A Rb-Sr geochronological study in the Proterozoic Tennant Creek Block, central Australia

L. P. Black

Rb-Sr isotopic data from total rock and mineral samples provide a broader geochronological framework than has hitherto been available for the Proterozoic rocks of the Tennant Creek Block. The oldest documented event is the amphibolite-facies metamorphism at 1920 ± 60 m.y. of possible basement rocks from the BMR 3 area, to the west-southwest of Tennant Creek township. The lower grade metamorphic rocks of the Warramunga Group were deposited before the major deformation eposide which is inferred to have occurred at about 1810 m.y. Certain of the units within the Warramunga Group, of which the Bernborough Volcanics are an example, underwent isotopic resetting of total-rock systems during subsequent deformation. Granite ages range from 1797 m.y. for a phase of the Tennant Creek Granite to less than 1500 m.y. for the Cabbage Gum and Gosse River East Granites. Dated lamprophyre and porphyry samples yield ages of about 1660 m.y. and 1760 m.y., respectively. Muscovite separates from the Juno, Warrego, Golden Forty, and Nobles Nob mines suggest a common origin for the ore deposits about 1810 m.y. ago.

Introduction

The Proterozoic Warramunga Group, which consists of interbedded sedimentary and volcanic rocks of eugeosynclinal origin, forms the major part of the Tennant Creek Block of central Australia. It is overlain unconformably by sediments of shallower water facies, the Hatches Creek Group in the south and the Tomkinson Creek Group to the north. Regional metamorphism within the Warramunga Group is generally of very low grade. Isolated occurrences of amphibolite-facies rocks have been interpreted as basement, possibly of Archaean age. The Warramunga Group is extensively intruded by igneous rocks which mostly crop out in a northwesterly striking zone centred on Tennant Creek. Granite and porphyry predominate, though diorite, dolerite, and lamprophyre are also present. The Proterozoic rocks are overlain by flat-lying Cambrian rocks and Mesozoic sediments.

There has been very little geochronological investigation of the Tennant Creek area even though it constitutes an important gold and copper mineral field. Only three K-Ar ages, which are reported in Hurley *et al.* (1961), were available for the entire Tennant Creek Block. These granite ages of 1400, 1510, and 1630 m.y. define minimum ages for the sediments within the Warramunga Geosyncline. This paper constitutes the first Rb-Sr study of the Tennant Creek Block. Although it represents a manifold increase in isotopic data, it should not be taken as a definitive study. Considerable future work, which must include the analysis of zircon concentrates, will be required to assess fully the chronology of all rock types.

Analytical techniques

Samples were collected almost exclusively from diamond drill cores to offset the widespread effects of generally deep weathering in the area. Analytical procedures for Rb and Sr were based on the techniques outlined in Page *et al.* (1976), and Williams *et al.* (1976). The 7-8 ng blank levels for both Rb and Sr were not large enough to warrant the application of blank corrections. Regression of the pooled analytical data is based on the work of McIntyre *et al.* (1966). Relative deviations of 0.5 per cent for Rb^{87}/Sr^{86}, and a standard deviation of 10 x 10^{-5} for Sr^{87}/Sr^{86}, have been used for all regressions, most of which involve samples analysed in 1974. All uncertainty limits are expressed at the 95 percent confidence level. The value 1.42 x $10^{-11}y^{-1}$ (Neumann & Huster, 1972), as provisionally recommended by the August 1976 meeting of the IUGS International Commission on Stratigraphy (Subcommission on Geochronology), has been used for the decay constant of Rb^{87}. The isotopic data for all samples are presented in Table 1.

A summary of isotopic ages appears in Figure 2.

'Basement' rocks

Diamond drilling has revealed high-grade gneiss below superficial cover about 30 km WSW of Tennant Creek. Whittle (1966) reports that the gneiss belongs to the sillimanite-almandine-muscovite subfacies (Turner & Verhoogen, 1960) of the almandine-amphibolite facies. Typical rock types are garnet-mica gneiss, grunerite-garnet gneiss, plagioclase gneiss, and hornblende-tremolite-garnet gneiss; interlayers of graphically intergrown quartz and feldspar are common. Mendum & Tonkin (in prep.) state that, because of their higher metamorphic grade, the rocks are probably older than those of the Warramunga Group. They do not, however, exclude the possibility that they represent merely higher grade equivalents of Warramunga Group rocks. Mendum and Tonkin (in prep.) are also undecided whether to suggest an Archaean age or to correlate the high-grade gneisses with the Lower Proterozoic Arunta Complex to the south. The metamorphics are intruded by adamellite, alkali microgranite, microdiorite dykes and sulphide-bearing quartz dolerite and gabbro (Whittle, 1966).

Samples used in this study comprise amphibolite collected from DDH 169 in the BMR 3 area. The rock is composed of hornblende, minor quartz, and opaque minerals; chlorite, reddish-brown biotite, and possibly muscovite and sphene appear to be of later origin.

Nine separate total-rock samples were prepared from core. Samples nearest the 192.6-metre level are designated 73063284 A to F; those from the 192.6-metre level, 73063283 A to C. Regression through the analytical points (Fig. 3) generates a model 3 (see McIntyre *et al.*, 1966 for a discussion of regression models) isochron with mean square of weighted deviate (MSWD) of 8.9. The indicated age is 1920 ± 60 m.y. Various workers, for example Lanphere *et al.* (1964), Pidgeon & Compston (1965), Nunes and Steiger (1974), and Marjoribanks & Black (1974), have demonstrated the migration of Sr over distances of at least a metre during amphibolite-grade metamorphism. The relatively high grade of these basic rocks, which are separated in DDH 169 by only 0.3 m, would thus strongly suggest that it is the amphibolite-facies metamorphism which is being documented by the total-rock system. The model 3 interpretation, however, would suggest that perfect Sr-isotope

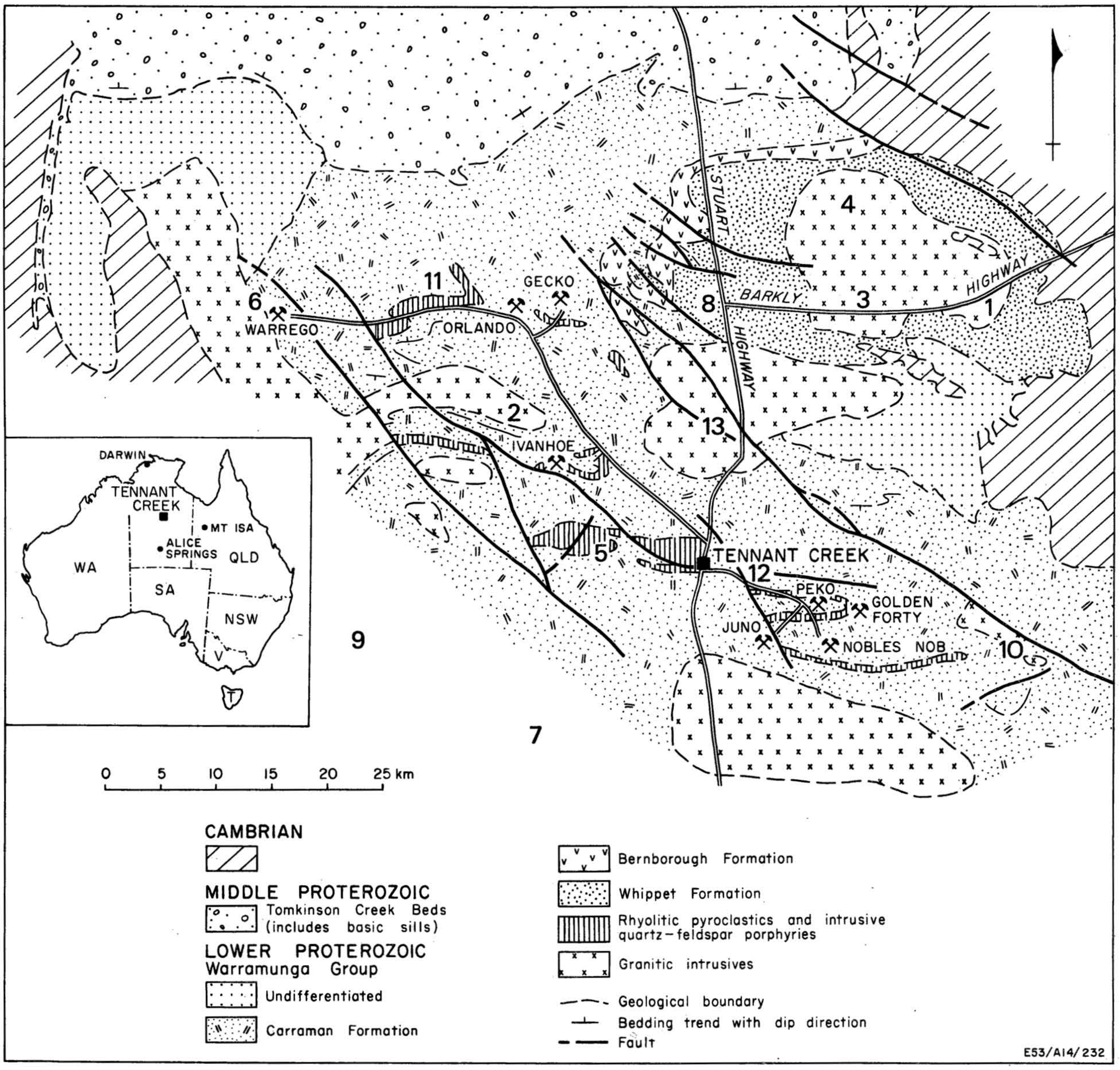

Figure 1. Geological locality map (after Large, 1975). Numbers represent sample locations: 1. Tennant Creek Granite, BMR-NTGS geochemical DDH 1, 2. Red Bluff Granite, BMR-NTGS geochemical DDH 2 & 6, 3. Tennant Creek Granite, BMR-NTGS geochemical DDH 3, 4. Tennant Creek Granite, BMR-NTGS geochemical DDH 4, 5. Porphyry, BMR-NTGS geochemical DDH 5, 6. Warrego Granite, BMR-NTGS geochemical DDH 7, 7. Cabbage Gum Granite, BMR-NTGS geochemical DDH 8, 8. Bernborough Volcanics, BMR-NTGS geochemical DDH 10 & 11, 9. 'Basement' metamorphics, BMR 3 area DDH's 1, 2, 6 & 169, 10. Lamprophyre, East New Hope area NTGS DDH's 1 & 2, 11. Intermediate to basic rocks, area 3 NTGS H7A, 12. Shale, anomaly 6 area NTGS H1, 13. Surface sample of Tennant Creek Granite at Station Hill. The North Seismic Ademellite and Gosse River East Granite sites are located south of the mapped area at latitude 19°46′30″, longitude 134°20′15″, and latitude 19°57′30″, longitude 134°45′21″, respectively.

equilibration has not occurred, even on this restricted scale. A biotite separate moderately enriched in Rb^{87}/Sr^{86} yields a significantly younger age of 1674 m.y., which must reflect a subsequent tectonic event of currently unknown significance.

Warramunga Group

The geology of the Warramunga Group is described at length in Crohn & Oldershaw (1965), Whittle (1966), Dunnet & Harding (1967), and Mendum & Tonkin (in prep.). The Group occupies much of the central part of the Tennant Creek 1:250 000 Sheet area. It is composed of dominantly eugeosynclinal deposits separated by angular unconformity from the overlying shallow-water marine deposits of the Tomkinson Creek and Hatches Creek Groups. Total thickness is difficult to estimate but probably does not exceed 3000 metres (Mendum & Tonkin, in prep.). The Warramunga Group consists of shale, siltstone, greywacke, and interbedded volcanics. Mendum and Tonkin (in prep.) have divided the Group into 10 units. Other recent workers (Large, 1975; Le Messurier, 1976) have incorporated the units of Crohn & Oldershaw (1965), and Dunnet & Harding (1967) into three main formations.

Volcanics from the Bernborough Formation and shale have been used in two independent attempts to date the Warramunga Group directly. The shale comes from Mendum & Tonkin's Bw_6 unit, from near the top of the Warramunga Group. It is equivalent to unit Bw_2 of Crohn & Oldershaw (1965), and Whittle (1966). The unit is uncon-

Sample No.	*D.D.H.*	*Depth in metres*	*Rb (ug/g)*	*Sr (ug/g)*	Sr^{87}/Sr^{86}	Rb^{87}/Sr^{86}
		'Basement'				
73063283 A T.R.	BMR 3, H169	192.9	40.53	211.5	0.72266	0.5542
73063283 B T.R.	"	192.9	36.14	236.6	0.71973	0.4416
73063283 C T.R.	"	192.9	41.78	244.2	0.72053	0.4946
73063284 A T.R.	"	192.6	46.80	146.4	0.73306	0.9251
73063284 A biotite	"	192.6	345.8	14.60	2.6728	81.55
73063284 B T.R.	"	192.6	37.40	197.3	0.72305	0.5483
73063284 C T.R.	"	192.6	79.84	128.4	0.75751	1.805
73063284 D T.R.	"	192.6	33.58	158.7	0.72437	0.6120
73063284 E T.R.	"	192.6	38.11	171.0	0.72578	0.6445
73063284 F T.R.	"	192.6	61.95	157.3	0.73843	1.1404
		Warramunga Group Shale				
73063285 A T.R.	Anomaly 6, H1	252	291.2	32.05	1.4330	28.10
73063285 B T.R.	"	252	278.9	33.48	1.3643	25.60
73063285 C T.R.	"	252	269.3	33.44	1.3460	24.71
73063285 E T.R.	"	252	298.9	30.68	1.4870	30.28
73063285 F T.R.	"	252	271.0	32.54	1.3640	25.59
73063285 G T.R.	"	252	303.8	30.06	1.5168	31.50
73063285 I T.R.	"	252	269.7	32.16	1.3701	25.79
73063285 K T.R.	"	252	261.6	29.76	1.4074	27.12
73063285 L T.R.	"	252	305.4	29.52	1.5326	32.29
		Bernborough Volcanics				
75063306 T.R.	BMR-NTGS 11	46.2	147.2	4.724	3.6736	116.1
75063307 T.R.	"	46.4	149.3	4.774	3.6643	116.4
75063308 T.R.	"	50.9	141.5	4.759	3.4791	109.1
75063310 T.R.	"	42.6	161.1	5.052	3.7383	119.4
75063311 T.R.	"	42.6	157.1	4.616	4.0452	130.4
75063312 T.R.	BMR-NTGS 10	57.6	42.38	31.34	0.81674	3.947
75063313 T.R.	"	47.8	111.3	10.67	1.51001	32.47
75063314 T.R.	"	43.2	178.3	8.638	2.3770	69.35
75063315 T.R.	"	50.8	189.9	11.18	2.0678	55.55
75063316 T.R.	"	63.0	69.04	22.88	0.93401	8.908
		Porphyry				
73063211 A T.R.	BMR-NTGS 5	13.7	320.7	44.46	1.2673	21.97
73063211 C T.R.	"	13.7	268.3	42.03	1.2010	19.32
73063211 J T.R.	"	13.7	299.5	38.57	1.3125	23.75
73063220 T.R.	"	10.7	252.7	43.96	1.1501	17.32
73063221 T.R.	"	11.0	260.5	42.97	1.1752	18.30
73063223 T.R.	"	21.2	262.1	39.25	1.2233	20.25
73063224 T.R.	"	27.3	259.8	44.42	1.1585	17.63
73063225 T.R.	"	25.3	272.3	42.58	1.2021	19.36
73063226 T.R.	"	52.1	266.2	44.11	1.1721	18.22
73063227 T.R.	"	43.3	278.6	62.85	1.0446	13.22
73063227 K-feldspar	"	43.3	432.2	99.55	1.0409	12.94
73063228 T.R.	"	51.8	234.3	47.84	1.0830	14.66
73063229 T.R.	"	64.6	255.6	52.92	1.0763	14.45
73063230 T.R.	"	75.6	260.7	43.64	1.1647	17.97
73063231 T.R.	"	78.0	258.8	40.62	1.1975	19.28
73063233 T.R.	"	88.2	363.9	57.85	1.1853	19.01
		Intermediate to basic rocks				
73063272 T.R.	Area 3, H7A	108.5	29.49	128.7	0.72670	0.6629
73063273 T.R.	"	109.4	39.05	133.1	0.73184	0.8490
73063274 T.R.	"	121.6	33.33	26.64	0.79690	3.644
73063275 T.R.	"	133.2	34.89	141.0	0.72469	0.7155
73063276 T.R.	"	146.2	48.47	151.5	0.73126	0.9259
73063277 T.R.	"	159.4	35.51	147.0	0.72269	0.6985
73063278 T.R.	"	175.6	45.70	122.2	0.73125	1.082
73063280 T.R.	"	216.4	49.31	134.3	0.73178	1.063
73063281 T.R.	"	236.2	67.29	144.7	0.74006	1.347
73063282 T.R.	"	247.8	42.66	123.6	0.73014	0.9984
		Lamprophyre				
73063265 T.R.	East New Hope, H 2	220.1	261.9	58.34	1.0208	13.36
73063266 T.R.	"	220.5	241.4	50.64	1.0406	14.21
73063266 chlorite	"	220.5	9.548	6.424	0.80703	4.333
73063266 K-feldspar	"	220.5	512.0	92.04	1.0856	16.05
73063267 T.R.	"	221.1	173.1	33.25	1.0692	15.56
73063268 T.R.	"	220.8	212.4	39.66	1.0820	16.03
73063269 T.R.	East New Hope, H 1	222.8	389.7	58.44	1.1847	20.15
73063270 T.R.	"	223.3	256.5	51.10	1.0634	15.00
72063493 T.R.	Ivanhoe Mine		104.0	62.51	0.81704	4.854
72063493 biotite	"		1015	40.78	2.7742	86.42

Table 1. Rb-Sr isotopic composition of Tennant Creek samples.

Sample No.	*D.D.H.*	*Depth in metres*	*Rb (ug/g)*	*Sr (ug/g)*	*Sr^{87}/Sr^{86}*	*Rb^{87}/Sr^{86}*
		Tennant Creek Granite				
71860059 biotite	surface sample		714.3	10.60	9.9797	371.0
73063234 T.R.	BMR-NTGS 1	105.5	204.8	82.75	0.89738	7.278
73063234 biotite	"	105.5	736.8	7.133	32.085	1214
73063241 T.R.	BMR-NTGS 3	66.8	168.3	84.65	0.85394	5.821
73063241 chlorite	"	66.8	212.1	101.9	0.86902	6.103
73063251 T.R.	BMR-NTGS 4	63.6	200.9	97.29	0.86099	6.051
73063251 biotite	"	63.6	573.3	18.83	3.621	113.0
		North Seismic Adamellite				
71860061 biotite	surface sample		683.9	8.427	14.295	545.8
		Red Bluff Granite				
73063235 T.R.	BMR-NTGS 2	81.8	88.30	72.87	0.79091	3.527
73063236 T.R.	"	105.8	32.26	105.8	0.72843	0.8825
73063237 T.R.	"	107.6	13.53	115.6	0.71600	0.3383
73063238 T.R.	"	118.3	11.01	117.0	0.71388	0.2719
73063239 T.R.	"	115.7	26.62	112.9	0.72352	0.6815
73063252 T.R.	BMR-NTGS 6	72.2	206.3	50.28	0.99926	12.19
73063253 T.R.	"	19.2	240.6	42.21	1.1357	17.15
73063254 T.R.	"	23.1	209.0	46.18	1.0310	13.48
73063254 K-feldspar	"	23.1	386.4	72.25	1.0913	16.02
73063254 chlorite	"	23.1	22.91	9.066	0.84746	7.396
73063255 T.R.	"	25.3	220.7	55.86	0.99565	11.73
73063256 T.R.	"	32.9	200.9	41.23	1.0554	14.25
73063257 T.R.	"	34.6	199.0	42.12	1.04555	14.09
73063258 T.R.	"	53.6	43.64	42.36	0.78740	2.998
		Warrego Granite				
73063259 T.R.	BMR-NTGS 7	76.5	501.9	39.61	1.6535	39.97
73063260 T.R.	"	77.7	449.3	38.92	1.5653	36.13
73063261 T.R.	"	80.2	367.3	28.30	1.6838	41.05
73063261 chlorite	"	80.2	42.32	8.489	1.0574	14.89
73063261 muscovite	"	80.2	1869	15.26	54.930	2229
73063262 T.R.	"	83.4	310.0	28.92	1.4879	33.31
73063262 chlorite	"	83.4	163.9	9.143	1.9775	58.20
73063262 muscovite	"	83.4	1802	14.53	55.456	2276
73063263 T.R.	"	85.6	520.5	46.53	1.5414	34.93
73063263 chlorite	"	85.6	163.2	11.84	1.6510	43.45
73063263 muscovite	"	85.6	1879	14.54	90.051	3674
73063264	"	83.5	312.3	22.43	1.7633	44.36
		Cabbage Gum Granite				
73063290 T.R.	BMR-NTGS 8	96.3	237.6	29.52	1.2611	24.50
73063291 T.R.	"	97.5	222.6	38.53	1.1166	17.44
73063291 K-feldspar	"	97.5	400.5	54.96	1.2373	22.13
73063291 plagioclase	"	97.5	231.0	53.62	1.0163	12.82
73063291 biotite-chlorite	"	97.5	115.1	4.858	2.3487	79.40
73063292 T.R.	"	99.1	264.9	35.89	1.2206	22.38
73063293 T.R.	"	100.3	256.1	32.45	1.2544	24.00
73063294 T.R.	"	105.5	245.6	36.97	1.1728	20.06
73063295 T.R.	"	106.4	274.9	23.31	1.5225	36.77
73063296 T.R.	"	109.1	237.9	28.35	1.2806	25.59
75063309 T.R.	BMR 3, DDH 1	195.2	222.9	97.15	0.87588	6.734
		Gosse River East Granite				
73063287 A T.R.	DDH 404	151	429.0	730.8	0.74546	1.701
73063287 B T.R.	"	151	425.6	788.7	0.74299	1.564
73063287 C T.R.	"	151	436.5	742.5	0.74585	1.704
73063287 D T.R.	"	151	433.5	767.8	0.74463	1.636
73063287 E T.R.	"	151	437.2	715.4	0.74670	1.771
73063287 F T.R.	"	151	419.0	692.5	0.74652	1.754
73063287 G T.R.	"	151	417.6	758.5	0.74362	1.595
73063287 H T.R.	"	151	421.5	760.0	0.74372	1.607
73063287 I T.R.	"	151	408.4	665.4	0.74742	1.779
73063287 J T.R.	"	151	426.2	736.2	0.74541	1.678
73063287 K T.R.	"	151	428.6	647.2	0.74956	1.920
73063287 K K-feldspar	"	151	547.7	915.8	0.74686	1.733
		Mineralised samples				
75063297 sericite	Warrego Mine		728.7	27.89	3.1556	100.4
75063297 muscovite	"		548.5	15.65	4.1238	135.0
75063298 muscovite	"		405.0	26.88	1.9871	48.95
75063299 muscovite	"		498.7	49.65	1.5222	31.32
75063300 biotite	"		514.7	20.15	2.8472	89.17
75063302 muscovite	Juno Mine		658.5	12.68	7.037	242.8
75063303 muscovite	Aquitaine, DDH 19, TC 8		596.6	14.41	5.1986	172.1
75063304 muscovite	Nobles Nob Mine		430.0	19.34	2.7244	76.87
75063305 muscovite	Golden Forty Mine		571.7	35.39	2.0708	52.87
75063305 muscovite	"		578.9	35.14	2.1419	54.25

Table 1 (continued). Rb-Sr isotopic composition of Tennant Creek samples.

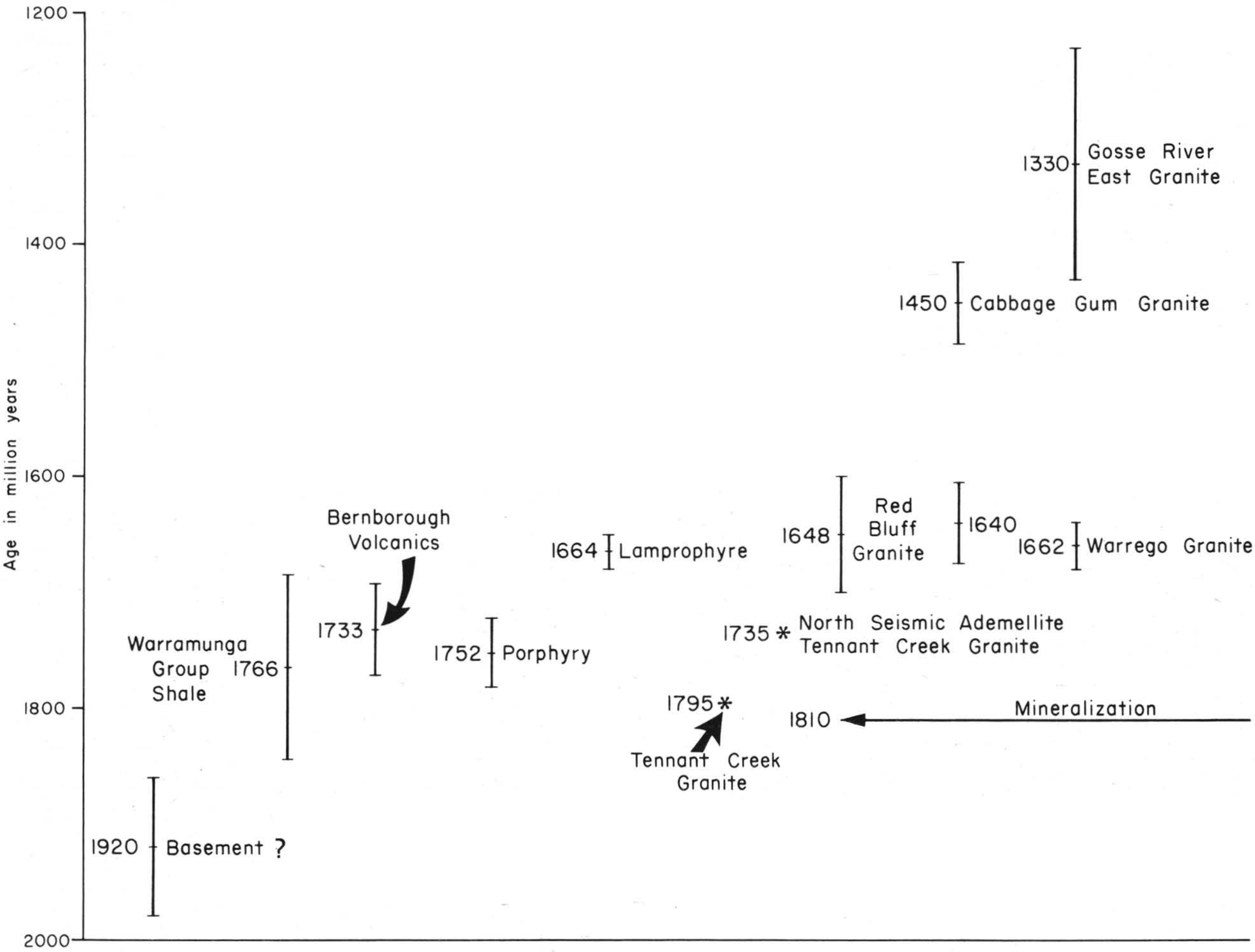

Figure 2. **Summary of isotopic ages for the Tennant Creek Block. Many of these ages do not define crystallization (see text).**

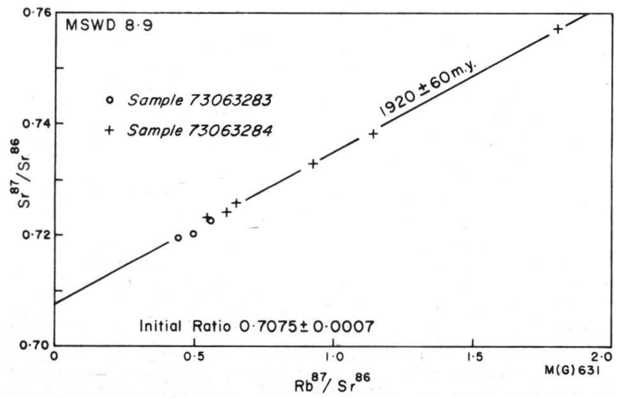

Figure 3. **Rb-Sr isochron diagram for the 'basement' rocks.**

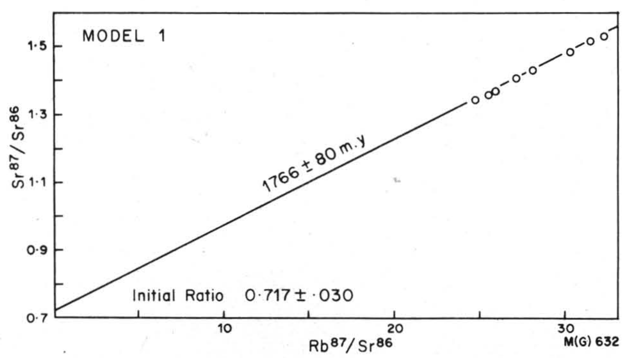

Figure 4. **Rb-Sr isochron diagram for shale from the Warramunga Group.**

formably overlain by the possibly Adelaidean Rising Sun Conglomerate and the Lower Cambrian Helen Springs Volcanics. Fresh and unoxidised greywacke, shale, siltstone and rare jasper bands from this unit occur in the Peko and Juno mines (Mendum & Tonkin, in prep.).

The newly dated shale sample comes from the 252-metre level of NTGS DDH 1 in the Anomaly 6 area. It consists of very fine-grained phyllosilicates and subsidiary opaque minerals. Nine total-rock samples were prepared from about one foot of continuous core. These samples define a model 1 isochron (i.e., all scatter can be attributed to experimental error alone) with age of 1766 ± 80 m.y. and initial ratio equal to 0.717 ± .030 (Fig. 4). The relatively large uncertainties relate entirely to the rather small spread (25 to 32) of Rb^{87}/Sr^{86} ratios. In their classic study of the Montagne Noire region of Southern France, Gebauer & Grunenfelder (1974) documented the behaviour of Sr in fine-grained sediments during incipient to low-grade metamorphism. The authors concluded that total-rock isochrons from stratigraphically uncontrolled sediments of this type should generally be interpreted in terms of metamorphic rather than sedimentary ages. Hence, the indicated age of 1766 ± 80 m.y. for the Warramunga Group shale probably reflects a metamorphic resetting; it is thus no more than a minimum age estimate for sedimentation. Further evidence on this matter, which is provided by micas from the ore bodies, and granites intruding the Warramunga Group, will be presented in the Discussion.

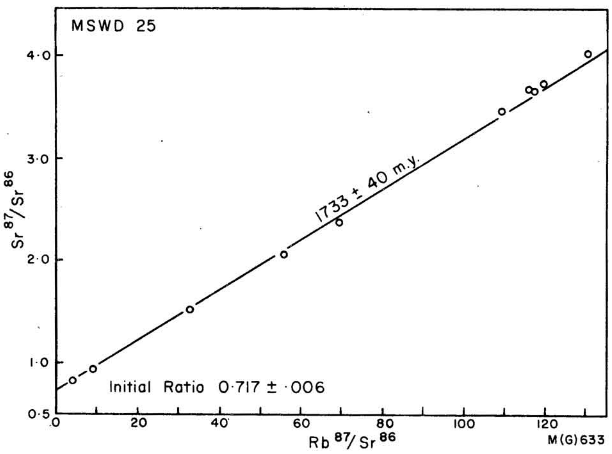

Figure 5. Rb-Sr isochron diagram for the Bernborough Volcanics.

The **Bernborough Formation**, which is comprehensively described by Dunnet and Harding (1967), is designated by Large (1975) and Le Messurier (1976) as the intermediate-level formation within the Warramunga Group. It consists of acid lava, tuff, interbedded tuffaceous greywacke and shale, siltstone, and minor ashstone, and reaches a maximum thickness of 800 metres in the type area.

The analysed samples were taken from two drillholes, DDH 10 (lat. 19°24′40″, long. 134°09′) and DDH 11 (lat. 19°26′, long. 134°8′2″), during the BMR-NTGS geochemical sampling program. Five samples were taken from between 43.2 and 63.0 metres in DDH 10, and five from between 42.6 and 46.4 metres of DDH 11. The rocks show marked signs of post-emplacement alteration. They consist of rounded quartz, variably altered feldspar, and opaque-mineral phenocrysts, set in a groundmass of quartz, fine white mica, and rare chlorite.

Regression through the entire 10 analyses (Fig. 5) yields an age of 1733 ± 40 m.y. from the assumption of a model 3 isochron; MSWD is 25. As was the case with the shale sample, this can be regarded only as a minimum age estimate for the Bernborough Formation. Page (in prep.) has shown that acid igneous rocks which have suffered low-grade metamorphism often yield anomalously young total-rock Rb-Sr ages. This observation has also been made in a study of submarine volcanics on the west coast of Tasmania (Black, unpublished analyses). The moderately large MSWD of 25 indicates non-ideal geological conditions for the generation of the Bernborough Volcanics isochron.

To summarize, then, the ages of 1766 ± 80 m.y. and 1733 ± 40 m.y. determined for the Warramunga Group do not represent crystallization or sedimentation, but appear to indicate a time of subsequent isotopic redistribution. Further evidence on this subject is presented in the Discussion.

Porphyry

The porphyries of the Tennant Creek area have been described by Crohn & Oldershaw (1965), and Mendum & Tonkin (in prep.). The latter have divided them into two lithological varieties, quartz porphyries and quartz-feldspar porphyries. Both types can occur as concordant bodies which are cleaved, and show no apparent contact effects. They can also occur as uncleaved cross-cutting bodies which have silicified adjacent sediments. Elliston (1963, 1968) postulated that the quartz-feldspar porphyry formed authigenically from a colloidal suspension of fine sediment. However, Spry (1963) and Large (1975, quoting his earlier work) have shown that chemical, mineralogical, and textural features relate to a felsic volcanic origin. Quartz-feldspar porphyry is particularly abundant in a northwest-trending granite-rich zone between the Gosse River and the Warrego mine.

The quartz-feldspar porphyry analysed in this study was sampled between the 10.8 and 89.1 metre levels of BMR-NTGS DDH 5, 11 km west-northwest of Tennant Creek. Microscopic examination reveals a high (30-40 percent) phenocryst content. Large, rounded, relatively unaltered alkali feldspar, which commonly displays microcline-twinning, and rounded, often deeply-embayed relict quartz grains dominate. Oligoclase-andesine and opaque minerals are also present. Relict ferromagnesian minerals are pseudomorphed by chlorite-muscovite-opaque mineral aggregates. Green biotite is locally present. Quartz, feldspar and fine-grained phyllosilicates dominate the groundmass.

Regression through the 15 isotopically analysed total-rock samples yields an age of 1760 ± 32 m.y. and an initial ratio of 0.711 ± .008. The relatively large uncertainty of the initial ratio is entirely due to a lack of analyses with Rb^{87}/Sr^{86} ratios less than 13; the analytical points themselves reveal no geological component of scatter about the isochron. Inclusion of an alkali-feldspar separate from sample 73063227 maintains model 1 conditions and produces indistinguishable parameters of 1752 ± 30 m.y. and 0.713 ± .0007 (Fig. 6). It is unlikely that perfect post-crystallization homogenization of Sr could have occurred over the 80 m by which these samples are separated. Hence the indicated age probably denotes the time of intrusion of this porphyritic body. A reset metamorphic interpretation cannot, however, be completely excluded.

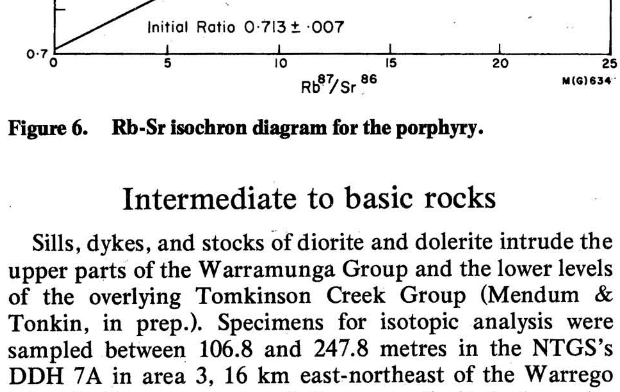

Figure 6. Rb-Sr isochron diagram for the porphyry.

Intermediate to basic rocks

Sills, dykes, and stocks of diorite and dolerite intrude the upper parts of the Warramunga Group and the lower levels of the overlying Tomkinson Creek Group (Mendum & Tonkin, in prep.). Specimens for isotopic analysis were sampled between 106.8 and 247.8 metres in the NTGS's DDH 7A in area 3, 16 km east-northeast of the Warrego mine. In this area an essentially quartz diorite body grades from monzonite towards a gabbroic composition with depth (M. R. Daly, written comm., 1975). Unfortunately, the small spread in Rb/Sr and considerable dispersion of points about the regression (Fig. 7) do not allow the deduction of a meaningful age. The dispersion may arise from primary influences—for example, composite intrusion, isotopically unequilibrated magma, or heterogenous isotopic contamination. Alternatively, it could derive from post-crystallization migration of Sr. Most samples are highly altered; chlorite and epidote commonly replace hornblende and pyroxene, and plagioclase is generally markedly

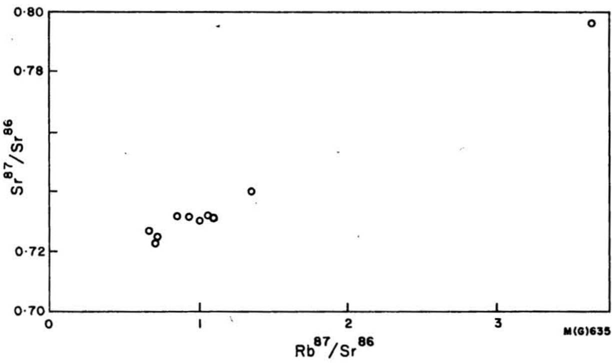

Figure 7. Rb-Sr isochron diagram for the intermediate to basic rocks.

sericitised. There is no correlation, however, between degree of alteration and isotopic composition.

Lamprophyre

Small sills, and dykes of lamprophyre which have been emplaced along faults and shear zones, occur in a NW-striking zone within the Warramunga Group. The lamprophyre is spatially associated with the Warrego, Tennant Creek, and Channingum Granites with which it is thought to relate (Mendum & Tonkin, in prep.). The samples used in this study were collected between 220.1 and 223.3 metres in NTGS's DDH 1 and 2 (350 m apart), near the Channingum Granite, in the East New Hope area. A further specimen, 72063493, was collected from the Ivanhoe mine. Mendum & Tonkin (in prep.) record that lamprophyre near the Channingum Granite consists of large books of biotite in a limonite, hematite, and feldspar groundmass containing minor quantities of quartz. Biotite has been completely replaced by chlorite in the analysed samples. Crohn & Oldershaw (1965) report the presence of amphibole and pyroxene-bearing lamprophyre elsewhere in the Sheet area.

Regression through all six total-rock analyses from DDH's 1 and 2 yields an age of 1673 ± 80 m.y. and initial ratio of 0.699 ± .017 from a model 1 isochron. The large error limits results from a small spread (13 to 20) in Rb^{87}/Sr^{86} ratios. Inclusion of the Ivanhoe mine lamprophyre, with Rb^{87}/Sr^{86} of 5, produces a further, more precisely defined model 1 isochron with age and intial ratio of 1664 ± 16 and 0.701 ± .002, respectively (Fig. 8). The low indicated initial ratio and ideal nature of both isochrons indicates that they define the original age of crystallization for the lamprophyres. Regression through feldspar, chlorite, and total-rock points for sample 73063266 produces values of 1650 ± 113 m.y. and 0.704 ± .011. The uncertainty limits reflect only the small number of analyses, for once more they define a model 1 isochron. A moderately enriched biotite separate from the Ivanhoe mine lamprophyre (72063493) yields an age of 1670 m.y. Comparison of the mean ages of the total-rock isochron, mineral isochron, and the biotite age, indicates 1670 m.y. as the approximate emplacement age. No significant post-crystallization thermal events occurred near either lamprophyre.

Granites

The granites of the Tennant Creek 1:250 000 Sheet area have been discussed by various authors—for example, Crohn & Oldershaw (1965), Dunnet & Harding (1967), and Mendum & Tonkin (in prep.), from whom this resume is derived.

Granites intrude the Warramunga and Hatches Creek Groups but have not been found intruding the Tomkinson Creek Group. They extend from the southeast corner of the Sheet area, northwestwards to beyond the Warrego Mine. Lithological varieties range from minor granodiorite, through fine-grained adamellite, to coarse porphyritic K-rich granite (*sensu stricto*). Foliation is reported to commonly parallel the regional cleavage; locally it appears to be primary. The granites have formed only a low-grade contact aureole. Xenoliths of country rock are not common.

Crohn & Oldershaw (1965) divided the granites of the Tennant Creek One-Mile Sheet area into the Tennant Creek and Cabbage Gum Granite Complexes, both of which were lithologically subdivided. Mendum & Tonkin (in prep.) have subsequently recognised and informally named 20 lithological varieties of granite in the 1:250 000 Sheet area. Their subdivision is followed in this text.

The main outcrops of the **Tennant Creek Granite** occur in the Station Hill, White Hill, and Whippet Trig areas to the north of Tennant Creek township. Le Messurier (1976), and Mendum & Tonkin (in prep.), assume a subsurface connection between these lithologically similar granites.

Sample 73063234 comes from BMR-NTGS DDH 1, situated immediately south of the Barkly Highway 35 km to the northeast of Tennant Creek. The analysed sample represents medium, even-grained, pinkish granite from the 105.5-metre level. It is composed of quartz, perthitic potash-feldspar, heavily sericitized and weakly zoned sodic plagioclase, and interleaved biotite and chlorite with associated opaque minerals. Aggregates of muscovite occur locally. Strain features are not pronounced. Some feldspar grains have iron-stained boundaries.

A small spread in Rb^{87}/Sr^{86} ratios (determined by X-ray fluorescence analysis) does not allow the derivation of a whole-rock age for granite from this drillhole. The only age estimate is provided by a biotite-total rock pair from sample 73063234, which yields a fairly precise value of 1798 m.y. Lithologically similar Tennant Creek Granite from BMR-NTGS DDH 4, 3 km south of Whippet Trig, yields a similar, though less precise, biotite-total rock age of 1794 m.y. Biotite from BMR-NTGS DDH 3, 8 km to the south of DDH 4 has completely altered to chlorite, from which it was not possible to derive a precise age.

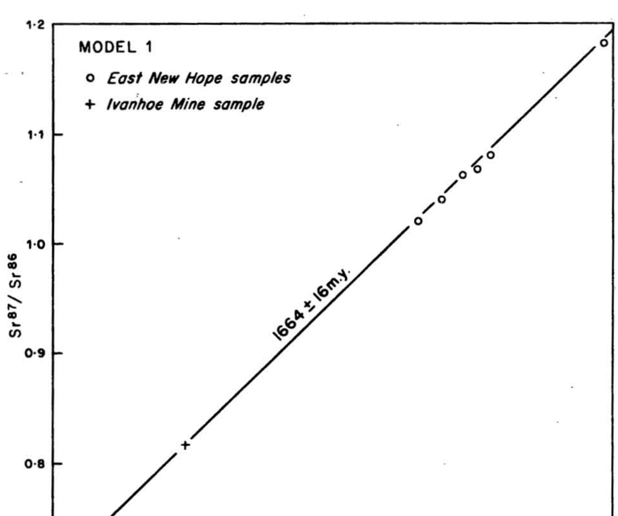

Figure 8. Rb-Sr isochron diagram for the lamprophyre.

A biotite separate from a sample (71860059) collected by Mendum, 12 km north of Tennant Creek produces an age of 1738 m.y. This granite is lithologically quite distinct from the other analysed granite samples. It displays a pronounced metamorphic fabric, and consists of large, rounded, perthitic orthoclase phenocrysts set in a groundmass of altered plagioclase, biotite, and blue opalescent quartz.

All values represent no more than minimum age estimates for the Tennant Creek Granite. The similar ages of the medium-grained granite from DDH's 1 and 4, which are 20 km apart, suggests, however, that a real geological event occurred at about 1796 m.y. This could correspond to the time of granite emplacement.

The **North Seismic Adamellite** crops out to the southeast of Nobles Nob. It has been subdivided by Mendum & Tonkin (in prep.) into two units. A biotite separate (71860061) from one of these, the black and white, mottled medium-grained adamellite, yields a precise Rb-Sr age of 1731 m.y. from an assumed initial Sr^{87}/Sr^{86} ratio of 0.71. The close similarity of this value to that of the porphyritic phase of the Tennant Creek Granite (1738 m.y.) may indicate a real event at this time, which may correspond to granite emplacement.

The **Red Bluff Granite** outcrops near Red Bluff, 20 km northwest of Tennant Creek. Two phases have been recognized by Mendum & Tonkin (in prep.), and both have been dated. Most of the 'granite' is a red-brown, medium to coarse-grained massive adamellite. This phase was collected from DDH 6 of the BMR-NTGS geochemical survey. The medium-grained granite consists of microcline and quartz, which commonly form granophyric intergrowths, heavily sericitized plagioclase, and biotite which has been completely replaced by chlorite. The latter is not sufficiently enriched in Rb with respect to Sr to allow mineral dating. However, seven total-rock samples from 19.2 to 72.2 metres do exhibit sufficient spread (3 to 17) in Sr^{87}/Sr^{86} to generate a well-defined isochron (Fig. 9). This yields an age of 1648 ± 50 m.y. and an initial ratio of 0.716 ± .005. The computer-selected model 2 regression with MSWD of 15 suggests either that there is a small age difference between samples or that the granite has suffered a slight redistribution of Rb and/or Sr since emplacement.

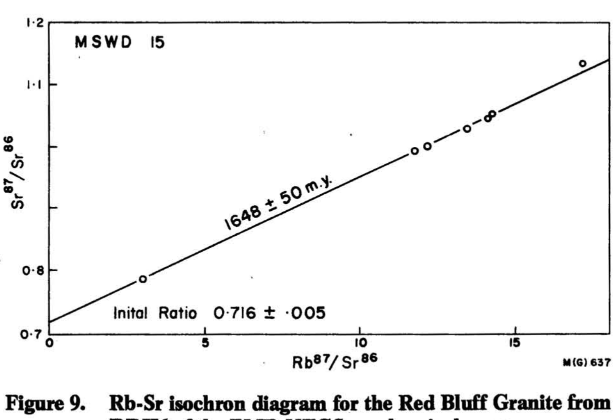

Figure 9. Rb-Sr isochron diagram for the Red Bluff Granite from DDH6 of the BMR-NTGS geochemical survey.

The northwestern part of the Red Bluff Granite was sampled in DDH 2 of the BMR-NTGS geochemical sampling program. Here the somewhat coarser-grained granite contains slightly porphyritic pink K-feldspar. Microscopic examination shows large microcline grains which frequently form granophyric intergrowths with quartz. Plagioclase is heavily sericitized. Biotite is absent, chlorite is rare. Patches of epidote and sphene occur locally. The five samples which generate the total-rock isochron

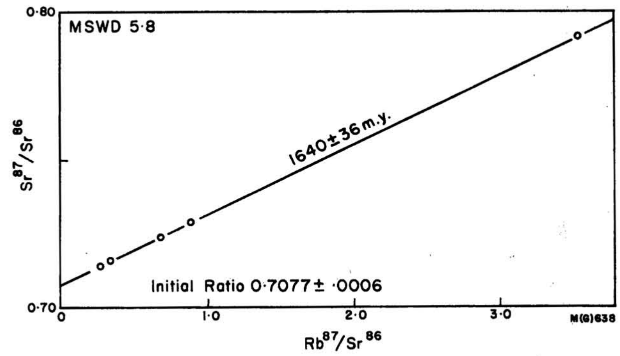

Figure 10. Rb-Sr isochron diagram for the Red Bluff Granite from DDH2 of the BMR-NTGS geochemical survey.

(Fig. 10) were taken from between 81.8 and 115.7 metres below surface. The resultant age is 1640 ± 36 m.y.; the initial Sr^{87}/Sr^{86} ratio is 0.7077 ± .0006. The model 3 isochron with MSWD of 6 implies the correlation of samples with slightly differing initial ratios. The agreement of these relatively precise ages for both phases of the Red Bluff Granite probably indicates a common emplacement age of about 1645 m.y. The significantly different initial ratios, however, show that, even though contemporaneous, the two phases of the granite were not generated from an isotopically common source region.

The **Warrego Granite** crops out in the vicinity of the Warrego mine, 50 km northwest of Tennant Creek. Mendum & Tonkin (in prep.) have divided it into three major lithological varieties. The analysed samples were collected 3 km west of the Warrego mine between 76.5 and 83.5 metres in DDH 7 of the BMR-NTGS geochemical project. The granite here is light-coloured, massive, and medium to coarse-grained. It is composed of unaltered microcline, quartz, and plagioclase (andesine?) which is atypically fresh for granites of this region. Biotite, commonly altered to chlorite, differs markedly in abundance. Books of coarse fresh muscovite occur locally.

Regression through the six total-rock analyses produces an age of 1703 ± 100 m.y. The large uncertainty does not relate to scatter about the isochron for the points fulfil model 1 conditions. It derives, in fact, from the small spread (33 to 44) in Rb^{87}/Sr^{86}. The addition of a chlorite analysis (73063261) maintains model 1 conditions (which may justify its inclusion), increases the range of Rb^{87}/Sr^{86} values to 15, and produces the improved figures of 1662 ± 20 m. y. and 0.702 ± .008 (Fig. 11). This is, however, a somewhat subjective procedure for two other chlorite separates are not concordant (see below). Three muscovite separates from samples 73063261, 73063262 and 73063263 yield ages of 1692, 1674 and 1692 m.y., respectively. The concordancy of these with the mean total-rock and total

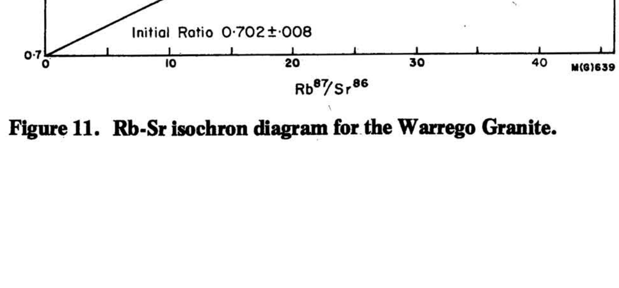

Figure 11. Rb-Sr isochron diagram for the Warrego Granite.

rock-chlorite isochron ages points to a reliable approximate age for the Warrego Granite of 1690 m.y. The low mean initial ratio for the total rock-chlorite isochron of 0.702 militates against a substantially older estimate than the mean age; the muscovite ages against a substantially younger value. The two other chlorite separates (73063262 and 73063263) which are not concordant plot below the total-rock isochron; this is presumably owing at least partly to a post-emplacement thermal event of insufficient magnitude, at this locality, to affect the Rb and Sr systematics of muscovite and chlorite 73063261. Younger granites, which may be the source of this thermal resetting, do exist in the Tennant Creek area, as discussed below.

The **Cabbage Gum Granite Complex** is so poorly exposed that it is known almost entirely from diamond-drill hole intersections. Consequently the relationship between the major phases, which include porphyritic adamellite, augen gneiss and medium-grained gneissic granite, is not known. The analysed samples were taken from pinkish, medium-grained, foliated adamellite in BMR-NTGS DDH 8, 24 km southwest of Tennant Creek. Microscopically the rock consists of slightly phenocrystic microcline, heavily sericitized plagioclase, granular quartz around feldspar and large quartz nuclei, and ragged greenish-brown biotite flakes which are partly altered to chlorite, and often occur with opaque minerals.

Seven total-rock samples were prepared from core taken between 96.3 and 109.1 meteres in DDH 8. These define a model 1 isochron of 1450 ± 36 m.y., and an initial ratio of 0.753 ± .012 (Fig. 12). A further total-rock sample (75063309), taken at 195.2 metres in a different drill hole (DDH 1 in the BMR 3 area), 18 km to the northwest of DDH 8, which does not fit this ideal isochron, indicates a slight but significant difference in age, or initial Sr^{87}/Sr^{86} ratio, or post-emplacement redistribution of isotopes within the Cabbage Gum Complex. This observation may explain the apparent anomaly between the rather precise total-rock Rb-Sr age of 1450 ± 36, and the older K-Ar age of 1630 m.y. reported by Hurley *et al.* (1961) from what Crohn & Oldershaw (1965), and Mendum & Tonkin (in prep.), claim to represent the Cabbage Gum Granite. The localities in question are separated by 27 km. It may be that the Cabbage Gum Complex is composed of granites of distinctly different ages, as might be anticipated from the textural variability shown in hand specimen.

Microcline and a mixed chlorite-biotite separate from specimen 73063291 do not fit the total-rock isochron. It seems quite probable, therefore, that this phase of the granite is not the last thermal manifestation in the Tennant Creek area. The calculated age (1370 m.y.) for the biotite-chlorite mixture should give an older limit for the time of the last event. This argument is supported by data from the Gosse River East Granite (see below). The metamorphic texture of the Cabbage Gum Granite would indicate that the derived

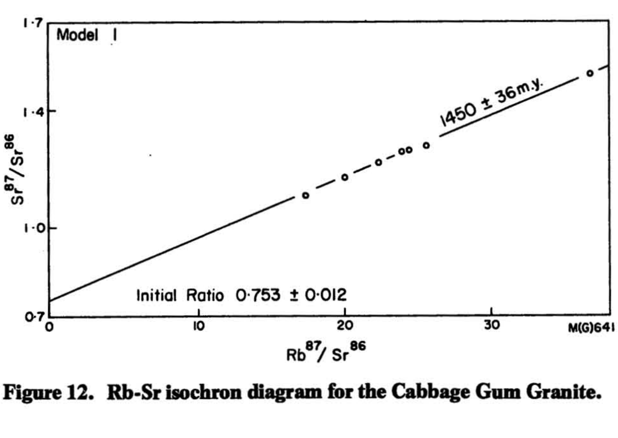

Figure 12. Rb-Sr isochron diagram for the Cabbage Gum Granite.

age of 1450 ± 36 m.y. could date either post-emplacement tectonism or the time of original emplacement. The ideal nature of the total-rock isochron for DDH 8 samples supports the second alternative. It is, moreover, quite conceivable that the development of metamorphic fabric was approximately synchronous with granite emplacement.

The **Gosse River East Granite** of Mendum & Tonkin (in prep.) forms sparse outcrops to the east of the Gosse River, 50 km east-southeast of Tennant Creek. It is a pinkish brown, medium and even-grained granite—in the strict sense, and consists of microcline, heavily sericitized plagioclase, quartz, chlorite, and opaque minerals. The analysed samples were taken from depths in DDH 404 (Australian Development Ltd) between 150.7 and 151.3 metres. Regression through 11 total-rock samples from this section yields a model 1 isochron with age and initial ratio of 1300 ± 100 m.y. and 0.714 ± .002. Addition of a microcline analysis yields a further model 1 isochron, with statistically unchanged values of 1330 ± 100 m.y. and 0.713 ± .002 (Fig. 13). The apparent equilibrium between total-rock and feldspar is a consistent, though not necessarily conclusive argument that the Gosse River East Granite represents one of the final thermal events within this area. It must be emphasised that the computer-generated age limits could conceivably be a little optimistic for this suite which has a spread in Rb^{87}/Sr^{86} from only 1.56 to 1.92.

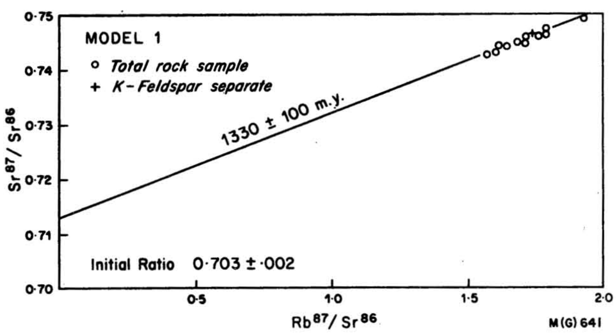

Figure 13. Rb-Sr isochron diagram for the Gosse River East Granite.

Economic geology

The following resume is drawn from the works of Ivanac (1954), Crohn & Oldershaw (1965), Whittle (1966), Dunnet & Harding (1967), Large (1975), Le Messurier (1976), and Mendum & Tonkin (in prep.). The Tennant Creek area is primarily an important gold and copper field, though small concentrations of bismuth, selenium, lead and zinc are also found. All economic mineralization in the Tennant Creek mineral field is associated with hematite and/or magnetite bodies. These range from a few inches to more than 10 metres in width and may be up to several hundred metres long. These 'ironstones', which are both structurally and lithologically localised, occur exclusively within the Carraman Formation (informal name, see Large (1975) and Le Messurier (1976)) of the Warramunga Group, for which a shale age of 1766 ± 80 m.y. was derived. Crohn & Oldershaw (1965) report that shear zones, nearby porphyry intrusions, the shale-greywacke succession, and especially the hematite shale horizon, provide favourable depositional loci. Most ironstone bodies are pipe-like to lenticular, but irregular bodies are also found. Their location is controlled by structures formed during the main folding episode.

Although there is agreement on the association of economic mineralization with the ironstones, there remains considerable controversy over their specific genesis. For example, the granites (Ivanac, 1954), 'sedimentary' porphyries (Elliston, 1963), igneous prophyries (Crohn & Oldershaw, 1965), and basic rocks (Whittle, 1966; Dunnet & Harding, 1967) have all been suggested as sources for the economic mineralization. The recent study by Large (1975) provides a strong case for the production of the hydrothermal ore-bearing fluids by dewatering of sediment near granitic intrusions. Reactions with host rocks produced a systematic chemical variation within the fluid, and the consequent zonation within the orebodies. New isotopic data have provided further evidence on the origin of the ironstones.

Speciments from various mineralized areas and relevant geological information were made available by local mining companies. Geopeko Ltd supplied samples from the Juno and Warrego Mines. That from Juno (75063302) comes from the footwall side partly below the No. 2 ironstone body, and is associated with a small body of mineralization. It is composed mainly of chlorite and magnetite. Small quantities of variably sized muscovite which are present yield a precise Rb-Sr age of 1810 m.y. P. Le Messurier (written comm., 1976) believes that, as there is no evidence of later thermal events, this sample from the hydrothermally altered zone should reflect the time of mineralization.

Four samples from the Warrego mine were dated. The first (75063297) is from 10 level in the No. 1 orebody. It consists of chlorite, magnetite, muscovite, and aggregates of sericite. Separated sericite and muscovite yield ages of 1693 and 1757 m.y., respectively. Sample 75063298 was collected on level 10 in the No. 3 orebody. It consists of quartz, magnetite, and interleaved muscovite and chlorite. The muscovite gives an age of 1810 m.y. Sample 75063299, which consists of quartz, chlorite, magnetite, and fine-grained muscovite, was collected from level 5 in the No. 1 orebody. This sample produces a relatively imprecise Rb-Sr muscovite age of 1803 m.y. from an assumed initial Sr^{87}/Sr^{86} ratio of 0.71. Quartz-chlorite-magnetite-apatite-biotite rock from level 5 in No. 1 orebody is represented by sample 75063300. Separated biotite indicates an approximate age of 1665 m.y. Samples 75063297, 75063298, and 75063299 represent hydrothermally altered wallrock adjacent to ironstone. Sample 75063300 is one of many chlorite-muscovite-biotite dykes which occur throughout the mine, and are most common within the ironstone. Le Messurier (1975) reports that the micas from both occurrences should have formed during mineralization. The older muscovite values of about 1810 m.y., then, probably define this time, whereas the younger muscovite age of 1757 and the sericite and biotite ages of 1693 and 1664 m.y., may reflect subsequent minor thermal events. Biotite responds more readily than muscovite to heating and the fine-grained sericite would be expected to behave similarly.

Australian Development Limited supplied specimens from their Nobles Nob and Golden Forty mines. The sample from the former consists mainly of chlorite, euhedral magnetite, abundant muscovite, and some quartz. As the muscovite is only moderately enriched in Rb^{87}/Sr^{86} (77), any calculated age is slightly dependent on assumed initial ratio. Variation from 0.71 to 0.73 produces ages between 1820 and 1805 m.y. The Golden Forty sample is rather fine-grained, and consists of a chloritic matrix containing euhedral magnetite, abundant small muscovite flakes, some of which form veins, and locally quartz. An age of 1810 m.y. is obtained from averaging the results of two somewhat mediocre Sr mass-spectrometer runs.

An additional sample was obtained from DDH 19 in the TC8 deposit, 4.5 km west of Tennant Creek, which is jointly owned by Aquitaine Australia Minerals Pty Ltd, Le Nickel (Australia) Exploration Pty Ltd, Gesellschaft mbH and Western Nuclear Australia Limited. This sample consists of chlorite, commonly acicular magnetite, quartz, and some small flakes of muscovite. A fairly precise age of 1816 m.y. obtained from muscovite is in agreement with the bulk of muscovite ages from mineralized samples in the Tennant Creek mineral field. The significance of these results is discussed in the next section.

Discussion

The low-grade metamorphic environment of the Tennant Creek Block does not favour the establishment of unequivocal geochronological ages. Any interpretation of the isotopic data must consequently depend heavily on observed geological relationships.

The key for correlation of isotopic data with the sequence of tectonic events affecting the Warramunga Group is provided by the relationships of economic mineralization to folding. The orebodies, which are dated at about 1810 m.y., are localized by structures formed during the main folding event with its associated, east-west-oriented, slaty cleavage. Furthermore, recent workers (e.g., Large, 1975; Le Messurier, 1976) maintain that the mineralization was contemporaneous with, rather than significantly later than, the main folding, and can consequently be dated at about 1810 m.y.

Error limits for the shale age (1766 ± 80 m.y.) in the Warramunga Group are not precise enough to decide whether the shale is significantly younger than 1810 m.y. However, the apparent age of the Bernborough Volcanics, which Mendum & Tonkin (in prep.) consider to be lower in the stratigraphic sequence than the dated shale, is significantly younger, at 1733 ± 40 m.y. The results of Gebauer and Grunenfelder (1974), reported earlier, indicate that shale ages are particularly susceptible to isotopic resetting. Hence, both total-rock ages could presumably have been reset by a subsequent event corresponding perhaps to the development of the 'phase 3' conjugate shear systems described by Dunnet and Harding (1967), and Mendum & Tonkin (in prep.). Further evidence for this conclusion is provided by the biotite age (1738 m.y.) for the Tennant Creek Granite near Station Hill. The phase 3 folding is more strongly developed at this place than elsewhere in the Tennant Creek area. The sedimentary rocks display strong S3 cleavage; strong deformation features within the granite itself would therefore be expected to be related, at least in part, to this deformation. Consequently, the biotite age of 1733 m.y. may be regarded as a probable minimum estimate for this period of folding. The similarity of this age to that of the North Seismic Adamellite may not be coincidental, and may in fact define the synchronous emplacement of both masses, the former in a region of high stress and the latter in a stress-free environment to the southeast. This value of 1733 m.y., which fits so closely the mean age for the Bernborough Volcanics, would then provide the most precise time estimate available for the phase 3 deformation.

Le Messurier (1976) notes several post-main-episode folding and shearing events. The limits provided by the foliated Cabbage Gum Granite of 1450 ± 36 m.y. may well reflect one of these. Poor outcrop, however, does not encourage detailed structural analysis of the deformation in the vicinity of the Cabbage Gum Granite.

There is currently no evidence for major tectonic activity after the emplacement of the Gosse River East Granite. Moreover, as might be expected from the stratigraphy, the Middle Palaeozoic Alice Springs Orogeny, which was sufficiently intense to reset mineral ages over large areas of the Arunta Block to the south, e.g., Stewart (1971), Marjoribanks and Black (1974), Armstrong and Stewart (1975) and Black (1975), is not expressed at all in the Tennant Creek Block.

The low regional metamorphic grade of the Warramunga Group should be noted here. Le Messurier (1976), and

Mendum & Tonkin (in prep.), ascribe greenschist facies conditions; Wyborn (pers. comm., 1976), however, postulates even lower grades, for detrital plagioclase is not albitized, and chert fragments in sediments have not recrystallized. In the absence of elevated regional temperatures, total-rock resetting, especially for shale, must relate principally to dynamic effects and the accompanying migration of residual water within these essentially unmetamorphosed rocks.

Some authors (e.g. Dunnet & Harding, 1967; Mendum & Tonkin, in prep.) consider the Tomkinson Creek Group to predate the main folding. If this is correct, the isotopic inferences would require a pre-Carpentarian initiation of sedimentation for that group. Recently, however, Australian Development Limited (1976) have suggested that the Hatches Creek and Tomkinson Creek Groups postdate the main folding and associated east-west axial-plane cleavage of the Warramunga Group. It will require detailed structural analysis within the Tomkinson Creek Group before the current isotopic data can be used to define its chronology.

The poorly exposed rocks to the southwest of Tennant Creek, which were metamorphosed to amphibolite grade at 1920 ± 60 m.y., currently yield the oldest isotopic age for the area. Even so, it cannot be stated unequivocally that these rocks predate those of the Warramunga Group which give substantially young mineral and total-rock ages. From previous discussion it is apparent that the Warramunga Group ages reflect only tectonic events subsequent to deposition. No reliable age estimate for the latter is yet available. Indeed, Dunnet & Harding (1967) have inferred a folding episode older than the main deformation. It could be speculated that this 'phase 1' folding was synchronous with the amphibolite-facies metamorphism at about 1920 m.y. The presently exposed parts of the Warramunga Group could have been at a sufficiently high crustal level to escape all but the slightest tectonic effects. The amphibolite-facies rocks, however, would have formed at deeper levels and been subsequently uplifted.

An alternative explanation is that the amphibolite-facies rocks do in fact represent basement to the Warramunga Group as a superficial examination of the isotopic data would suggest. In this case the inferred phase 1 folding of Dunnet & Harding (1967) could either not have taken place, as contended by Mendum & Tonkin (in prep.), or be completely masked by the effects of the subsequent dominant deformation. Current isotopic data are not sufficient to decide whether the amphibolite-facies rocks represent basement or merely higher grade equivalents of the Warramunga Group. U-Pb zircon studies on the Bernborough Volcanics should resolve this problem.

Overall, the data indicate a considerable range of emplacement ages. The Tennant Creek Granite biotite age of about 1800 m.y. can be confidently assumed as a minimum estimate for the initiation of intrusion. The age grouping around 1660 m.y. must be also primary for the following reasons. First, the two different phases of the Red Bluff Granite, from separate drillholes, yield indentical total-rock ages. Second, the low initial ratio of 0.701 ± .002 for lamprophyre, combined with its moderate Rb^{87}/Sr^{86} values (average about 15), precludes post-emplacement isotopic redistribution. Lastly, the combination of muscovite ages and low mean initial Sr^{87}/Sr^{86} ratio for the total-rock isochron representing the Warrego Granite, does not allow significant variation of postulated age from the preferred value of about 1690 m.y.

The present isotopic data apparently indicate subsequent relative quiescence for about 200 m.y. up to the emplacement of the Cabbage Gum and Gosse River East Granites. Evidence for the primary nature of the youngest granite ages is not as conclusive as for the other groups. It is, however, reasonably persuasive. Confidence in the age of the Gosse River East Granite (1300 ± 100 m.y.), for example, is restricted by the small spread in Rb^{87}/Sr^{86}. This is offset, however, by the ideal nature of the total-rock isochron, whether or not the K-feldspar analysis is included. Moreover, mixed biotite-chlorite ages of 1370 and 1390 m.y. for the Cabbage Gum and Warrego Granites (sample 73063262) may support a geological event at this time. The high initial ratio and deformation structures within the Cabbage Gum Granite could be taken as suggestive of a reset isotopic age. As stated earlier, though, the perfect nature of the total-rock isochron, for samples separated by up to 13 metres, should indicate a primary age, perhaps synchronous with the deformation.

Some of the marked initial Sr^{87}/Sr^{86} variability for the igneous rocks of the area—for example the value for the Bernborough Volcanics—relates to post-emplacement isotopic re-equilibration. Most, however, appears to be primary. Even within a single rock type, for example the Red Bluff Granite with values of 0.7077 ± .0006 and 0.716 ± .005, there is evidence of initial Sr^{87}/Sr^{86} variation. The high and somewhat variable values are characteristic of the S-type granite as defined by Chappell & White (1974). Petrographic and chemical evidence also indicates an S-type origin for these rocks (Wyborn, pers. comm., 1976). The low indicated initial ratio for the Warrego Granite is puzzling however, especially as it appears petrologically comparable to the other granites. Further, detailed isotopic work will be required to resolve this apparent anomaly.

The isotopic evidence, then, suggests a range in granite ages of perhaps as much as 500 m.y. The distribution of this age range conflicts with the field observations, for most authors (e.g. Crohn & Oldershaw (1965), Dunnet & Harding (1967), and Large (1975)), at least by inference, consider the granites to predate or be roughly contemporaneous with the main deformation. So far no granites have been found to be as old as the minimum deduced age of the main deformation (1810 m.y.) However, the 1796 m.y. age for biotite from the Tennant Creek Granite is only one percent less. In that this is a minimum age, the difference may not be significant. Further, some of the granites which remain to be dated may prove to be older than those already studied.

Large (1975) has developed a theory of ore formation in the Tennant Creek area from detailed studies of the Juno mine. He envisages a hydrothermal solution derived by release of formation water within argillaceous sediments by heat from adjacent granite and porphyry intrusives. Leaching from the sediments increased the acidity of the solution, which subsequently reacted with favourable host rocks to form the iron-rich ore bodies. Large considers that both ore (Au, Cu, Bi and Se) and gangue components may have originated in the sedimentary rocks. The present isotopic data are clearly incompatible with Large's suggestion that the last phase of igneous activity is related to economic mineralization. They would suggest that only the earliest granites might provide a favourable heat source for the release of water from the sediments to form the ore-bearing fluids.

As deduced earlier, the agreement, with one exception, of muscovite ages from the mineralized rocks indicates 1810 m.y. as the approximate time of ore formation. The lone exception was probably reset by a local thermal event, as was postulated for the biotite and sericite samples from the Warrego Mine. The concordance of muscovite ages is strong evidence for a common age and, by inference, common origin for the ore deposits of at least the Warrego, Juno, Golden Forty and Nobles Nob mines.

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