DEPARTMENT OF NATIONAL RESOURCES

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

RECORD 1975/26

GEOCHRONOLOGY AND RELATED ASPECTS OF PROTEROZOIC ACID VOLCANICS AND ASSOCIATED GRANITES OF THE GRANITES-TANAMI REGION, NORTHWESTERN AUSTRALIA

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ABSTRACT

Proterozoic acid volcanics are associated with granitic intrusions in the northeast and southwest parts of The Granites-Tanami region, in northwestern Australia. In the northeast the Mount Winnecke Formation, which consists of rhyolitic lava flows and pyroclastics, and tuffaceous and non-tuffaceous sediments, is intruded and weakly metamorphosed by the high-level Winnecke Granophyre. Most, if not all, of the acid volcanicity probably took place under water. The acid volcanics and the Winnecke Granophyre have similar major element compositions, and this, together with the field evidence, indicates that they were probably comagmatic. Rb-Sr total rock and mineral data for the Winnecke Granophyre are concordant, and yield an isochron indicating the age of emplacement at 1802 $\pm$ 15 m.y. and an initial Sr^{87}/Sr^{86} of 0.7074 $\pm$ 0.0036. Isotopic data for the lavas of the Mount Winnecke Formation are somewhat equivocal, but provide a preferred age estimate of 1808 $\pm$ 15 m.y. and an initial Sr^{87}/Sr^{86} of 0.7052 $\pm$ 0.0038. The possible correlation between these acid igneous rocks and similar rocks in the Kimberley region to the west is discussed.

In the southwest of the region another acid volcanic suite, belonging to the Pollock Hills Formation, is intruded and weakly metamorphosed by the Mount Webb Granite. As in the northeast, the volcanics and intrusives have similar major element compositions, and are considered to be comagmatic. Combining Rb-Sr isotopic data from both the volcanics and intrusives yields an isochron indicating an age of 1526 $\pm$ 25 m.y. and an initial Sr^{87}/Sr^{86} of 0.711 $\pm$ 0.004. These rocks are appreciably younger than those of the Winnecke igneous suite, and are also younger than other granitic rocks cropping out between the two suites.

INTRODUCTION

Acid volcanics and associated granitic rocks were mapped in the northeast and southwest parts of The Granites-Tanami region, northwestern Australia, during a recent geological survey by the Australian Bureau of Mineral Resources and the Geological Survey of Western Australia. The acid volcanics in the northeast form part of the Mount Winnecke Formation (Blake et al., 1975), previously named the Mount Winnecke Sandstone (Traves, 1955), and the associated granitic unit which intrudes the formation is the Winnecke Granophyre (Traves, 1955). The acid volcanics in the southwest belong to the Pollock Hills Formation and are intruded by the Mount Webb Granite these two units are defined by Blake & Towner, 1974. In both the northeast and southwest the geological setting and petrographic and chemical features indicate that the volcanics and associated granitic rocks may be comagmatic and of more or less similar age. An Rb-Sr age study has been undertaken to test this hypothesis, and also to determine the initial Sr^{87}/Sr^{86} of the plutonic and volcanic units. The ages obtained, which are the first recorded for igneous rocks from The Granites-Tanami region, are compared with those of similar rocks in the Precambrian Kimberley and Arunta regions.

The Granites-Tanami region straddles the Northern Territory/ Western Australia border northwest of Alice Springs, and is a semi-desert area in which mainly Precambrian rocks are largely covered by superficial Cainozoic sediments. It lies between the Precambrian Halls Creek Mobile Zone to the northwest, the Victoria River Basin to the north, and the Arunta Block to the south and southeast, and is bounded to the west and east respectively by the Phanerozoic Canning and Wiso Basins (Fig. 1). The oldest rocks exposed are regionally metamorphosed sedimentary and volcanic rocks which are mapped as the Tanami complex and, in the south, as part of the Arunta Complex. These rocks are correlated with the Halls Creek Group of the Halls Creek Mobile Zone in the Kimberley region, and are Archaean or Lower Proterozoic (Dow &

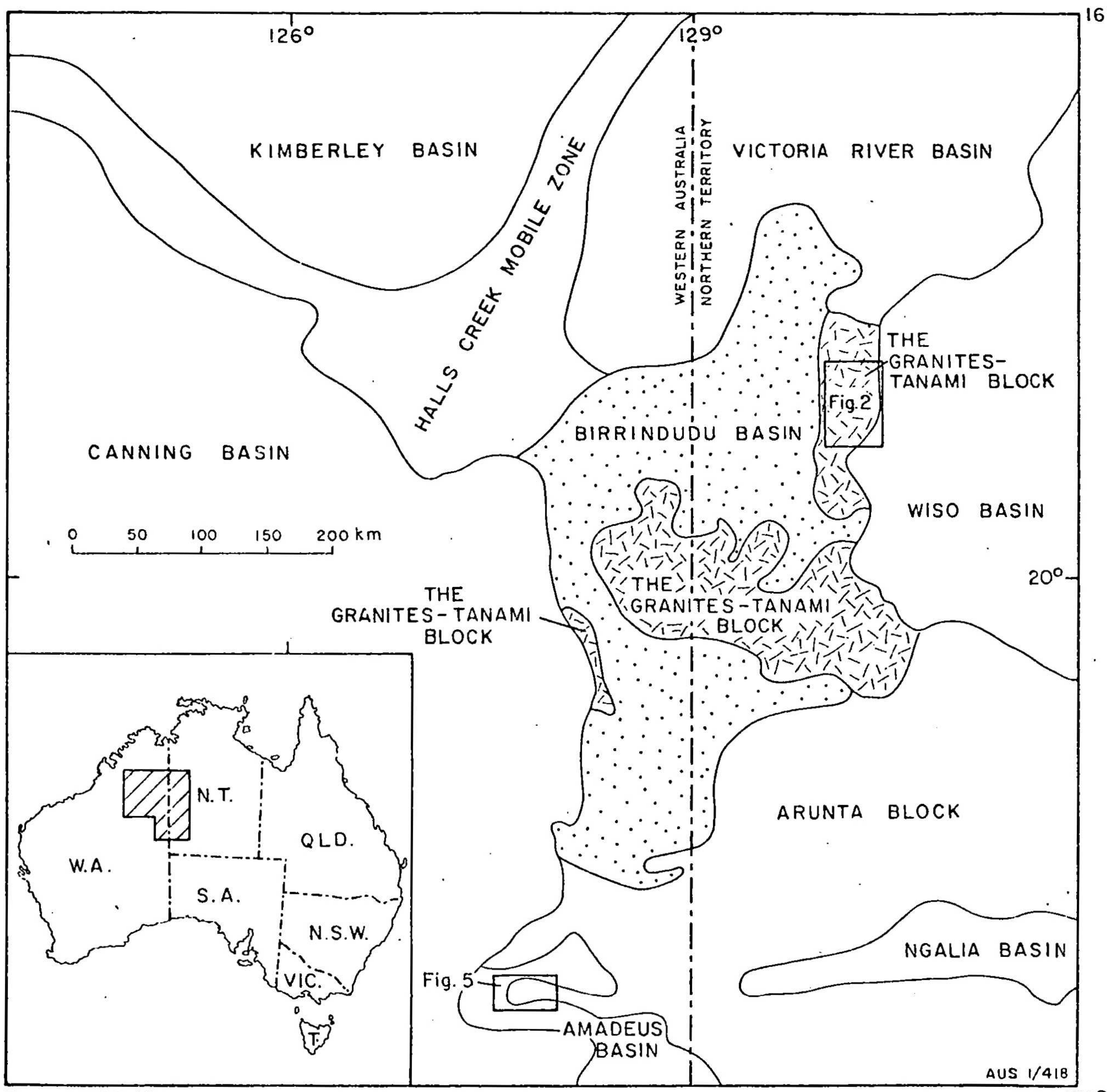

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Fig. 1 Locality map of The Granites-Tanami Region

Gemuts, 1969; Gellatly, 1971). They are overlain unconformably by Lower Proterozoic and Carpentarian units, including the Mount Winnecke and Pollock Hills Formations, and are intruded by Lower Proterozoic and Carpentarian granitic rocks. The granites and the rocks they intrude together form The Granites-Tanami Block and part of the Arunta Block, and are the basement on which the mainly clastic sediments of the Birrindudu Basin and northwestern part of the Amadeus Basin were deposited. Most of the Birrindudu Basin sediments belong to the Carpentarian Birrindudu Group and the Adelaidean Redcliff Pound Group, and the Amadeus Basin sediments are represented by the Adelaidean Heavitree Quartzite and Bitter Spring Formation.

Sampling and geochronological methods

Samples for Rb-Sr geochronological work were collected from The Granites-Tanami region in 1972 (Mount Winnecke Formation and Winnecke Granophyre) and 1973 (Pollock Hills Formation and Mount Webb Granite The chief criterion for choosing sample sites was the availability of exposed fresh rock, as over much of their outcrop areas the volcanic and granitic rocks are either intensely weathered or covered by superficial deposits. Where possible, several samples of visibly different rock types were collected from a site, either by hammer or by drilling and blasting, to give a maximum dispersion in Rb/Sr.

Most of the geochronological work was carried out using the Rb-Sr total rock technique. In addition, three biotite and five plagioclase mineral separates were isotopically analysed to test the behaviour of the Rb-Sr clock within these minerals, and hence determine whether or not there had been any significant tectonism subsequent to the igneous events. The analytical methods employed are described elsewhere (Page and Mahon in prep.). The Rb^{85}/Rb^{87} in natural Rb was taken as 2.600, Sr measurements were normalized to 8.3752 for Sr^{88}/Sr^{86}, and the value of $1.39 \times 10^{-11} yr^{-1}$ was used for the decay constant of Rb^{87}. Statistical regression of the Rb-Sr isochron was carried out using the computer program of McIntyre et al. (1966). The coefficients of variation for Rb^{87}/Sr^{86} and Sr^{87}/Sr^{86} have been taken as 0.5 percent and 0.01 percent, respectively.

MOUNT WINNECKE FORMATION AND WINNECKE GRANOPHYRE

The Mount Winnecke Formation and the Winnecke Granophyre which intrudes it are confined to the northeast of The Granites-Tanami region (Fig. 2). Contact metamorphic effects are only minor, and indicate, together with the types of intrusives rocks present, that the Winnecke Granophyre is a high-level intrusion. Both units are inferred to be overlain unconformably by the Carpentarian Birrindudu Group which crops out to the west, but contacts are concealed by superficial sediments.

The Mount Winnecke Formation is at least 4800 m thick, and consists of interbedded lithic to sublithic sandstone, tuffaceous sandstone, and siltstone containing over 15 percent volcanic material, acid lava flows, minor conglomerate and tuff, and rare agglomerate. These rocks have been folded into major anticlines and synclines with moderately to steeply dipping limbs. The lava flows and tuffs are generally less resistant to erosion than the sandstones, and commonly form depressions between steep-sided sandstone ridges and plateaux that are up to 50 m high. The sandstones are commonly poorly sorted, medium to coarse and locally pebbly, and show cross-bedding. Most sandstone beds are 1 m or more thick, but some beds of tuffaceous sandstone which are interbedded with tuffaceous siltstone are much thinner; only these thin beds commonly show ripple marks. Conglomerate is present locally, generally closely associated with tuffaceous sediments and acid volcanics.

The acid lava flows tend to be dome-shaped in cross-section, and some are probably over 200 m thick. The flows occur both singly and in groups, and they interfinger laterally with tuff, tuffaceous sediments, sandstone, and conglomerate. The interiors of the flows appear massive and structureless,

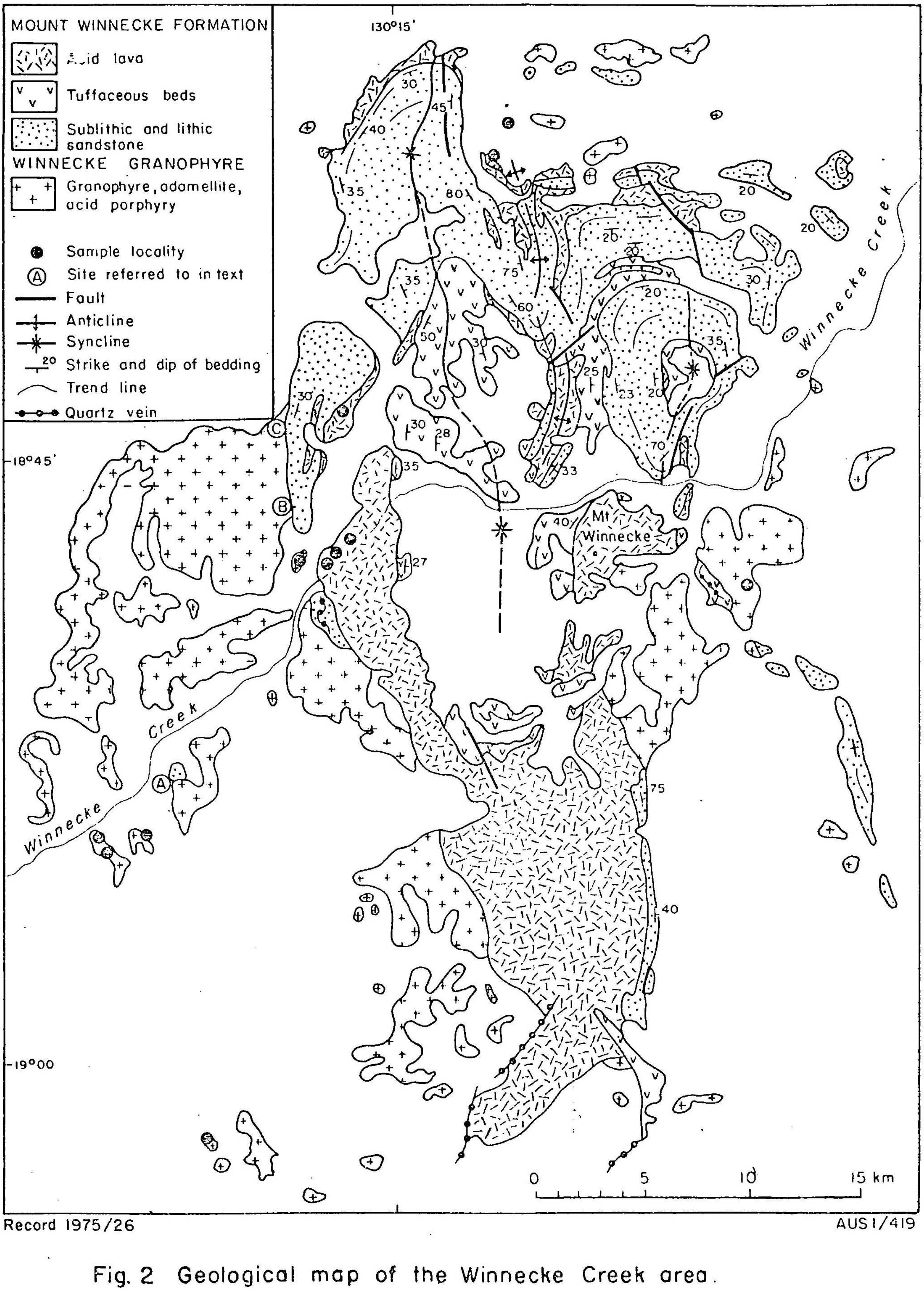

Fig. 2 Geological map of the Winnecke Creek area.

but the margins are blocky, owing to autobrecciation, and commonly scoriaceous, and at several localities they show contorted flow-banding. The exposed lavas are generally friable and iron-stained to bleached, owing to weathering, and exposures of relatively fresh lava are restricted to where the massive interiors of the thickest flows crop out.

The majority of the lavas contain phenocrysts of feldspar (sodic plagioclase or alkali feldspar or both), quartz and ferromagnesian minerals, and microphenocrysts of opaque minerals. The phenocrysts constitute up to 20 percent of the total rock, and are generally less than 1 cm across. Most phenocrysts of feldspar and all those of ferromagnesian minerals are completely altered, mainly to clay and sericitic material. Quartz and alkali feldspar phenocrysts show resorption features. The groundmass of the least altered parts of the lava flows is a medium to fine mosaic of quartz and alkali feldspar with some chlorite, but probably consisted originally of either microlites and glass or microcrystalline quartz and feldspar. Outlines of original microlites are commonly indicated by dust particles and opaque granules. Vesicles in scoriaceous lava are filled with quartz, celadonite and, at one locality, diaspore and pyrophyllite.

Most of the pyroclastics within the Mount Winnecke Formation are laminated to thin-bedded, medium to very fine tuffs which are closely associated spatially with acid lavas. Some of the fine tuffs show graded bedding. Coarse lapilli tuff exposed 6 km south-southwest of Mount Winnecke forms a series of beds, each 1 to 2 m thick, made up of unsorted angular fragments, mostly less than 2 cm across, of maroon non-porphyritic acid lava. This tuff was laid down in water, probably close to the vent from which it was erupted.

Most, if not all, the acid volcanicity probably took place under water. This is indicated by the intimate association of lava flows with water-laid tuffaceous and non-tuffaceous sediments, and by the absence of air-fall pyroclastics. Eruption under water could also account for the lack of ignimbritic deposits, in spite of the abundance of fragmentary volcanic material, and could partly explain the highly altered nature of most of the acid lava. Acid magma erupted into water chills rapidly, and abundant hydrous volcanic glass is formed; this glass is especially susceptible to contemporaneous hydrothermal alteration, to any subsequent thermal and regional metamorphism, and to weathering.

The Mount Winnecke Formation is intruded by Winnecke Granophyre at several localities. For example, an irregular roof contact is exposed at site A, where altered granophyre is overlain by sandstone that has been thermally metamorphosed to tourmaline-bearing hornfels, and at sites B and C granophyre is exposed in contact with weakly hornfelsed sandstone (Fig. 2). At these localities only sandstone within a few metres of the intrusive contact has been thermally metamorphosed, and at site C apparently unaffaceted acid lava crops out less than 10 m from granophyre.

Neither the base nor top of the Mount Winnecke Formation are exposed. However, the formation is inferred to be unconformable on metamorphic rocks of the basement Tanami complex, and to be overlain unconformably by Carpentarian sediments of the Birrindudu Group to the west , and by Cambrian sediments of the Wiso Basin succession to the east.

The Winnecke Granophyre is commonly exposed in breakaways up to 10 m high, where it is strongly weathered and capped by laterite. However, in several places the weathered rock has been stripped off by erosion, and spheroidal boulders and tors of fresh granophyre, adamellite, and acid porphry are revealed. Consequently, exposures of unweathered Winnecke Granophyre are much more numerous than those of unweathered acid lava of the

Mount Winnecke Formation.

Both the granophyre and adamellite of the Winnecke Granophyre are pinkish where fresh, and contain biotite as the main ferromagnesian mineral. The granophyre commonly contains phenocrysts up to 1 cm long, and also small drusy cavities containing quartz, chlorite, epidote, and, in one specimen, prehnite. The adamellite is generally non-porphyritic, but some contains poikilitic feldspar crystals up to 3 cm across. Acid porphyry, the least widespread of the main intrusive rocks, contains up to 30 percent phenocrysts which are generally less than 1 cm long.

Small fine-grained xenoliths and cross-cutting quartz veins are common within the Winnecke Granophyre, and greisen is present locally at intrusive contacts. Dykes of pink aplitic microgranite and dark aphyric 'andesite' cut the granophyre and adamellite at some localities. In places the intrusive rocks are strongly sheared, and resemble schist.

The fresh granophyre consists essentially of quartz, alkali feldspar, sodic plagioclase, and brown biotite. The quartz is confined mainly to the groundmass but also forms euhedral to partly resorbed anhedral phenocrysts. The alkali feldspar appears to be orthoclase in some specimens and microcline in others; it is variably turbid but otherwise unaltered, and forms both phenocrysts and micrographic intergrowths with quartz. Plagioclase is present as phenocrysts of oligoclase-andesine composition, and appears to be generally subordinate to alkali feldspar. Biotite forms phenocrysts, fine-grained crystal aggregates which may be xenolithic, and small flakes in the groundmass. The granophyre also contains minor amounts of allanite, apatite, clinozoisite, epidote, fluorite, leucoxene, sphene, zircon, and metamict and opaque minerals.

The adamellite is similar mineralogically to the granophyre, but is coarser and mainly non-porphyritic, and has a general granitic rather than graphic texture.

Phenocrysts of quartz, plagioclase normally zoned from albite to labradorite, orthoclase, biotite, and in some places blue tourmaline and orthopyroxene are present in the acid porphyry. They are enclosed in a very fine to fine granitic to patchily graphic mosaic of quartz and alkali feldspar, with flakes of biotite (commonly replaced by chlorite), opaque granules, and microphenocrysts of plagioclase.

Petrographic variations within the outcrop area indicate that the Winnecke Granophyre is probably made up of several separate high-level stocks derived from a common magma chamber. These stocks intrude the Tanami complex as well as the Mount Winnecke Formation, and are overlain by Carpentarian and Cambrian rocks.

Chemistry

Chemical analyses (Table 1) show that the acid lavas of the Mount Winnecke Formation and the intrusive Winnecke Granophyre are similar in composition, lending support to the hypothesis that they were comagmatic. Most o the analyses are of samples that were used in the Rb-Sr geochronological work. The lavas analysed show little variation in silica content, and are rhyolites. They have an average K/Na of 2.2, virtually identical to the average, 2.1, for the granophyre samples.

Six of the seven samples of Winnecke Granophyre analysed have micrographic textures only one, the most basic, with 71·4 per cent SiO_2, contains hornblende as well as biotite; the other samples are richer in silica than the volcani The volcanics have, in general, higher Sr and lower Rb contents, and higher K/Rb, than the intrusives. These differences indicate that the granophyre, as might be expected, is a later fractionation product than the lavas; it crystallized more slowly, and is younger than the associated volcanics which it intrudes.

TABLE 1: Average chemical compositions of volcanic and granitic rocks (percentage)

ROCK LIST	MOUNT WINNECKE FORMATION	WINNECKE GRANOPHYRE	POLLOCK HILLS FORMATION	MOUNT WEBB ADAMELLITE
No. of samples	6	7	5	5
SiO_2	71.7	74.9	69.4	74.1
TiO_2	0.40	0.26	0.82	0.21
Al_2O_3	13.1	12.8	12.9	13.0
Fe_2O_3	0.65	0.64	2.70	0.84
FeO	2.87	1.32	2.35	1.63
MnO	0.08	0.04	0.08	0.04
MgO	0.48	0.22	0.73	0.36
CaO	1.14	0.86	2.57	1.75
Na_2O	2.46	2.69	2.60	2.70
K_2O	5.45	5.69	4.28	5.27
P_2O_5	0.15	0.10	0.19	0.06
H_2O +	0.78	0.24	0.60	0.36
H_2O -	0.36	0.34	0.22	0.20
CO_2	$<$ 0.05	$<$0.05	0.38	0.08
S	-	-	0.02	0.03
Totals	99.62	100.10	99.84	100.63

Analyses by The Australian Mineral Development Laboratories, Adelaide.

Rb-Sr geochronology

Mount Winnecke Formation. Ten rhyolitic lava samples were used in the Rb-Sr isotopic study, of which eight, samples 73-476A to 73-478 (Table 2), were collected from exposures 12 km west of Mount Winnecke (Fig. 2). The lavas analysed have well preserved igneous textures, but all show some alteration probably deuteric, indicated by some sericitization and chloritization.

Rb-Sr isotopic analyses of the ten total rocks are given in Table 2, together with analyses of deuterically altered plagioclase separated from three of the rocks. The data are plotted on a conventional isochron diagram in Figure 3. Regression of all the total rock and mineral data gives an isochron age of 1807 $\pm$ 18 m.y. (95 percent confidence level) and an initial Sr^{87}/Sr^{86} of 0.7070 $\pm$ 0.0056. A similar result, 1809 $\pm$ 21 m.y., is obtained when only the total rock points are used in the regression. The data do not fit the isochron to within experimental error (Mean Square of Weighted Deviates, MSWD, = 53.8), and both regressions assume a model of calculation in which there was some primary variation in initial Sr^{87}/Sr^{86} in the samples (model 3). The most aberrant point is that of 73-479, and its deletion from the combined total rock and mineral data results in a model 3 isochron with a significantly lower MSWD (14.7) but essentially the same resultant age (1808 $\pm$ 15 m.y.) and initial Sr^{87}/Sr^{86} (0.7052 $\pm$ 0.0038). Another sample, 73-480, is much more radiogenically enriched than the others, and thus has a major influence on the slope of the 1808 m.y. isochron. Because of this and because it is the most strongly altered of the samples analysed, it was analysed three times. The triplicate analyses of this sample, with respect to the 1808 m.y. isochron, are consistent and virtually concordant, although, because of the small amount of sample used in the isotope dilution procedure, there is up to ten percent variation in the Rb^{87}/Sr^{86} and Sr^{87}/Sr^{86} values

TABLE 2 : Rb-Sr data for the Mount Winnecke Formation and Winnecke Granophyre

Rock Unit	Sample No*	Locality Latitude	Locality Longitude	Rock Type/Mineral Separate	Rb ppm	Sr ppm	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}
Mount Winnecke Formation	73-476A			Porphyritic acid lava	307.5	80.5	11.344	0.99363
	73-476C			"	312.7	73.1	12.748	1.02740
	73-476D			"	309.4	76.0	12.108	1.01111
	"	18°47'50"	130°13'10"	Plagioclase	120.5	178.5	1.959	0.75842
	73-476E			Porphyritic acid lava	275.3	59.9	13.719	1.04699
	73-476H			"	301.6	80.7	11.084	0.98342
	"			Plagioclase	256.3	101.9	7.394	0.89399
	73-476K			Porphyritic acid lava	308.8	86.8	10.541	0.97627
	73-477	18°47'30"	130°13'30"	"	309.6	66.1	13.983	1.05783
	73-478	18°47'10"	130°13'40"	"	309.2	70.3	13.114	1.03996
	"			Plagioclase	315.5	203.9	4.518	0.82832
	73-479	18°44'05"	130°13'40"	Sparsely porphyritic acid lava	38.2	17.9	6.294	0.88617
					38.3	17.6	6.386	0.88803
	73-480	18°37'55"	130°17'40"	Sparsely porphyritic acid lava	240.1	9.3	91.513	3.03504
					234.2	8.6	97.992	3.22332
					237.3	8.5	101.087	3.29054
Winnecke Granophyre	73-465B			Acid porphyry	256.6	98.9	7.637	0.90337
	"	19°02'48"	130°10'12"	Biotite	1255.9	17.0	455.61	12.3078
	"			Plagioclase	57.9	147.4	1.137	0.73666
	73-466A			Granophyre	379.8	28.8	42.116	1.77971
	73-466C	18°54'30"	130°08'30"	"	433.7	13.2	124.63	3.86991
	73-466D			"	389.5	10.7	141.09	4.21569
	73-466F			"	440.8	18.0	85.600	2.85097
	73-467B	18°55'00"	130°07'30"	Porphyritic granophyre	391.2	24.1	53.070	2.06778
	73-467C			"	384.4	71.5	14.592	1.08366
	73-468A			Biotite adamellite	387.4	77.0	15.075	1.09444
	73-468B			Aplite	483.1	12.4	156.33	4.71973
	"	18°54'45"	130°07'10"	Biotite	1614.1	16.5	930.16	24.0544
	"			Plagioclase	314.0	186.5	4.917	0.82476
	73-468D			Acid Porphyry	365.5	41.4	27.239	1.40280
	73-471	18°47'40"	130°12'30"	Granophyre	479.8	28.3	55.535	2.08922
	73-481A			Porphyritic granophyre	305.9	79.8	11.382	0.99715
	"	18°36'50"	130°18'10"	Biotite	1132.6	19.5	289.23	8.11884
	73-481B			Porphyritic granophyre	302.2	83.8	10.693	0.97918
	73-484	18°48'20"	130°24'20"	Acid porphyry	252.1	97.4	7.619	0.90083

* ANU number

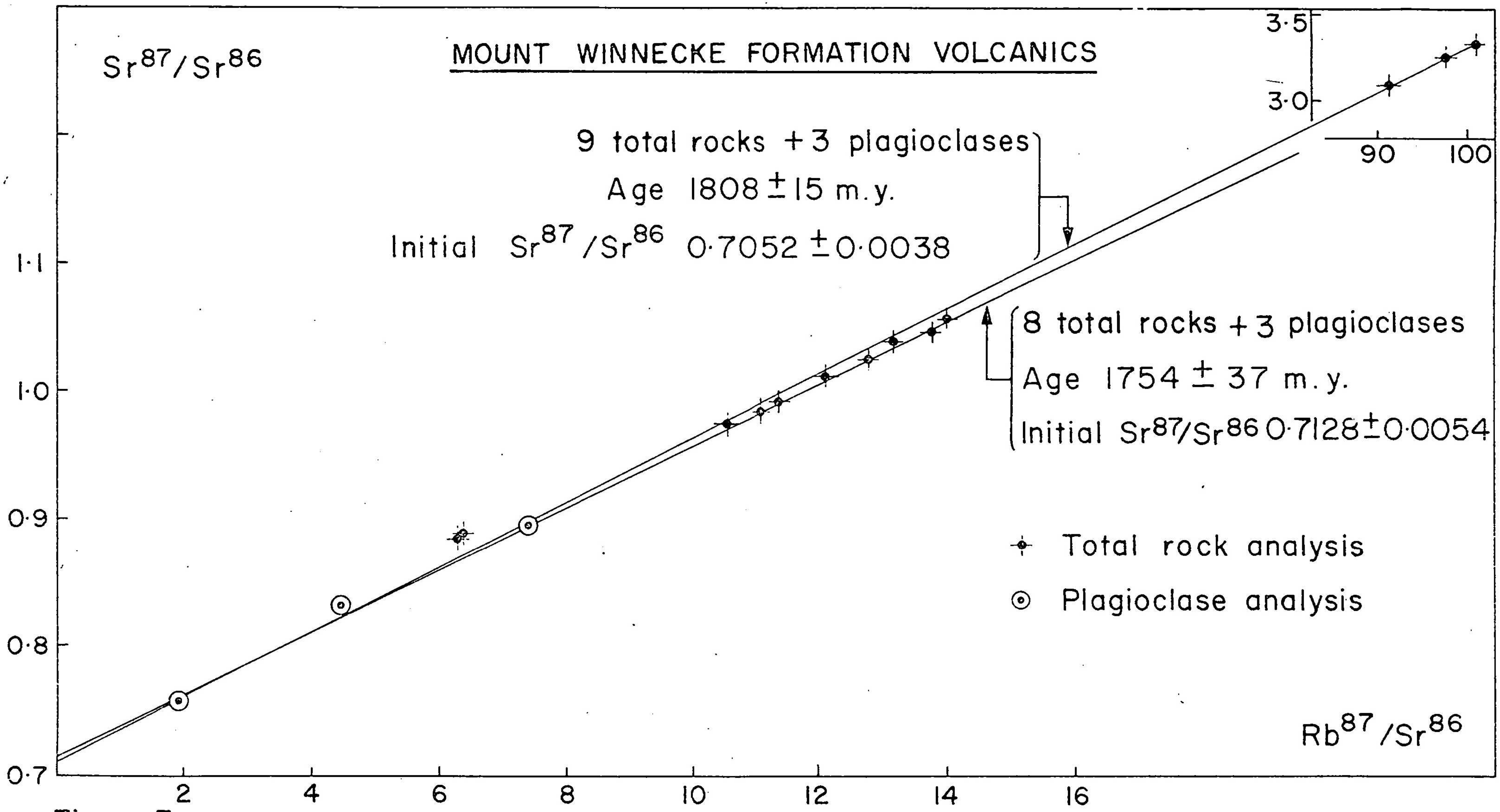

Figure 3

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between the three runs. In the statistical regressions of the data the mean value of the three isotopic analyses of 73-480 has been used.

For the above reasons, the data were again regressed, omitting the most radiogenically enriched sample, 73-480. The regression involving the eight remaining total rocks and three plagioclase mineral separates, again resulted in a model 3 isochron (Fig. 3), with a similar MSWD (13.5). However, a somewhat younger age, 1754 ± 37 m.y., is indicated.

It is difficult to judge from the isotopic data whether the younger (1754 ± 37 m.y.) or older (1808 ± 15 m.y.) isochron result is the more realistic. As sample 73-480 is the most altered of those analysed, its inclusion in the regression would be expected to result in an isochron giving a minimum age. Instead, its deletion from the regression leads to an isochron giving the younger age. The eight samples that make up the latter isochron come from the one relatively restricted area about 12 km west of Mount Winnecke (Fig. 2). Sample 73-480, however, comes from a site 19 km to the north-northeast, and it could be argued that its isotopic relationships to the main group of samples are therefore uncertain, and consequently the younger age of 1754 ± 37 m.y. (initial Sr^{87}/Sr^{86} 0.7128 ± 0.0054) should be preferred. Nevertheless, the triplicate analyses of sample 73-480 indicate an age of a little over 1800 m.y., which is independent of any initial Sr^{87}/Sr^{86} up to 0.725; a most unlikely high initial ratio of 0.79 would be required to develop a 1754 m.y. isochron incorporating the 73-480 analyses. We therefore conclude that the rhyolite lavas of the Mount Winnecke Formation are at least as old as 1754 ± 37 m.y., and there is evidence from at least one part of the formation that their age may be slightly over 1800 m.y.

Winnecke Granophyre. The relatively abundant exposures of fresh unaltered Winnecke Granophyre make this unit much more suitable for isotopic analysis than the acid lavas of the Mount Winnecke Formation. The Rb-Sr data given in Table 2 were obtained on 14 samples from seven sites (Fig. 2). Samples of several different varieties of granophyric rocks were collected, nine (73-466 to 73-468) coming from one small outcrop area, and these give a suitably broad dispersion in Rb/Sr values. Isotopic analysis of the 14 total rocks yields a model 2 isochron age of 1797 ± 18 m.y., and an initial Sr^{87}/Sr^{86} of 0.7098 ± 0.0037. The slight scatter of the data points about the line (MSWD = 4.9) may be due to some isotopic disturbance after the time of cooling. Analyses of three biotite and two plagioclase mineral separates from the Winnecke Granophyre are also given in Table 2. The biotite ages range from 1784 to 1818 m.y., and are virtually independent of initial Sr^{87}/Sr^{86}. These ages are the same as the total rock isochron age, to within experimental error, indicating that there has been little post-emplacement disturbance. Hence the ages obtained correspond to the time of cooling of the Winnecke Granophyre. Regression of the total-rock and mineral data from one small area (73-466, 73-467, 73-468) is again in agreement, giving an age of 1813 ± 27 m.y. and an initial Sr^{87}/Sr^{86} value of 0.7014 ± 0.0054. Combining all the mineral and total-rock data is thus justified, and this gives an overall preferred age of 1802 ± 15 m.y. and an initial Sr^{87}/Sr^{86} of 0.7074 ± 0.0036 (Fig. 4). Although the 95 percent uncertainties are low, there is more scatter (MSWD = 13.1) about the isochron than can be expected from experimental error alone, and the statistical treatment assumes a model 4 fit. This indicates a variation in initial Sr^{87}/Sr^{86} for the samples, as well as some minor post-crystallization isotopic disturbance.

<u>Discussion.</u> The close affinity between the Mount Winnecke Formation rhyolite lavas and their probable high-level intrusive equivalents that make up the Winnecke Granophyre is indicated by field evidence and petrographic and chemical data. As the Winnecke Granophyre intrudes the Mount Winnecke Formation, and its age is unequivocally determined, it is clear that the older of the two alternative isochrons for the Mount Winnecke Formation rhyolites

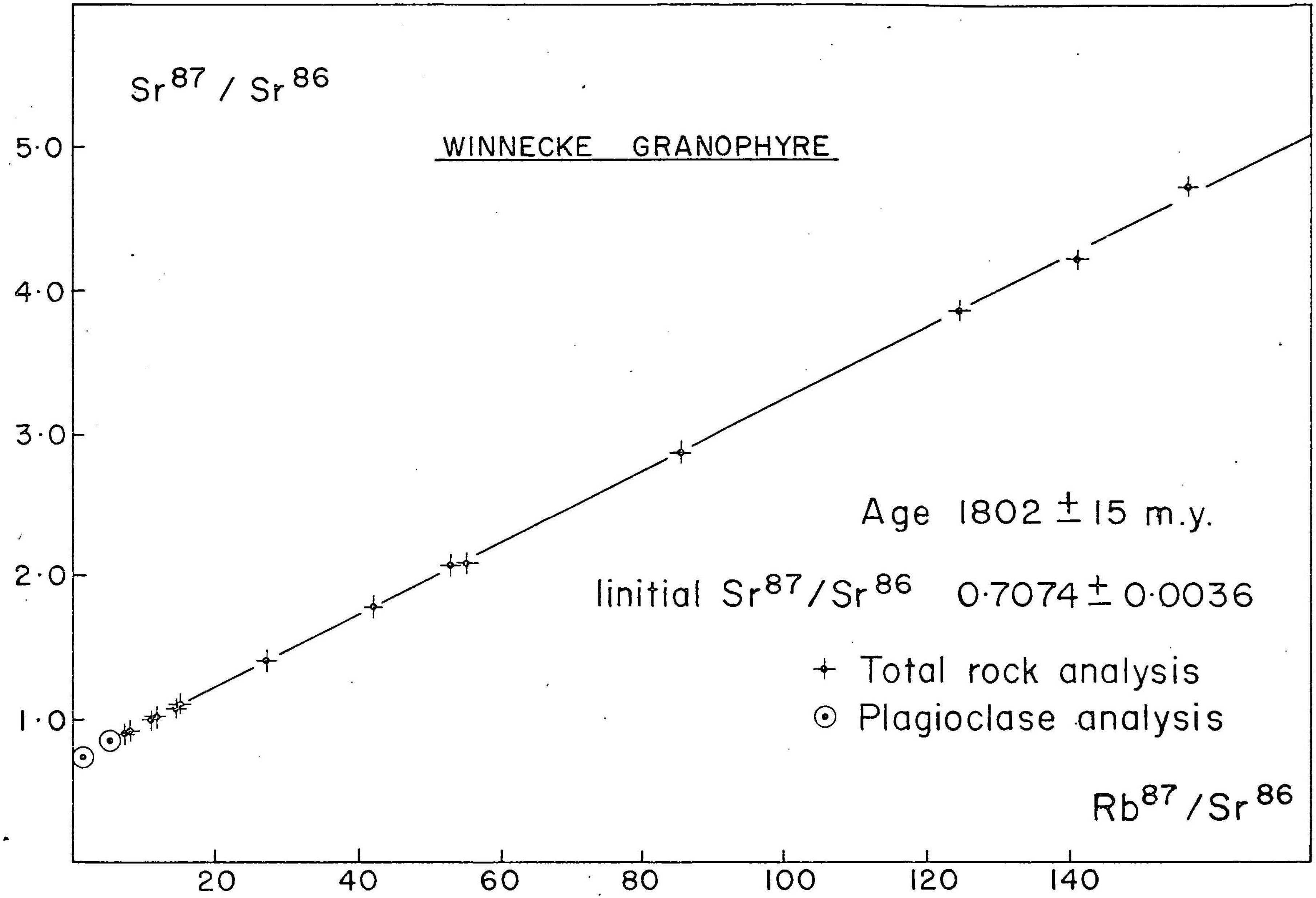

Figure 4

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(Fig. 3), 1808 ± 15 m.y. and an initial Sr^{87}/Sr^{86} of 0.7052 ± 0.0038, is the more preferable.

The significance of the anomalously younger isochron for the rhyolite lavas, 1754 ± 37 m.y., is uncertain. It seems unlikely that the 1754 m.y. age is due to updating through tectonic disturbance, as both the mica and total rock data for the Winnecke Granophyre are internally consistent at about 1800 m.y. An alternative explanation is that the young apparent age can be attributed to partial open-system behaviour of the Rb and/or radiogenic Sr for some tens of millions of years after extrusion and cooling of the lavas. Such could have been the case if the acid volcanism took place beneath the sea. Under these conditions some exchange of alkalis between the lavas and sea water could take place during deuteric alteration and any subsequent devitrification processes. Such migration of Rb into the lavas, or loss of radiogenic Sr from them, would be enhanced by even the mildest conditions of hydrothermal alteration. A number of examples in which dating of extrusive acid volcanics by the Rb-Sr whole rock method provides anomalously young ages have been cited by Fairbairn & Hurley (1969), showing that the Mount Winnecke Formation lavas are not unique in this respect. It is considered that the special susceptibility of submarine acid volcanic rocks to alteration and incomplete chemical and isotopic closure could sometimes be the prime cause of non-adherence to true isochron relationships. Clearly, unless independent age control is available, such as the dating of high-level intrusives equivalent to the extrusives as in the Winnecke area, the interpretation of Rb-Sr whole rock isochrons on acid volcanic rocks must be approached with caution.

The initial Sr^{87}/Sr^{86} ratios for the Mount Winnecke Formation lavas and the Winnecke Granophyre are 0.7052 and 0.7074, respectively, and are experimentally indistinguishable. This and the other isotopic data, together with the field, petrographic, and major element evidence, are consistent with the view that the extrusive and intrusive rocks were comagmatic, and crystallized about 1800 m.y. ago in the late Lower Proterozoic.

POLLOCK HILLS FORMATION AND MOUNT WEBB GRANITE

The geological setting in the southwest of The Granites-Tanami region, where the Pollock Hills Formation and Mount Webb Granite crop out (Fig. 5), is somewhat similar to that in the Mount Winnecke area to the northeast. The Pollock Hills Formation, like the Mount Winnecke Formation, includes acid lava flows and pyroclastics, and it is intruded by the Mount Webb Granite which, like the Winnecke Granophyre, is considered to have been emplaced at a high structural level (Blake, in prep.). The Pollock Hills Formation and Mount Webb Granite are both overlain unconformably by the Heavitree Quartzite, which from evidence elsewhere in the Arunta Block is known to be younger than 1076 $\pm$ 50 m.y. (Marjoribanks & Black, 1974).

The Pollock Hills Formation is probably over 1000 m thick, and is made up of acid lava overlain by tuffaceous and non-tuffaceous sandstone, and minor lapilli tuff and agglomerate. The sandstone forms a series of cuestas and hogback ridges, whereas the lava mainly forms rounded, undulating to hilly terrain. The base of the formation is concealed, but is presumed to be unconformable on metamorphic rocks of the Arunta Complex.

Differences in petrography indicate that several flows may be present, although no contacts between flows have been identified. At several localities, mainly in or near scarp faces, the tops of lava flows are exposed, overlain directly by either sandstone or, less commonly, lapilli tuff, laminated fine tuff, and agglomerate. The flow tops consist of much altered flow-banded and brecciated lava, in places over 10 m thick. The altered lava passes down into dark greyish hard massive lava. The dark lava has a prominent close steep jointing trending north to west-northwest, and is exposed

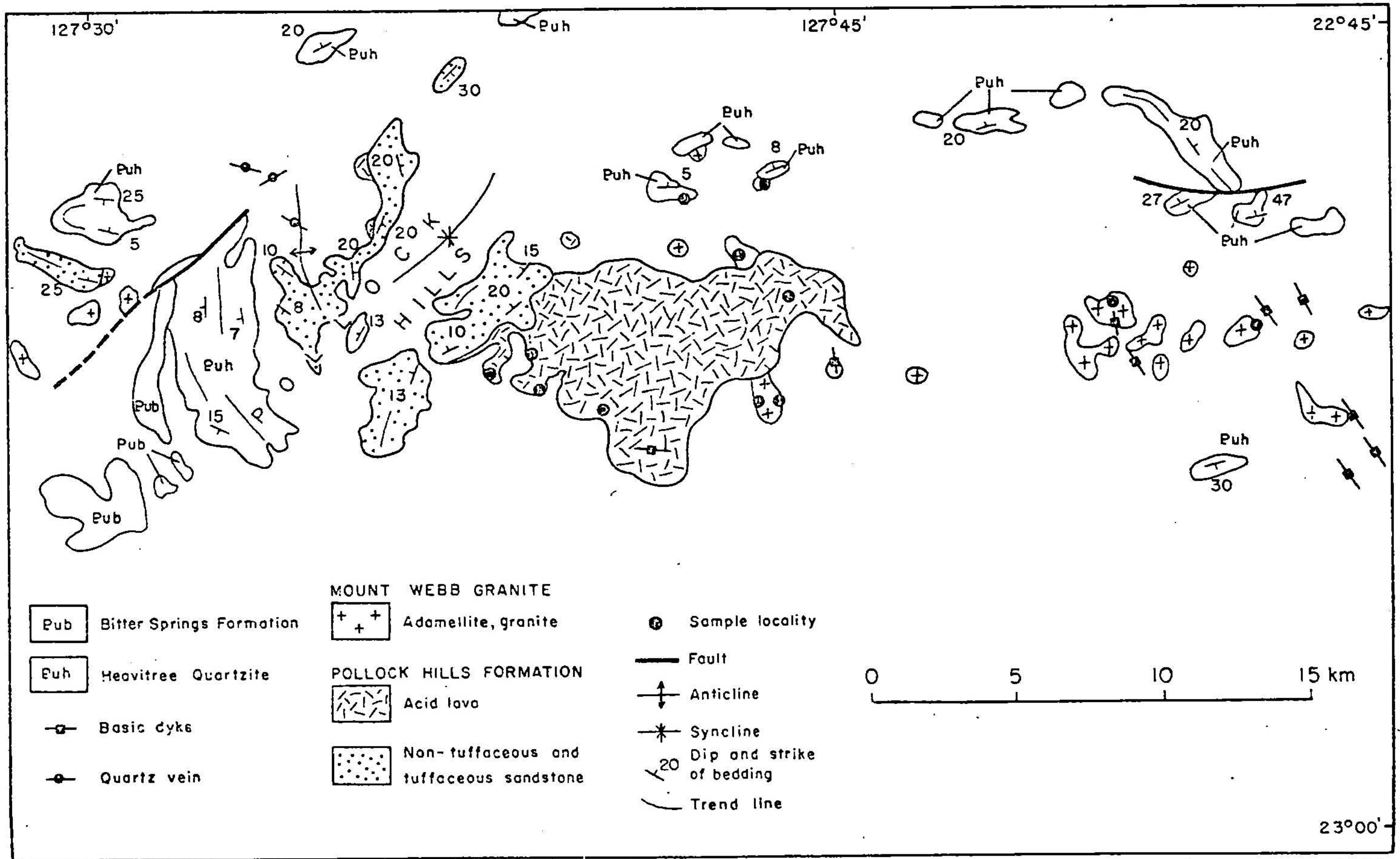

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Fig. 5. Geological map of the Pollock Hills area.

as low tors and rocky outcrops consisting of angular to rounded blocks.

The acid lava contains 10 to 20 percent phenocrysts, less than 5 mm across, of feldspar and commonly quartz. Pseudomorphed ferromagnesian phenocrysts and microphenocrysts of apatite and opaque minerals are commonly present. The groundmass is fine to very fine-grained, ranges from felsitic to microgranitic and patchily micrographic, and consists mainly of quartz, alkali feldspar, and opaque granules. Most feldspar phenocrysts are sodic plagioclase, which shows alteration to clay minerals, epidote, sericite, and calcite. Sparse alkali feldspar phenocrysts have been identified in a few specimens. Quartz phenocrysts are commonly partly resorbed. Ferromagnesian phenocrysts are psuedomorphed by aggregates of chlorite, iron oxide, greenish biotite, pale green amphibole, and sphene.

The upper part of the Pollock Hills Formation consists of a succession of lithic, sublithic, and tuffaceous sandstones similar to those of the Mount Winnecke Formation. In the type section of the formation these sediments are 600 m thick (Blake, in prep.). The sandstones contain clasts of acid lava, some of which have shard-like forms, and also clasts of both plagioclase and alkali feldspar. They are water-laid sediments, and their close association with acid lavas and tuffs indicates that the acid volcanics of the Pollock Hills Formation, like those of the Mount Winnecke Formation, were probably erupted under water.

The Pollock Hills Formation is intruded by the Mount Webb Granite whose emplacement, like that of the Winnecke Granophyre, was accompanied by only minor thermal metamorphism. Within a few metres of the intrusive contacts acid lava and sandstone have become mottled, dense, and hornfelsic, and at one locality (site 120 in Fig. 5) acid lava is cut by veins of granite. The virtual lack of much thermal metamorphism indicates that the Mount Webb Granite was probably intruded at a high structural level, and it may have been comagmatic with the acid volcanics of the Pollock Hills Formation.

The Mount Webb Granite crops out mainly east of the Pollock Hills, where unweathered granitic rocks are exposed as scattered spheroidal boulders and as tors up to 30 m high. It also crops out west of the Pollock Hills, where it is generally somewhat weathered. The granite is mainly pinkish to pale grey, medium to coarse, and non-porphyritic. It commonly shows moderately to steeply dipping foliation which locally is sufficiently intense to give the rock a gneissic appearance. The foliation generally trends west to north-northwest. The granite is cut by quartz and sparse aplite veins generally less than 1 m thick, and by post-foliation basic dykes, most of which trend northwest.

The granite consists essentially of quartz, plagioclase, alkali feldspar, and in most cases biotite, locally accompanied by green to greenish blue hornblende. Some augite-bearing granite is also present, mainly in the east. The quartz is strained and locally granulated, but the other minerals show evidence of shearing only in gneissic samples. The plagioclase is oligoclase-andesine showing weak normal zoning and partial alteration to epidote, white mica, clay minerals, and chlorite. The alkali feldspar is mainly slightly perthitic microcline, and generally unaltered. Biotite is commonly partly altered to chlorite and epidote. Augite, where present, is partly uralitized. Apatite, sphene, zircon, and metamict and opaque minerals are common accessory minerals, and minor allanite and tourmaline are present in some specimens.

The foliation of the granite and the straining and local granulation of the quartz are presumed to have taken place at or near the time of intrusion: if the foliation was a regional, post-crystallization feature, constituents other than quartz should also be affected, and the Pollock Hills Formation would show obvious signs of deformation.

Chemistry

The analysed lava samples from the Pollock Hills Formation are slightly less rich in silica than the analysed samples of Mount Webb Granite , and are rhyodacites, but otherwise the lavas and granite are closely similar in chemical composition (Table 1), at least as far as major elements are concerned. They are also chemically similar to the Mount Winnecke Formation acid volcanics and the Winnecke Granophyre.

Rb-Sr geochronology

Rb-Sr data for the Pollock Hills lavas and the intrusive granite are given in Table 3, and the data are plotted separately in Figures 6 and 7.

Pollock Hills Formation. Seven lava samples (Fig. 5) were selected for Rb-Sr isotopic analysis; all show some deuteric alteration, such as sericitization of feldspar. The samples have only a moderate dispersion in Rb^{87}/Sr^{86}, and show considerable scatter about the fitted isochron (MSWD = 66.3, model 4 fit). Consequently the 95 percent uncertainty limit on the age obtained, 1510 $\pm$ 240 m.y., is rather high. It is therefore appropriate to examine once again the probable high-level intrusive equivalents of the volcanics in order to possibly substantiate the age and improve the precision.

Mount Webb Granite. The isochron plot of six samples of Mount Webb Granite (Fig. 7) is a model 3 regression with an age of 1518 $\pm$ 40 m.y. and initial Sr^{87}/Sr^{86} of 0.7146 $\pm$ 0.009; the slope of the isochron is not very different from that given by the lava samples (Fig. 6). The granitic samples come from four different sites up to 10 km apart (Fig. 5). Given this sampling limitation, the fit of the data is as good as can be expected, and indicates some variation in initial Sr^{87}/Sr^{86} betwen samples. Three of the analysed samples are of medium-grained biotite adamellite, and two (101A, 276) are from cross-cutting veins of leucocratic biotite adamellite a few centimetres thick. The remaining sample (274A) differs from the others in

TABLE 3: Rb-Sr data for the Pollock Hills Formation and Mount Webb Adamellite

Rock Unit	Sample No*	Locality Latitude	Locality Longitude	Rock Type/ Mineral Separate	Rb ppm	Sr ppm	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}
Pollock Hills Formation	088	22°51'25"	127°38'10"	Porphyritic acid lava	206.1	98.7	6.107	0.84132
	097	22°51'00"	127°38'50"	"	208.3	135.9	4.471	0.80831
	098	22°51'40"	127°39'00"	"	184.7	128.3	4.194	0.80269
	099	22°52'00"	127°40'20"	"	122.0	115.9	3.057	0.77225
	103	22°51'20"	127°43'30"	"	176.7	175.8	2.921	0.77298
	115A	22°48'05"	127°42'00"	"	163.7	83.5	5.725	0.82644
	122	22°50'00"	127°44'00"	"	178.9	140.9	3.697	0.79274
Mount Webb Adamellite	101	22°52'00"	127°43'30"	Strongly foliated biotite adamellite	239.0	98.5	7.119	0.86960
	102A)	22°52'00"	127°43'50"	(Aplite	279.6	20.5	42.968	1.62849
	102B)			(Biotite adamellite	260.1	94.5	8.089	0.88786
	121	22°49'10"	127°43'00"	Biotite adamellite	246.7	84.3	8.618	0.90563
	274A	22°50'30"	127°53'25"	Foliated hornblende - augite-albite granite	7.3	172.7	0.123	0.70879
	276	22°50'00"	127°50'35"	Aplite	256.6	36.4	21.508	1.17222

* BMR Registered number, prefix 73490

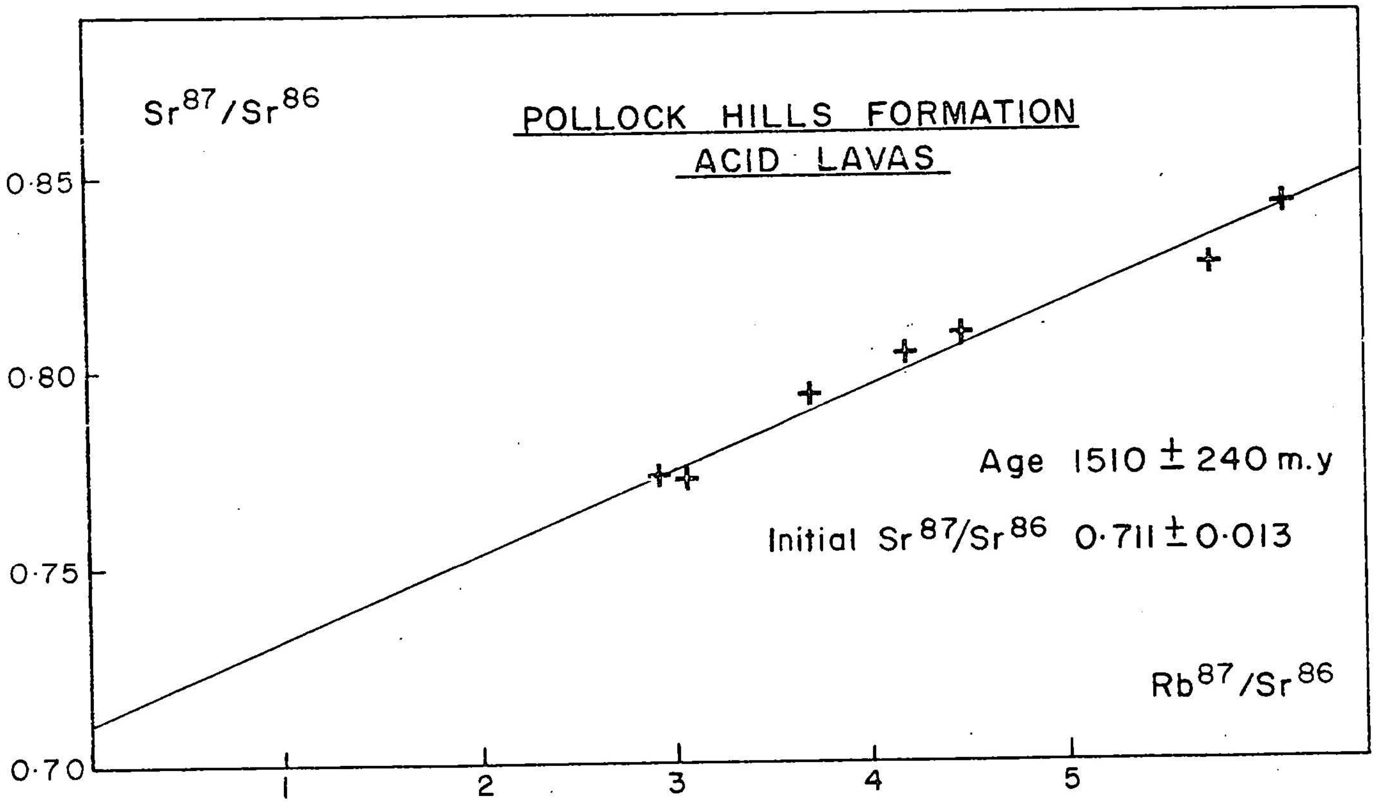

Figure 6

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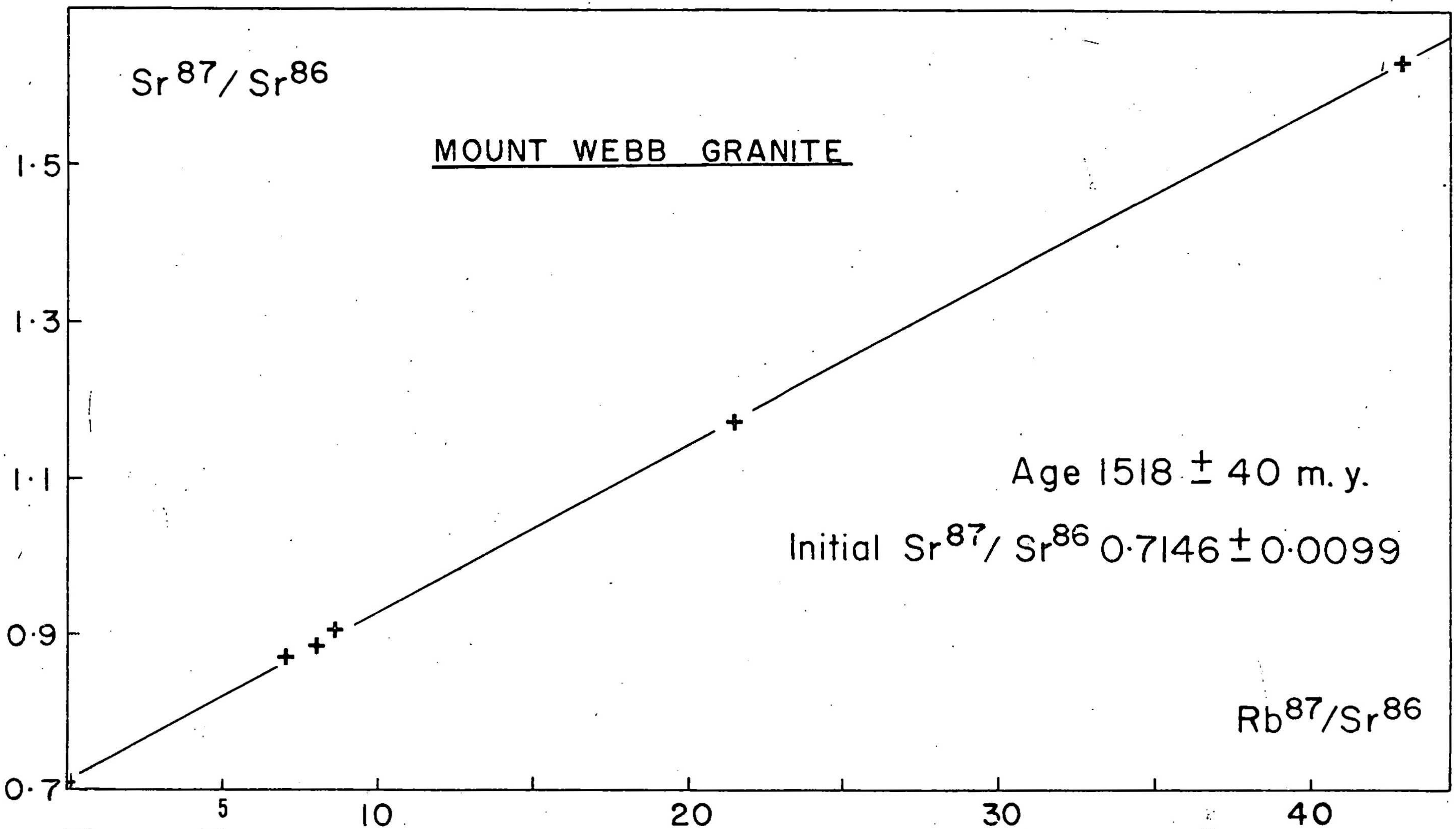

Figure 7

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containing only minor alkali feldspar and no biotite, the main constituents being quartz, sodic plagioclase, clinopyroxene, and pale green amphibole; epidote and sphene are abundant accessories. If this last sample is deleted from the regression analysis, the MSWD is markedly lowered, from 45.5 to 9.6, but the resultant age, 1504 ± 33 m.y. and initial Sr^{87}/Sr^{86} of 0.7197 ± 0.008, are not much changed.

Discussion. Both field and isotopic evidence indicate that it is probably justifiable to group the Rb-Sr data from the volcanics of the Pollock Hills Formation with those from the Mount Webb Granite. When this is done the combined regression gives an age of 1526 ± 25 m.y. and an initial Sr^{87}/Sr^{86} of 0.7114 ± 0.004. This date is considered the best estimate for the age of crystallization of both the intrusive and extrusive rocks. The close jointing of the acid lava and the foliation and partial recrystallization of the granite do not appear to have had a major influence on the determined age, indicating that they probably took place close to the time of the primary igneous event. The slightly high indicated initial Sr^{87}/Sr^{86} values for the dated rocks are not sufficiently precise to warrant detailed interpretations, but it is clear that this igneous suite did not have any significant crustal prehistory, as the maximum age that can reasonably be derived by averaging the Rb^{87}/Sr^{86} values, and assuming a low initial Sr^{87}/Sr^{86}, is about 1650 m.y. This rules out any notion that the Pollock Hills-Mount Webb igneous suite could represent the metamorphosed equivalent of the 1800 m.y. Winnecke igneous rocks in the northeast The Granites-Tanami area.

GENERAL DISCUSSION

Acid volcanics and intrusives of possibly similar Lower Proterozoic age to the Mount Winnecke Formation and Winnecke Granophyre crop out in the Halls Creek Mobile Zone of the Kimberley region, 300 km west of the Mount Winnecke area. The Kimberley units are the Whitewater Volcanics, Castlereagh

Hill Porphyry, and Bow River Granite, all three of which are considered to have been comagmatic (Dow & Gemuts, 1969). The Whitewater Volcanics, which consist of porphyritic, rhyolitic ignimbrites, minor andesitic lavas, and some interbedded volcanic conglomerate, sandstone, chert, and lapilli tuff near the top have been isotopically dated by the Rb-Sr total rock method by two independent groups at 1823 ± 17 m.y. (Bofinger, 1967) and 1940 ± 110 m.y. (Bennett and Gellatly, 1970). These ages are experimentally indistinguishable from each other at the stated 95 percent confidence levels and using the statistical 't' test. The validity of the two isochrons needs to be carefully assessed as some of the samples used came from sites more than 100 km apart. Both isochrons also include samples from associated high-level intrusive rocks. Because of these uncertainties, two additional statistical regressions of the earlier reported data have been made. The first regression involves the samples dated by Bofinger, which were collected from the east Kimberley region, and gives an age of 1802 ± 35 m.y. and an initial Sr^{87}/Sr^{86} of 0.7165 ± 0.0050. The second regression involves seven samples from the Whitewater Volcanics of the west Kimberley region, and yields an age of 1953 ± 109 m.y. and an initial Sr^{87}/Sr^{86} of 0.7065 ± 0.0059. The apparent age discrepancy is now further enhanced, but is unlikely to be geologically meaningful, as both sets of rocks have been mapped as part of the same formation. Bennett & Gellatly (1970) noted that all the west Kimberley samples that make up the older isochron have lower Rb^{87}/Sr^{86} ratios (less than 10) than the east Kimberley samples (ratios 14 to 104). If both sets of samples are combined, the resulting isochron shows an apparent curvature accompanied by an increase in extrapolated initial Sr^{87}/Sr^{86}. This phenomenon has been reported previously for a suite of late Precambrian - early Cambrian acid volcanic rocks in New Brunswick, Canada (Fairbairn et al., 1966; Cormier, 1969), but no satisfactory explanation is known. By analogy with the New Brunswick study, in which fossiliferous control demands acceptance of the oldest isochron given by samples with the lowest Rb^{87}/Sr^{86} values, the better of the two interpretations for the age of the Whitewater Volcanics is likely to be 1953 ± 109 m.y. This age would now be in accord with Bofinger's (1967) age of 1854 ± 14 m.y. for the pooled Rb-Sr data from the Sophie Downs and Bow River Granites, the latter of which intrudes the Whitewater Volcanics in the east Kimberley region. However, because of the present uncertainties regarding the isotopic data for the Whitewater Volcanics, any correlation based on ages alone with the Mount Winnecke Formation remains fairly tenuous.

No igneous rocks similar in age to the Mount Webb Granite and the acid lavas of the Pollock Hills Formation are known elsewhere in the general area. This igneous suite is appreciably younger than the 1800 m.y. Winnecke suite, and is also younger than granitic rocks dated at 1720-1780 m.y.(Page and Mahon, in prep.) which crop out in the area between the two suites (Blake et al, 1973). On the other hand, it is older than the acid volcanic and high level intrusive rocks of the Tollu Volcanics, dated at 1060 ± 140 m.y. (Compston & Nesbitt, 1967) and 1084 ± 17 m.y. (Gray, 1971), which crop out in the Tomkinson Ranges 400 km to the south. The age of the Mount Webb Granite and Pollock Hills Formation acid volcanics fits in between two metamorphic events which affected the Arunta Block to the east (Shaw & Stewart, 1973; Marjoribanks & Black, 1974) - a regional metamorphism dated at about 1700 m.y. and a late migmatitic event dated at 1076 ± 50 m.y.

ACKNOWLEDGEMENTS

We are indebted to J. Pollard who assisted in the field work, and to M.W. Mahon for careful sample preparation in the Rb-Sr chemistry laboratory. The rocks and mineral separates were prepared by M. Cowan and R. Rudowski. On - line reduction of the isotopic data was computer-programmed by P.A. Arriens whose assistance in this manner is greatly appreciated.

We are grateful to W.B. Dallwitz, K.R. Walker, and L.P. Black for their comment and criticism of the text

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