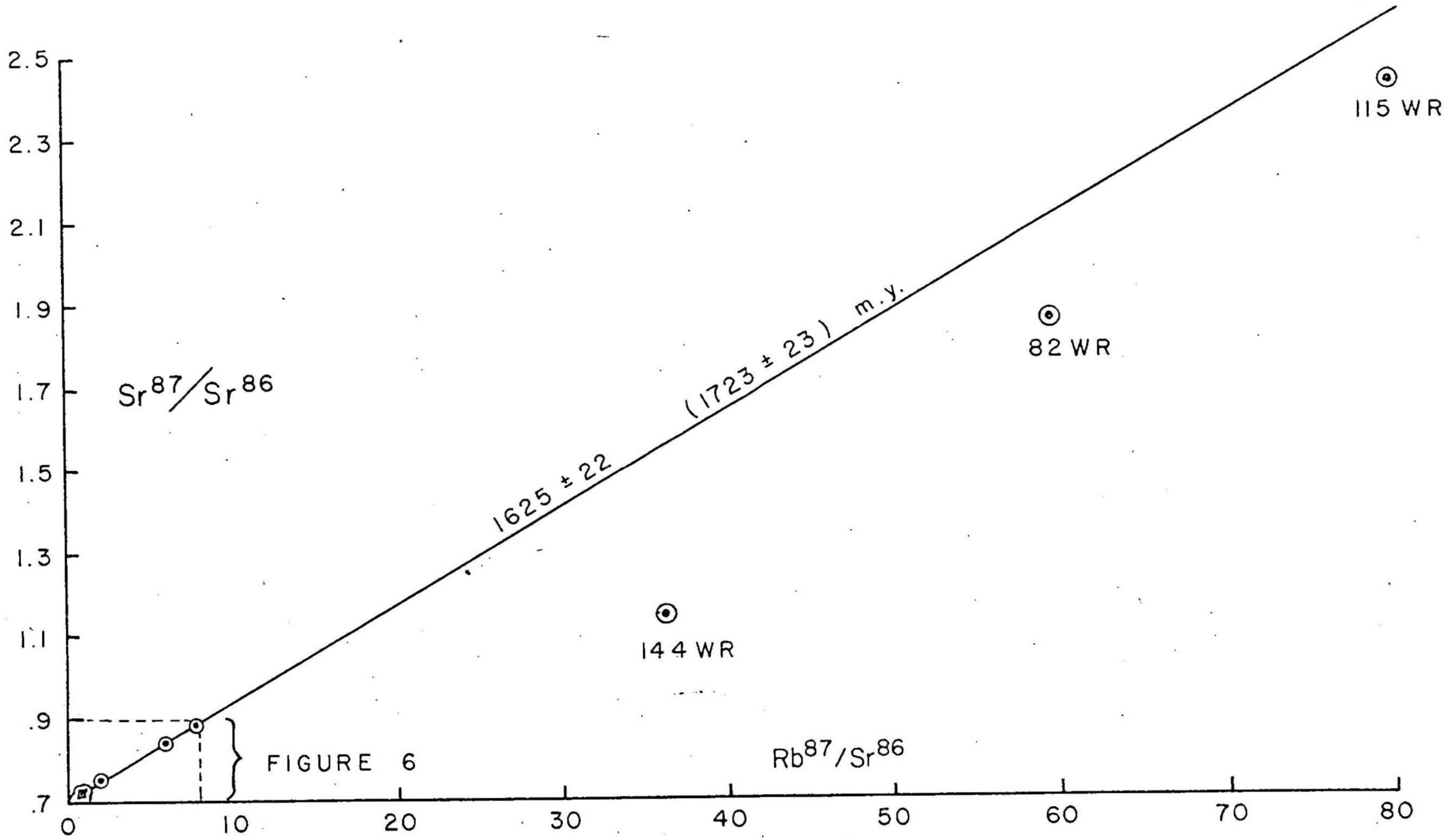
Sample data and Rb/Sr analytical data on basement rocks and minerals from the western part of the Arltunga Nappe Complex*

Sample No.	Material dated	Rb ppm	Sr ppm	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Whole rocks						
39	Metatonalite	81	307	.264	.764	.7203
40	Metatonalite	50	437	.114	.331	.7127
32	Biotite-muscovite schist	227	11	20.6	59.6	1.8608
95	Granodiorite gneiss	174	254	.685	1.98	.7544
96	Gneissic granite	258	891	.289	.836	.7261
97	Gneissic granite	374	141	2.65	7.68	.8854
115	Coarse biotite mass in amphibolite	348	13	27.6	79.9	2.4395
144	Biotite gneiss	176	14	12.5	36.3	1.1455
200	Amphibolite	26	131	.196	.567	.7210
350	Garnet-biotite gneiss	107	52	2.05	5.94	.8490
Minerals						
39	Biotite	380	35	10.9	31.6	.8672
40	Muscovite ($\rho < 2.9$)	168	100	1.68	4.85	.7380
40	Biotite	378	102	3.73	10.79	.7534
96	Biotite	396	194	2.04	5.91	.8057
350	Biotite	380	41	9.3	27.2	1.1148

* Rb and Sr concentrations and ratios were measured by X-ray fluorescence using U.S. Geological Survey rock standards to establish working curves. Estimated 1σ errors for concentration are 1 ppm or 5% (whichever is larger), and for Rb/Sr ratio 3%, if ratios lie between 0.1 and 10. Sr isotopic compositions were measured on a 60° sector 12-inch-radius solid-source mass spectrometer of modified U.S. National Bureau of Standards design, constructed by H. Faul. The data were obtained on a strip chart recorder with expanded scale and have 1σ errors of approximately 0.0003. All results are normalized, and adjusted so that the Eimer & Amend standard Sr gives $^{87}Sr/^{86}Sr$ = 0.7080.

All dates were calculated using the ^{87}Rb decay constant = 1.47×10^{-11} yr^{-1}. However, the convention in Australia is to use the ^{87}Rb decay constant = 1.39×10^{-11} yr^{-1}, and the corresponding dates using this value are shown in parentheses. The correct value probably lies between these extremes, close to 1.43×10^{-11} (Armstrong, in prep.). Brief petrographic descriptions of the rock samples are given in the Appendix.

Fig. 7



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the autochthon, gave a Rb-Sr date of 1060 (1124) m.y., compared to a K-Ar date of 997 m.y., and sample 350 from the northern part of the White Range Nappe gave a Rb-Sr date of 850 (901) m.y., compared to a corresponding K-Ar date of 780 m.y. (Fig. 8). Sample 96 shows only slight retrogressive metamorphic effects (which are indistinguishable from deuteric alteration; see Appendix), and sample 350 shows no apparent retrogression. Thus, it seems that these dates result from different degrees of Sr and Ar loss (Ar more than Sr). This is identical with the loss pattern observed by Hart et al. (1968) and Aldrich et al. (1965). The losses probably occurred during the Alice Springs Orogeny, as this was the only event accompanied by significant warming that affected the area after the regional metamorphism at about 1700 m.y. ago.

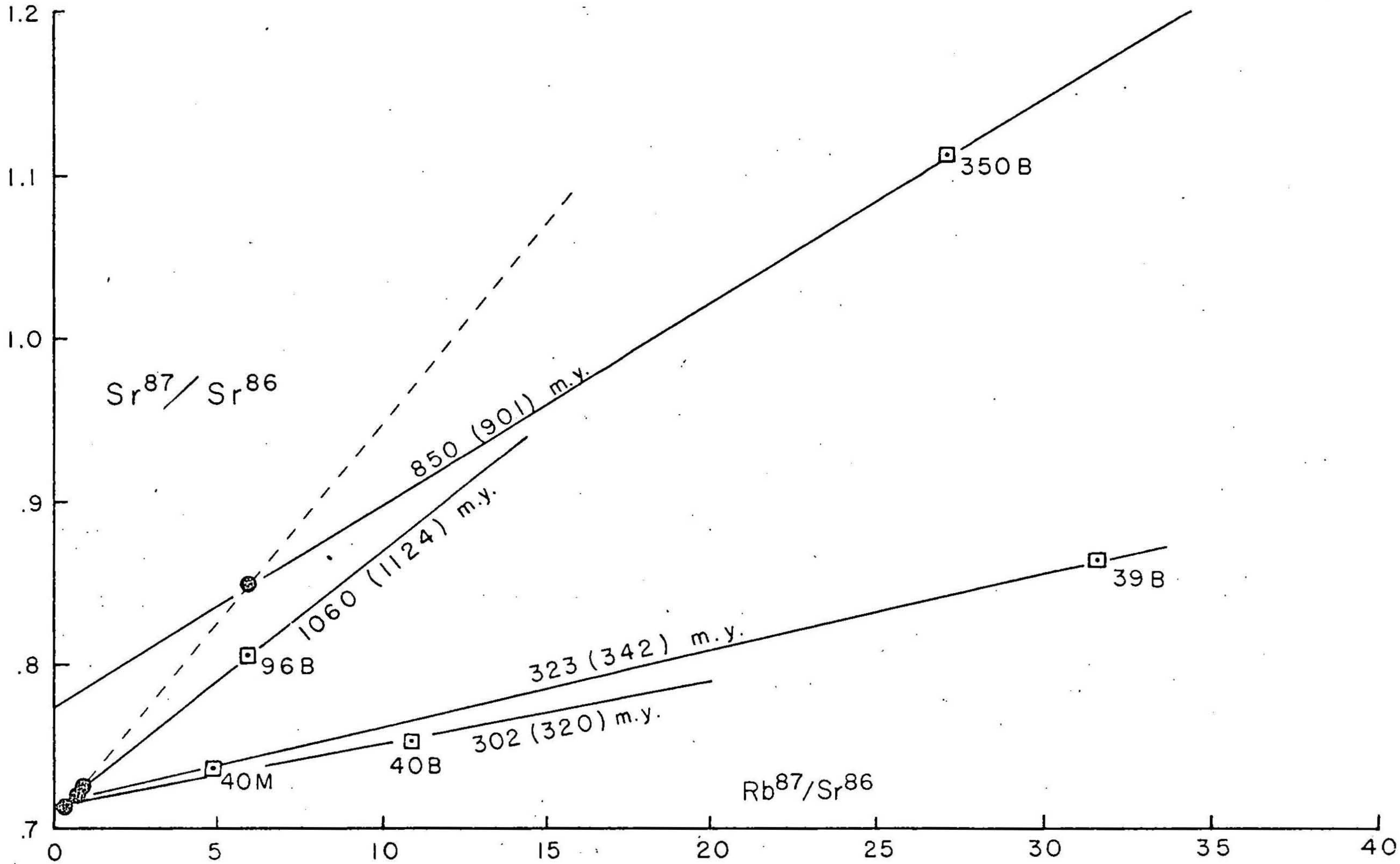
Rb-Sr mica dates from retrograded basement rocks

Sample 39 gives a whole-rock-biotite isochron of 323 (342) m.y. (Early Carboniferous) (Fig. 8), indicating that the biotite crystallized (or completely recrystallized) during the Alice Springs Orogeny. The same biotite gave a conventional K-Ar date of 889 m.y. The large discordance with Rb-Sr date $\ll$ K-Ar date indicates the existence of a considerable amount of excess ^{40}Ar in the biotite of sample 39.

Sample 40 gave a whole-rock-muscovite-biotite isochron of 302 (320) m.y. (Middle Carboniferous) (Fig. 8), and so, as in sample 39, complete (re)crystallization of the biotite during the Alice Springs Orogeny is indicated. The biotite (40B) gave a conventional K-Ar date of 548 m.y., and lies distinctly above the K-Ar isochrons of Figures 4 and 5. The muscovite (40M(light)) gave a conventional K-Ar date of 431 m.y. Evidently, both micas contain a moderate amount of excess ^{40}Ar.

Samples 39 and 40 come from the same deformed and retrogressively metamorphosed body of tonalite on the northern side of the White Range (Fig. 1). Neither thin-section examination of the rocks nor the Rb-Sr dates given by the biotites, tells us whether the biotite is an old (Precambrian) mineral that was completely recrystallized during the later

Fig. 8



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(Carboniferous) retrogressive metamorphism, or a new mineral that formed a for the first time during the retrogressive metamorphism. The tonalite is thoroughly retrograded, and the alteration includes brecciation of andesine and its conversion to albite + epidote + white mica (muscovite and paragonite), and the recrystallization of quartz (see Appendix). Nevertheless, in spite of the alteration the tonalite parentage of the rock is still easily seen, and so the rock presumably contained biotite as a normal and essential original constituent. Thus, the biotite now present in the samples is probably an old mineral that was completely recrystallized under middle greenschist facies conditions during the Alice Springs Orogeny, and contains excess argon in amounts that differ from place to place.

DISCUSSION

The K-Ar isochron diagrams for basement rocks of the Arltunga area suggest excess ^{40}Ar in the biotite and muscovite samples that scattered above the calculated isochrons, and this has been confirmed by Rb-Sr dating. The micas containing excess Ar come from rocks that underwent extensive retrograde metamorphism 1400 m.y. after their initial crystallization. Thus considerable radiogenic Ar would have been available for incorporation into newly formed minerals or to inhibit diffusion loss of Ar from old minerals. Sr on the other hand was free to exchange between mineral phases even though not removed or redistributed on a large scale. By analyses of whole-rock-mineral pairs we can correct for anomalous initial Sr in new or reconstituted minerals. This is simply not possible in the case of Ar, as we can assume neither a constant level of excess Ar in different minerals nor a constant $^{40}Ar/^{36}Ar$ ratio in rock systems undergoing metamorphism. In fact, most of the ^{36}Ar comes from atmospheric contamination which is quite independent of the geological history of an analysed specimen. Thus, much of the scatter on the $^{40}Ar/^{36}Ar$ isochron diagram is meaningless (as is shown by the spread of results for 39M). This criticism does not apply to the Ar/%K diagram.

The mineral most susceptible to excess ^{40}Ar incorporation in the Arltunga area is biotite, but muscovite is not immune. Excess ^{40}Ar did not appear in progressively metamorphosed cover rocks. In relatively young and wet sediments undergoing heating, the fluid phase is probably predominantly H_2O; the mole fraction of Ar, even if it were quantitatively retained within the rocks during metamorphism (and it probably is not) would be exceedingly low, and thus unlikely to be incorporated into minerals. Conversely, in old basement rocks little water and relatively large amounts of Ar will be available for interstitial fluids.

If excess argon is suspected, the only really significant line that can be drawn on the K-Ar isochron diagram is the lower-bound isochron drawn to pass through the origin (0 Ar, 0%K) or through $^{40}Ar/^{36}Ar = 295.5$. The isochron date thus obtained will have the same significance as any conventional K-Ar date, being close to, or even younger than, the age of metamorphism of the rocks being studied.

CONCLUSIONS

The conclusions can be summarized as follows:

1. The Rb-Sr whole-rock isochron determined on seven samples of Arunta basement rock from the autochthonous and root zones of the Arltunga Nappe Complex indicates that differentation or intense regional metamorphism in these rocks finished about 1723 m.y. ago.

2. The Rb-Sr whole rock-mica isochrons determined on retrogressively metamorphosed basement rocks from the root zone of the Altunga Nappe Complex date the time of the Alice Springs Orogeny as Early to Middle Carboniferous. This agrees with K-Ar lower-bound isochron dates from the same rocks, with K-Ar dates (isochron or conventional) from the progressively metamorphosed Heavitree Quartzite in the nappe complex (Stewart, 1971b), and with the stratigraphic evidence.

3. The retrogressive metamorphism that accompanied the Alice Springs Orogeny was of the middle greenschist facies in the root zone of the nappe complex. However, the 1723 m.y. whole rock date and the low initial ratio indicate that the retrogression was unable to homogenize the $^{87}Sr/^{86}Sr$ ratio throughout the Arunta basement, although it was able to do this on the millimetre to centimetre scale.

4. Comparison of K-Ar and Rb-Sr dates of the micas in the basement rocks from the root zone of the nappe complex indicates that the spread in the conventionally computed K-Ar dates from the same micas has two causes:

(i) In thoroughly retrograded rocks, it is caused by the presence of excess argon in recrystallized (or new) biotite.

(ii) In slightly retrograded or seemingly non-retrograded rocks, it is caused by partial loss of argon from old (Precambrian) biotite.

It thus appears that K-Ar dating of metamorphic rocks, especially those in or near a region of retrogressive metamorphism, is likely to give equivocal results. Confirmation of these results by Rb-Sr dating is desirable, and necessary in situations where partial argon loss has occurred, or excess Ar is suspected.

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Appendix I - Descriptions of samples used in Rb-Sr study

The specimen localities of the samples described below are shown in Figure 1. Hand specimens and thin sections of all the samples are stored in the Kline Geology Laboratory, Yale University, New Haven, Connecticut; thin-section off-cuts are held at the Bureau of Mineral Resources, Canberra, A.C.T. Volume percentages of minerals are visual estimates only. Anorthite (An) percentages of plagioclase are estimated from extinction angles of lamellar albite twinning.

Sample 39: <u>Metatonalite</u>

This rock consists of broken fragments of andesine (An_{41}) (52%), commonly much sericitized, in a medium-grained streaky groundmass of quartz (35%) with a polygonal mosaic texture, oriented flakes of biotite (5%) and muscovite (5%), and clear anhedral to subhedral grains of epidote (3%). Chlorite is absent, both in thin section and in X-ray diffractograms of the biotite concentrate. X-ray diffraction analysis of the white mica concentrate showed that it consists of about 75% muscovite and 25% paragonite (by comparison of the heights of the 3.3 Å and 3.2 Å peaks). The small polygonal grains of quartz show undulatory extinction and deformation lamellae.

Sample 40: <u>Metatonalite</u>

This rock is similar to sample 39, and consists of broken pieces of poikiloblastic albite (An_{03}) (46%) containing coarse laths of muscovite, in a groundmass of recrystallized quartz (35%) in elongate aggregates of small polygonal grains, biotite (2%), muscovite (12% total), epidote (5%) in strings of small grains, and rare sphene and apatite. Some albite fragments have small irregular cores of microcline microperthite (less than 1% of the total), and the albite filaments of the microperthite are in optical continuity with the host albite. No chlorite was detected in thin section nor in X-ray diffractograms of the biotite concentrate.

The textures and mineral assemblages of samples 39 and 40 indicate that the albite originated by the breakdown of andesine, the anorthite component reacting to form additional albite as follows:

$$6CaAl_2Si_2O_8 + KAlSi_3O_8 + 3H_2O + Na^+$$

anorthite microcline

$$= NaAlSi_3O_8 + 3Ca_2Al_3(O(OH)Si_2O_7.SiO_4) + KAl_2Si_3AlO_{10}(OH)_2 + H^+$$

albite epidote muscovite

A possible source for the water and sodium necessary for the reaction could have been the Upper Proterozoic marine sediments below the White Range Nappe, which would have lost connate water and water bound in clay during their progressive metamorphism to sericitic quartzite and schist.

Sample 82: Biotite-muscovite schist

This sample in the field appears to be a strongly foliated schistose granite with no trace of bedding or layering visible. It consists of quartz (60%) as small anhedral grains and large lenticular grains with numerous deformation lamellae, muscovite (30%) in large kinked blades, and biotite (10%) which is also kinked. No feldspar is present, but if the rock is a metamorphosed granite (as indicated by the field evidence), the reaction

$$3KAlSi_3O_8 + 2H^+ = KAl_2Si_3A_{10}(OH)_2 + 6SiO_2 + 2K^+$$

microcline muscovite quartz

could account for the lack of feldspar, and would be consistent with the high quartz content.

Sample 95: Gneissic granodiorite

This is a typical medium-grained foliated granodiorite, and consists of anhedral elongate grains of quartz (20%) with undulatory extinction, andesine (50%), biotite (15%), microcline (10%) in large anhedral grains with very indistinct twinning, hornblende (5%), and sphene (about 1%) as an abundant accessory.

Sample 96: Gneissic granite

This rock is a somewhat retrogressively metamorphosed granite, and consists of quartz (10%) with undulatory extinction, microcline (62%), strongly sericitized plagioclase (22%), biotite (3%) substantially altered to chlorite, hornblende (2%), sphene (1%), and accessory epidote and allanite.

Sample 97: Gneissic granite

This rock is a fine-grained leucocratic granite with a xenoblastic texture, and is composed of large grains of quartz (30%) with prominent prismatic kink bands, together with numerous small anhedral quartz grains, microcline (60%) with patchy uneven twinning and undulatory extinction, sericitized oligoclase (5%), and biotite (5%).

Sample 115: Biotite rock

This rock forms a tabular dyke-like mass of coarse mica with garnet porphyroblasts up to 10 cm across, cutting through an outcrop of garnet-bearing amphibolite. In thin section, the garnet-free part of the rock is found to consist solely of green biotite with uneven extinction.

Sample 144: Biotite gneiss

The rock is a specimen of the medium to coarse-grained quartz-rich biotite gneiss that makes up much of the basement rock of the western part of the White Range Nappe. It is composed of quartz (65%) with strong undulatory extinction, oligoclase (28%) which is strongly sericitized, biotite (5%), and muscovite (2%); both micas are markedly bent and kinked.

Sample 200: Amphibolite

This sample is typical of the pods of amphibolite in the basement rock of the White Range Nappe, and consists of green hornblende (85%), andesine (15%) substantially altered to sericite + epidote + calcite, and accessory ilmenite rimmed with sphene.

Sample 350: <u>Garnet-biotite gneiss</u>

This is a fine-grained garnet-bearing variant of the quartz-rich biotite gneiss, and is composed of quartz (40%) with undulatory extinction, oligoclase (40%) which is markedly fractured, biotite (15%), garnet (2%), opaque iron oxide (2%), and microcline (1%).