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Sedimentology, geochronology and provenance of the Proterozoic Itremo Group, central Madagascar, and implications for pre-Gondwana palaeogeography

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Abstract: Proterozoic metasediments of the Itremo Group in central Madagascar probably represent a passive margin sequence predating Gondwana assembly. The quartzites are well-sorted quartz arenites that contain flat lamination, wave ripples, current ripple cross-lamination, and dune cross bedding. The carbonate rocks preserve abundant stromatolites and algal laminates. A continental source is indicated by mudrock major and trace element chemistry. The combination of lithologic association, sediment architecture and mudrock chemistry indicates that the sequence was deposited on a continental shelf or platform.

SHRIMP data from detrital zircons indicate that the source area included early Proterozoic and late Archean rocks with ages between 1.85 and 2.69 Ga, and that the depositional age of the Itremo Group must be less than 1855 ± 11 Ma. The sequence has been deformed into a series of large-scale folds separated by ductile shear zones. SHRIMP data indicate both massive lead loss from detrital zircons and new zircon growth in the metasediments at 833 ± 112 Ma, which we interpret as the age of metamorphism of the sequence. Comparison of detrital grain ages with basement ages in East Africa and in India indicates that the source area for the Itremo Group probably lay on the present African mainland.

Keywords: Madagascar, Gondwana, Proterozoic, sedimentology, geochemistry.

The Madagascar microcontinent exposes approximately 400 000 km^2 of strongly deformed and metamorphosed Precambrian basement, the geology of which is extremely poorly understood. Current knowledge comes mainly from work done prior to 1970, summarized by Besairie (1967, 1968, 1969*a*, 1969*b*, 1970). Most existing maps are lithologically detailed, but include little or no structural data and are essentially non-interpretive. Although there has been a recent increase in U–Pb data acquisition (Paquette *et al*. 1994; Ashwal *et al*. 1996; Tucker *et al*. 1996), the geochronological database is small and dominated by Rb–Sr data (Caen-Vachette 1979; Cahen & Snelling 1984).

Most of the Precambrian rocks of Madagascar are deformed and metamorphosed, commonly to upper amphibolite or granulite grade (Bazot *et al*. 1971; Nicollet 1990). The scarcity of U–Pb ages, coupled with the complex tectonic history in most areas, has confused or obscured the distinction between ancient cratonic nuclei and subsequent orogenic crustal additions. Some recent papers have been published on large-scale aspects of the Precambrian geology of Madagascar (Ackermand *et al*. 1989; Nicollet 1990; Windley *et al*. 1994), but most of their conclusions are poorly constrained because many questions remain about structural and stratigraphic relationships and regional correlation of lithologies and tectonothermal events. There is, therefore, a strong need for detailed local and regional field and geochronological studies such as those of Andriamarofahatra *et al*. (1990), Paquette *et al*. (1994) Ashwal *et al*. (1995) and Morel *et al*. (1995).

This paper reports the results of initial work in the outcrop belt of the Itremo Group, a sequence of low- to medium-grade Proterozoic metasediments in central Madagascar (Figs 1 & 2). The overall aims of this contribution are to evaluate the stratigraphy, environment of deposition and provenance of the sedimentary sequence; to establish a geochronological framework for the geology of the Itremo Group; and to relate this to possible correlative units in Africa and India.

Geological setting

The Itremo Group consists of quartzite, pelite and dolomitic carbonate rocks representing a continental setting (Moine 1967). It outcrops over an area of approximately 110×120 km in the central highlands of Madagascar, south of Antananarivo (Fig. 1). The metasedimentary sequence has been deformed into a series of upright to recumbent folds, separated by mylonitic shear zones (Fig. 2). Metamorphic grade increases from east to west. In the east, the rocks are dominated by greenschist or sub-greenschist assemblages. To the centre and west of the belt these give way to kyanite-and sillimanite-bearing rocks (Raoelison 1997). The sequence is intruded by granitic rocks and gabbros that are undeformed or weakly deformed, and which give U–Pb zircon ages of 770–800 Ma (R.D. Tucker, unpublished data).

The Itremo Group represents a Proterozoic depocentre which was closed and deformed during the amalgamation of Gondwana in late Precambrian time. It bears lithological similarities to Proterozoic sequences in Africa and India, with which it has been tentatively correlated (e.g. Pinna *et al*. 1993).

Analytical procedures

XRF major and trace element analyses were carried out at Rocklabs in Pretoria, South Africa, using an ARL-8420 spectrometer with Rh-target, end-window tube. Samples were prepared as fused disks with a lithium metaborate and lithium tetraborate flux mixture and as pressed pellets using a dilute solution of water-soluble PVA.

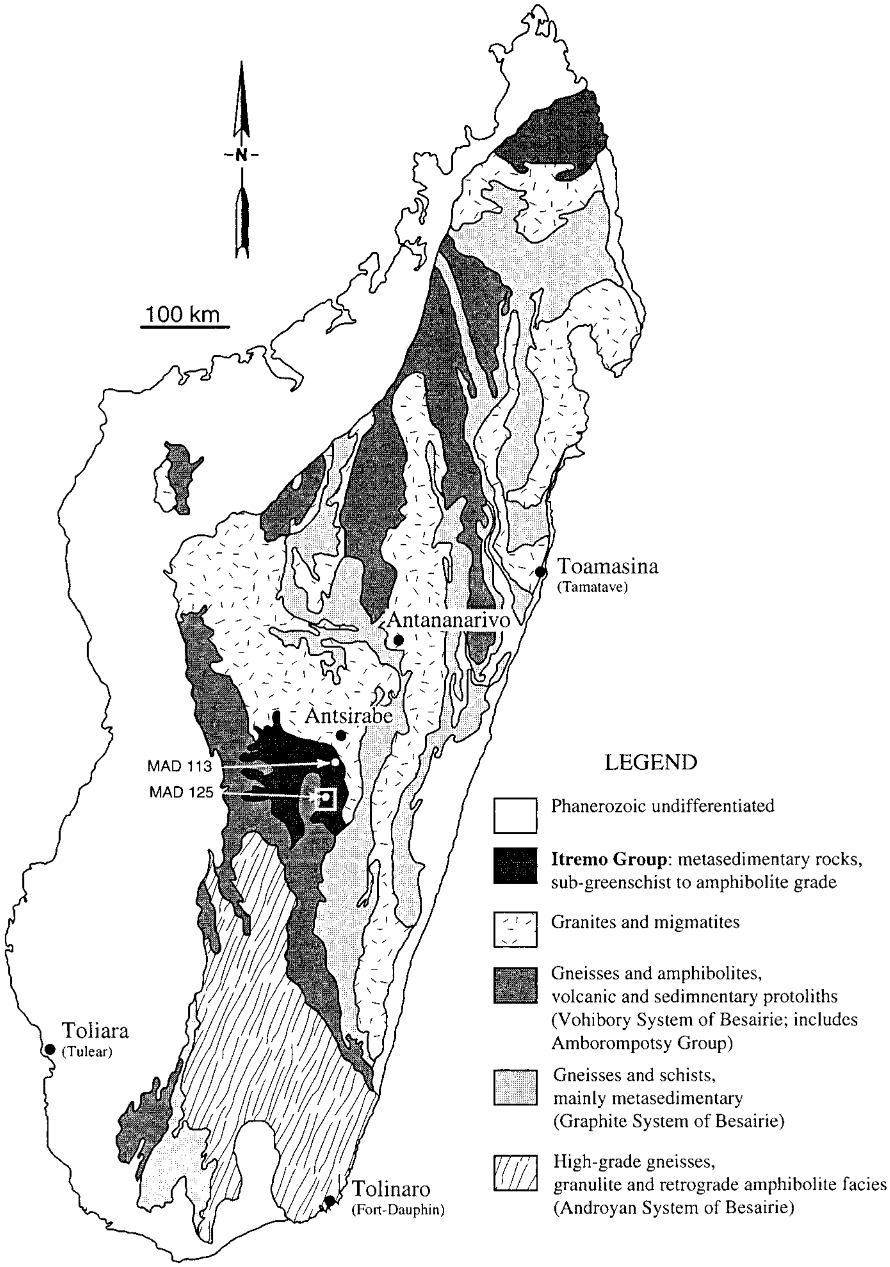

Fig. 1. Generalized geological map of Madagascar. Modified after Besairie (1964, 1973). Boxed area is enlarged in Fig. 2. Locations of geochronology samples MAD 113 and MAD 125 are shown.

Inter-element interference effects were corrected for using the methods of Norrish & Hutton (1969), but with proprietary matrix factors (M. R. Sharpe pers. comm.) Results for concurrently-run USGS standard GSP-1 are shown in Table 1.

The concentrations of seven rare earth elements (La, Ce, Nd, Sm, Eu, Tb, Yb) were determined by instrumental neutron activation at the University of Illinois after methods given in Gordon *et al.* (1968) and Jacobs *et al.* (1977). Results for concurrently-run standards are given in Table 2.

The rare earth element (REE) data are normalized to chondrite abundances using the values of Evensen *et al.* (1978). Eu* (the value that Eu would have if not fractionated relative to the other REE) is calculated by interpolating between the normalized values for Sm and Tb (Sm_n, Tb_n) using the equation for a geometric progression:

$$\mathrm{Eu}^* = \mathrm{Tb_n}(\sqrt[3]{\mathrm{Sm_n}/\mathrm{Tb_n}})^2.$$

Similarly, Ce* is calculated by interpolating between La and Nd.

U–Th–Pb analyses of zircon grains were made on the sensitive high-resolution ion microprobes (SHRIMP I and SHRIMP II) at the Research School of Earth Sciences (RSES) at the Australian National University, Canberra (Table 3). Zircons were separated from crushed whole-rock samples using conventional heavy liquid and magnetic separation techniques and were mounted in epoxy together with chips of the RSES standard zircon SL13. The zircons were then sectioned, polished and photographed. For these detrital zircons each analysis included a 4-scan data acquisition routine, each scan sequentially stepping through the masses Zr_2O^+, $^{204}Pb^+$, $^{206}Pb^+$, $^{207}Pb^+$, $^{208}Pb^+$, $^{238}U^+$, ThO^+, UO^+. Data reduction follows the methods of Williams & Claesson (1987) and Compston *et al.* (1992), with the Pb/U ratios normalized to a ^{206}*Pb/^{238}U value of 0.0928 for the SL13 standard, corresponding to an age of 572 Ma. All U/Pb ages were calculated using the decay constants recommended by the IUGS Subcomission on Geochronology (Steiger & Jäger 1977), and have been corrected for common Pb using the directly measured ^{204}Pb abundances and the appropriate compositions according to the model of Cumming &

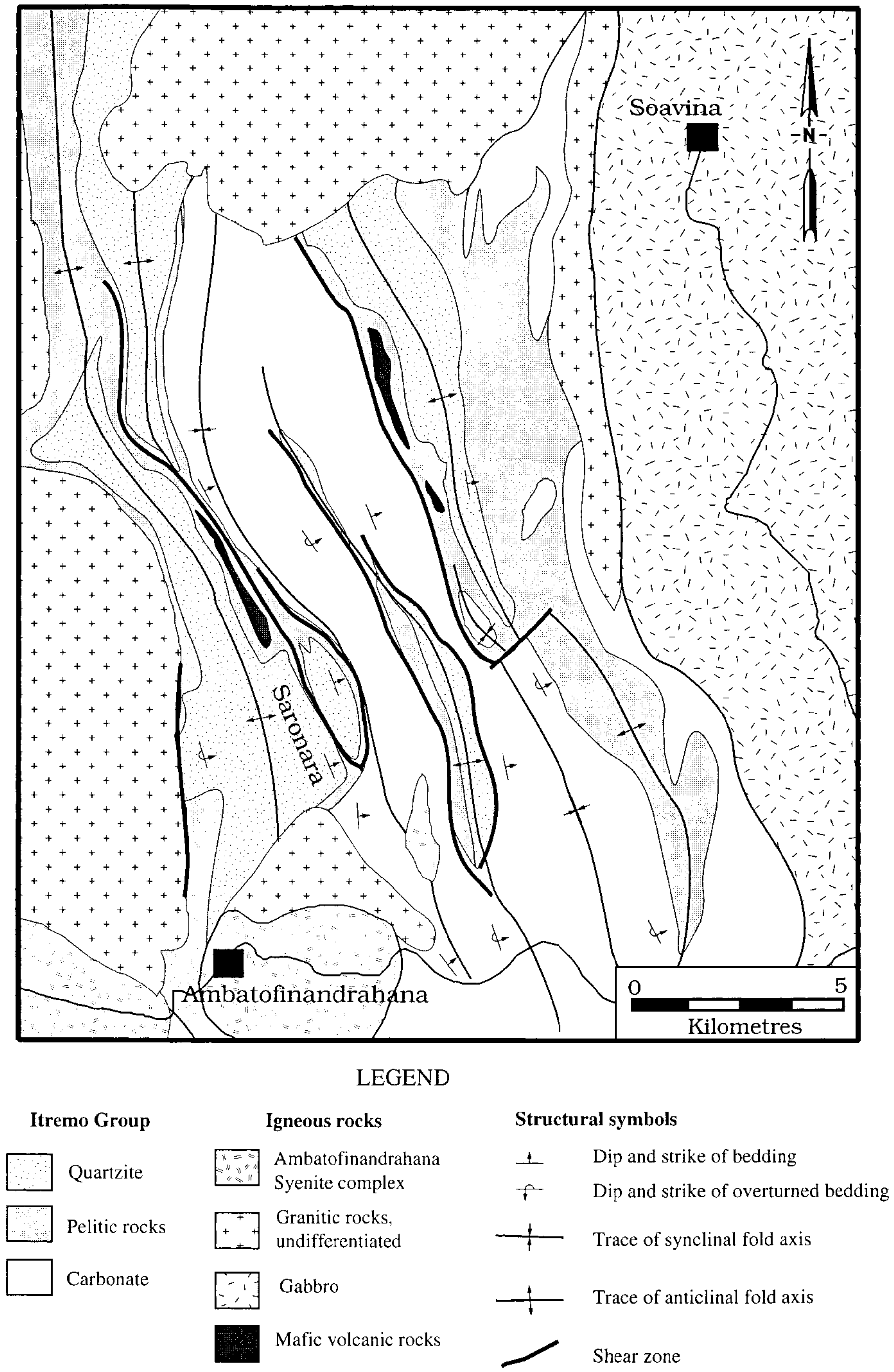

Fig. 2. Simplified geologic map of part of the Itremo Group. Data from mapping by the Klay *et al.* (1963) and this study.

Richards (1975). Uncertainties in the isotopic ratios and ages given are one standard error precision estimates based on counting statistics.

Itremo group Nomenclature

The Itremo Group (Emberger 1955; Moine 1974) (Figs 1 & 2), has also been referred to as the série Schisto-Quartzo-Calcaire (Besairie 1970; Hottin 1976; Moine 1967, 1974; Tucker *et al.* 1996; Windley *et al.* 1994), Série Schisto-Quartzo-Dolomitique, (Moine 1974), and the série Supérieure du Socle (Trottereau 1969). The name Itremo Group, which was introduced by Emberger (1955) and formalized by Moine (1974) is preferred because it conforms to international stratigraphic usage. We formally define the Itremo Group to include the outcrop area shown in Fig. 1.

The name Amborompotsy Group or Ikalamavony–Amborompotsy Group has occasionally been used to refer to the quartzites, carbonates and pelites of the Itremo Group (Boast & Nairn 1982; Nicollet 1990), but this is incorrect. The name Amborompotsy Group is defined for the high-grade gneisses and migmatites which occur to the west of the Itremo Group (Besairie 1970; Emberger 1955; Moine 1967, 1974).

Table 1. *Major and trace element compositions of carbonates and mafic volcanic rocks of the Itremo Group*

	Carbonates and calc-silicates					Mafic rocks			Standard: GSP-1	
	157	213	214	94-53A	94-54	94-19	94-75	94-77	Mean (n=14)	S.D.*
Oxides: weight %										
SiO_2	7.41	60.17	56.88	57.42	62.72	49.49	43.95	51.30	67.48	0.34
TiO_2	0.42	0.54	0.43	0.45	0.47	1.10	1.09	1.46	0.66	0.04
Al_2O_3	7.99	8.89	6.58	7.99	8.60	14.07	16.67	15.74	15.43	0.21
Fe_2O_3 (t)	4.84	4.99	3.97	3.55	3.44	13.19	14.75	12.98	4.32	0.09
MnO	0.44	0.04	0.05	0.09	0.08	0.18	0.09	0.20	0.04	0.01
MgO	11.16	8.21	7.86	11.28	9.58	3.79	2.61	5.56	0.97	0.09
CaO	17.71	12.10	19.37	14.55	10.54	16.11	18.75	8.64	2.01	0.11
Na_2O	0.18	0.82	1.09	0.35	0.32	0.37	0.15	3.01	2.89	0.58
K_2O	2.39	3.56	0.13	3.49	3.14	0.01	0.00	0.17	5.58	0.08
P_2O_5	0.10	0.07	0.08	0.09	0.11	0.14	0.10	0.14	0.30	0.03
H_2O-	0.05	0.04	0.05	0.04	0.06	0.04	0.03	0.10	0.08	0.00
LOI	7.04	0.65	3.22	1.03	1.19	1.39	1.68	0.80	0.10	0.00
Total	99.73	100.08	99.71	100.33	100.25	99.88	99.87	100.10	99.86	1.02
Trace elements: ppm										
Zr	78	210	168	200	173	98	105	118	527	14
Sr	105								235	12
U	<5	<5	<5	7	6	<5	<5	6	3	2
Th	5	<5	<5	14	15	<5	<5	<5	107	10
Cr	83	94	59	76	84	217	223	199	17	4
V	57								56	6
Ba	1065								1318	25
Sc	12	5	6	6	7	31	27	35	7	2
Ni		27	12	17	19	40	32	61		
Nb						6	8	8		
B		<20	<20							

*S.D. = standard deviation.

Stratigraphy

Although the Itremo Group has been strongly deformed, local strain variations have resulted in the preservation in many areas of essentially undeformed rock packages. The stratigraphy of the Itremo Group has been described in the far eastern part of the outcrop belt, where deformation is least penetrative and the metamorphic grade is lowest. In this area, approximately 1000 m of quartzite is overlain by 500 m of pelitic rocks, which is overlain by a minimum of 1000 m of carbonate rocks (Moine 1967, 1974).

In the western part of the area deformation is intense and sedimentary units are dismembered so that stratigraphic relationships are less clear. The lithologies are broadly similar (quartzites, pelites and dolomitic carbonates), but more variable (muddy sandstones, calc-silicates and graded units occur).

In many areas, strain within the lithological units tends to increase towards their contacts, so that boundaries between the different lithologies are commonly tectonic. Therefore the nature of transitions between the lithological units is often unclear, and it is not known whether the stratigraphic succession described by Moine (1974) applies generally throughout the outcrop belt. Given that passive margin sequences commonly consist of cyclic alternations of mudrocks, sandstones and carbonates, it is possible that the stratigraphy is more complicated, and detailed structural analysis is needed to evaluate this.

The base of the sequence

In several areas there is evidence that the Itremo Group quartzites structurally overlie highly deformed paragneisses of the undated Amborompotsy Group. These relationships are preserved only at a few localities because the western margin of the belt is structurally complex, but they support the idea of a significant unconformity at the base of the Itremo Group.

Based on map relationships, Emberger (1955) proposed an unconformable relationship between the Itremo and Amborompotsy Groups. In contrast, Moine (1966, 1967, 1974) hypothesized that the Amborompotsy Group is a lateral facies equivalent of the Itremo Group, representing deeper water sedimentation oceanwards of the shelf.

Our examination of outcrop relationships in the western part of the Itremo Group (Fig. 1) shows that shallowly dipping quartzites overlie biotite gneisses of the Amborompotsy Group and we conclude that they are not coeval. The underlying gneisses show polyphase deformation and evidence for partial melting whereas the quartzites record only one deformation event.

The quartzite–gneiss contact is marked by a thin (approx. 15 cm) bed of quartz-cobble conglomerate which probably represents an unconformity. However, the conglomerate clasts are stretched (aspect ratios exceed 10:1), and so it is possible that there has been movement along the basal plane.

Sedimentology and depositional setting

Quartzites

The quartz arenites of the Itremo Group are moderately to very well sorted, and medium grained on average. Numerous primary sedimentary structures are preserved, including

Table 2. *REE data for Itremo Group pelites*

	Pelite samples																Standards	
	149	151	157	94-1	94-11	94-2	94-14	94-23	94-25	94-28	94-29	94-44	94-47	94-48	94-69	94-71	AGV-1	G-2
La	2.0	9.8	16.1	32.2	41.4	45.4	27.9	37.7	36.7	41.6	50.8	53.0	59.1	46.5	52.2	53.8	38.3 ± 0.6	84.4 ± 1.2
Ce	32.9	12.7	32.4	47.7	61.0	80.9	50.9	61.4	61.8	77.0	87.7	66.5	54.6	63.2	70.8	26.0	62.6 ± 0.2	143.4 ± 0.3
Nd	20.7	10.5	12.1	22.7	31.5	44.7	23.3	29.4	26.3	29.7	36.2	35.2	34.0	32.1	39.4	65.5	33.9 ± 0.3	56.5 ± 0.3
Sm	4.4	2.8	2.7	4.8	5.9	9.5	8.5	6.2	5.0	6.0	7.5	6.4	6.1	6.5	6.9	13.6	6.0 ± 0.1	7.2 ± 0.1
Eu	0.87	0.53	0.58	0.93	1.03	1.91	1.65	1.22	0.82	0.99	1.31	1.12	1.12	1.22	1.25	2.80	1.56 ± 0.01	1.30 ± 0.01
Tb	0.76	0.48	0.35	0.41	0.67	1.10	1.16	0.81	0.63	0.62	0.94	0.70	0.88	0.82	0.66	1.79	0.67 ± 0.01	0.40 ± 0.01
Yb	2.71	2.54	1.24	2.69	2.27	1.67	3.91	2.56	1.94	2.36	3.22	2.18	2.50	2.34	3.00	6.10	1.65 ± 0.03	1.00 ± 0.02
ΣLREE/ΣHREE	23.7	11.9	39.6	34.6	47.5	65.1	21.9	40.0	50.5	51.8	43.8	55.9	45.5	46.9	46.2	20.2		
Eu/Eu*	0.59	0.57	0.70	0.74	0.61	0.69	0.63	0.65	0.55	0.59	0.59	0.62	0.59	0.62	0.67	0.68		
Ce/Ce*	0.69	0.61	1.06	0.80	0.77	0.86	0.93	0.85	0.90	0.99	0.93	0.69	0.53	0.73	0.71	0.22		

Derivation of Eu/Eu* and Ce/Ce* given in text.

Table 3. *Summary of ion probe U–Pb results for detrital zircons from Itremo Group quartzites*

						Isotopic ratios			Apparent ages (Ma)			
Grain.Spot	U (ppm)	Th (ppm)	Th/U	^{204}Pb (ppm)	%f^{206}	^{206}Pb/^{238}U	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb	206/238	207/235	207/206	Concordance (%)
MAD-113: Kiboy Mt, S20°03.8′, E46°59.8′												
1.1	119	53	0.45	4	0.17	0.3217 ± 123	5.093 ± 223	0.1148 ± 19	1798 ± 60	1835 ± 38	1877 ± 31	96
2.1	272	174	0.64	3	0.06	0.3216 ± 111	6.919 ± 247	0.1561 ± 9	1798 ± 54	2101 ± 32	2413 ± 10	75
2.2	286	283	0.99	2	0.03	0.3279 ± 112	6.203 ± 225	0.1372 ± 12	1828 ± 55	2005 ± 32	2192 ± 15	83
3.1	321	42	0.13	5	0.09	0.3024 ± 137	5.213 ± 261	0.1250 ± 20	1703 ± 68	1855 ± 44	2029 ± 29	84
4.1	69	46	0.67	<1	0.03	0.4151 ± 156	9.550 ± 376	0.1669 ± 14	2238 ± 71	2392 ± 37	2527 ± 14	89
5.1	290	226	0.78	11	0.16	0.4030 ± 144	8.985 ± 329	0.1617 ± 7	2183 ± 66	2336 ± 34	2473 ± 8	88
6.1	249	192	0.77	5	0.08	0.4486 ± 154	10.27 ± 37	0.1662 ± 12	2389 ± 69	2460 ± 34	2519 ± 12	95
7.1	324	126	0.39	6	0.15	0.2163 ± 74	3.715 ± 141	0.1246 ± 15	1262 ± 40	1575 ± 31	2023 ± 22	62
8.1	93	63	0.68	8	0.43	0.3661 ± 134	6.264 ± 260	0.1241 ± 19	2011 ± 64	2013 ± 37	2016 ± 27	100
8.2	116	72	0.62	2	0.11	0.3082 ± 112	5.102 ± 202	0.1201 ± 14	1732 ± 56	1836 ± 34	1957 ± 21	89
9.1	141	115	0.82	3	0.09	0.4017 ± 151	7.364 ± 296	0.1330 ± 14	2177 ± 70	2157 ± 37	2137 ± 18	102
10.1	214	189	0.89	1	0.03	0.3894 ± 141	8.493 ± 315	0.1582 ± 8	2120 ± 66	2285 ± 34	2436 ± 8	87
11.1	117	94	0.8	8	0.2	0.5445 ± 219	14.18 ± 59	0.1888 ± 14	2802 ± 92	2762 ± 40	2732 ± 12	103
12.1	116	109	0.94	9	0.26	0.4991 ± 180	12.65 ± 481	0.1838 ± 15	2610 ± 78	2654 ± 36	2688 ± 14	97
13.1	318	122	0.38	8	0.14	0.3242 ± 120	5.070 ± 194	0.1134 ± 7	1810 ± 59	1831 ± 33	1855 ± 11	98
13.2	231	77	0.33	3	0.07	0.3500 ± 122	5.508 ± 201	0.1141 ± 9	1935 ± 58	1902 ± 32	1866 ± 14	104
14.1	109	50	0.46	1	0.03	0.4606 ± 166	10.55 ± 39	0.1661 ± 10	2442 ± 74	2484 ± 35	2518 ± 10	97
15.1	209	15	0.07	8	0.65	0.1083 ± 38	1.024 ± 51	0.0685 ± 22	663 ± 22	716 ± 26	885 ± 67	75
15.5	509	92	0.18	92	5.36	0.0645 ± 31	0.600 ± 83	0.0674 ± 84	403 ± 19	477 ± 54	850 ± 282	47
15.6	445	752	1.69	47	2.13	0.0993 ± 18	0.849 ± 49	0.0621 ± 32	610 ± 11	624 ± 27	677 ± 116	90
15.7	211	50	0.24	47	3.66	0.1183 ± 70	1.067 ± 252	0.0654 ± 145	721 ± 40	737 ± 132	788 ± 549	92
16.1	490	114	0.23	11	0.23	0.1790 ± 61	2.482 ± 91	0.1006 ± 9	1061 ± 34	1267 ± 27	1635 ± 18	65
17.1	539	171	0.32	10	0.22	0.1591 ± 54	2.496 ± 100	0.1138 ± 21	952 ± 30	1271 ± 30	1861 ± 33	51
19.1	158	100	0.63	2	0.05	0.3839 ± 75	6.907 ± 151	0.1305 ± 10	2094 ± 35	2100 ± 20	2105 ± 13	100
20.1	335	79	0.24	2	0.04	0.2793 ± 52	5.547 ± 121	0.1440 ± 13	1588 ± 26	1908 ± 19	2276 ± 16	70
21.1	72	45	0.63	3	0.16	0.4882 ± 107	11.06 ± 27	0.1643 ± 14	2563 ± 46	2528 ± 23	2500 ± 14	103
22.1	607	29	0.05	9	0.18	0.1572 ± 27	1.880 ± 45	0.0868 ± 13	941 ± 15	1074 ± 16	1355 ± 29	70
23.1	209	102	0.49	4	0.09	0.3837 ± 82	7.573 ± 243	0.1432 ± 31	2093 ± 38	2182 ± 29	2266 ± 37	92
25.1	168	47	0.28	7	0.22	0.3194 ± 72	7.300 ± 196	0.1658 ± 20	1787 ± 35	2149 ± 24	2516 ± 20	71
MAD-125: Saronara Mt, S20°30.3′, E46°49.7′												
1.1	268	7	0.03	<1	0	0.3338 ± 76	5.777 ± 142	0.1255 ± 8	1857 ± 37	1943 ± 21	2036 ± 12	91
2.1	449	226	0.5	<1	0	0.2973 ± 70	5.904 ± 146	0.1440 ± 7	1678 ± 35	1962 ± 22	2276 ± 9	74
3.1	278	314	1.13	10	0.16	0.4024 ± 92	7.470 ± 184	0.1347 ± 9	2180 ± 42	2169 ± 22	2159 ± 12	101
4.1	53	54	1	2	0.12	0.5182 ± 153	13.05 ± 53	0.1827 ± 44	2692 ± 65	2684 ± 39	2677 ± 40	101
5.1	287	161	0.56	<1	0	0.3886 ± 90	7.394 ± 181	0.1380 ± 8	2116 ± 42	2160 ± 22	2202 ± 10	96
6.1	148	33	0.22	<1	0	0.4690 ± 111	10.74 ± 27	0.1661 ± 10	2479 ± 49	2501 ± 24	2518 ± 10	98
7.1	316	133	0.42	1	0.01	0.3880 ± 92	8.460 ± 214	0.1581 ± 11	2114 ± 43	2282 ± 23	2436 ± 11	87
8.1	406	184	0.45	<1	0	0.2749 ± 60	4.477 ± 107	0.1181 ± 8	1566 ± 30	1727 ± 20	1928 ± 13	81
8.2	243	74	0.31	2	0.04	0.3544 ± 90	5.990 ± 212	0.1226 ± 27	1956 ± 43	1974 ± 31	1994 ± 39	98
9.1	214	225	1.05	<1	0	0.4409 ± 116	9.925 ± 271	0.1633 ± 8	2354 ± 52	2428 ± 26	2490 ± 9	95
11.1	494	168	0.34	9	0.15	0.2190 ± 49	3.154 ± 80	0.1045 ± 10	1276 ± 26	1446 ± 20	1705 ± 17	75
12.1	147	196	1.33	1	0.01	0.4706 ± 117	10.70 ± 30	0.1649 ± 17	2486 ± 51	2497 ± 26	2507 ± 17	99
13.1	335	48	0.14	<1	0	0.3369 ± 86	5.594 ± 149	0.1204 ± 6	1872 ± 41	1915 ± 23	1962 ± 9	95
14.1	137	107	0.78	<1	0	0.4398 ± 108	10.18 ± 29	0.1678 ± 20	2350 ± 48	2451 ± 27	2536 ± 20	93
15.1	140	90	0.64	10	0.24	0.4887 ± 122	12.30 ± 33	0.1825 ± 15	2565 ± 53	2627 ± 26	2676 ± 13	96
16.1	236	48	0.2	1	0.03	0.4190 ± 96	9.097 ± 229	0.1575 ± 13	2256 ± 44	2348 ± 23	2429 ± 14	93
17.1	174	244	1.41	5	0.1	0.4572 ± 123	10.40 ± 31	0.1650 ± 15	2427 ± 55	2471 ± 28	2508 ± 15	97
18.1	594	238	0.4	15	0.21	0.2143 ± 46	3.538 ± 86	0.1197 ± 11	1252 ± 24	1536 ± 19	1952 ± 17	64
19.1	526	90	0.17	6	0.08	0.2590 ± 59	4.538 ± 113	0.1271 ± 10	1485 ± 30	1738 ± 21	2058 ± 14	72
20.1	169	68	0.4	5	0.11	0.4349 ± 114	9.902 ± 306	0.1651 ± 22	2328 ± 51	2426 ± 29	2509 ± 23	93
21.1	276	156	0.57	<1	0	0.2560 ± 107	4.107 ± 178	0.1164 ± 8	1469 ± 55	1656 ± 36	1901 ± 13	77
22.1	20	14	0.7	4	0.69	0.4345 ± 196	9.589 ± 714	0.1601 ± 86	2326 ± 89	2396 ± 71	2456 ± 94	95
23.1	513	234	0.45	5	0.07	0.2575 ± 56	4.888 ± 142	0.1377 ± 23	1477 ± 29	1800 ± 25	2198 ± 29	67
24.1	180	138	0.76	<1	0	0.4123 ± 96	8.936 ± 220	0.1572 ± 9	2225 ± 44	2331 ± 23	2426 ± 9	92
24.2	214	126	0.59	<1	0	0.3852 ± 88	8.295 ± 199	0.1562 ± 9	2101 ± 41	2264 ± 22	2415 ± 9	87
25.2	286	69	0.24	2	0.02	0.4430 ± 99	10.04 ± 24	0.1644 ± 11	2364 ± 44	2439 ± 22	2501 ± 11	95

%f^{206} = % of total ^{206}Pb which is common ^{206}Pb.
Uncertainties are given at the one sigma level.
Ratios are corrected for common Pb.

abundant flat lamination, wave ripples and dune cross-bedding. Current ripple cross-lamination occurs less commonly. There are rare occurrences of hummocky cross stratification. The quartzites are remarkably homogeneous. Argillaceous interbeds are very rare, and are never more than a few centimetres in thickness. Conglomerates are uncommon, but those that do occur are always clast supported, generally well sorted, and consist of rounded quartzite cobbles in a matrix of quartz sand.

The suite of sedimentary structures indicates deposition under shallow, subaqueous conditions, and the regular grain size, good sorting, abundance of wave-rippled beds and absence of interbedded fine material are consistent with a shallow subtidal setting.

Where exposed, the transition from quartzite to pelite is gradual. Thin (0.5–2.0 cm) argillaceous beds appear in the upper part of the quartzite sequence, and become thicker and more common upwards. Occasional sandstone beds up to 1 m thick occur within the lower parts of the pelite succession, decreasing in abundance upwards.

Pelites

Previous workers have referred to the fine-grained rocks of the Itremo Group as 'micaschiste' (Besairie 1970; Hottin 1976; Moine 1967, 1968, 1974). However, these rocks consist of a number of different lithologies at varying grades of metamorphism, and only in some areas are they schistose, so the more general term 'pelites' is preferred.

The pelitic units are dominated by finely laminated siltstones and mudrocks, and include interbedded fine-grained sandstones which commonly show fine-scale flat and cross-lamination, indicating that currents were periodically active. Occasional starved ripples occur. Thin (2–3 cm) graded layers indicate event deposition in some areas from sediment gravity flows. Toward the west, where the metamorphic grade is higher, the pelitic rocks are often schistose, and fine-scale sedimentological detail is generally not preserved. Lithological variability is greater, and in some places rhythmic graded bedding is represented by quartzite–aluminosilicate layers.

The lithological association is suggestive of deeper water, although the absolute depth is debatable. The graded units make up only a small proportion of the pelitic deposits, and most of the sediments show traction structures. These deposits probably represent a subtidal shelf environment, and would be consistent with a prodelta setting.

Carbonates

The carbonates, which consist of dolomitic marble and sandy marble, are found at the top of the Itremo Group. In most areas the transition from pelite to carbonate appears quite abrupt, but whether this reflects primary stratigraphy or subsequent tectonic modification has not been established.

Two major facies are recognized within the carbonates: a stromatolitic white marble, and a sandy buff marble. In low-strain areas, the white carbonate stratigraphically underlies the sandy carbonate, and the contact between the two is gradational.

The white marble is completely recrystallized, but in low-strain areas weathering surfaces preserve stromatolites. Many sections consist entirely of domal, pseudocolumnar and stratiform (cryptalgal laminate) stromatolites. The carbonate is very pure, with rare scattered quartz and K-feldspar grains. There are no traction structures or other evidence for current activity; and there is no evidence for subaerial exposure.

The stromatolites are mainly domal and pseudo-columnar. They have synoptic relief from 3–30 cm, with vertical inheritance of 20–100 cm. They are circular in cross-section. This combination of features implies deposition in a low-energy shallow water setting (Bauld *et al*. 1992; Walter *et al*. 1992). The purity of the carbonate indicates that terrigenous input was very minor or absent.

In contrast to the pure marbles of the white carbonate facies, the sandy carbonate is generally a recrystallized mixed carbonate–clastic sandstone in which the amount of carbonate varies between about 20% and 80%. The remainder of the rock consists of quartz and phlogopite in varying proportions: both quartz-dominated and mica-dominated examples occur. In low-strain areas the rocks are current structured, and show flat lamination and small-scale cross-bedding. Occasional dessication features in association with small-scale scour and fill structures indicate subaerial exposure in an intertidal setting. Stromatolites do not occur in this facies.

In contrast to the subtidal white carbonates, the sandy carbonates appear to represent a more energetic environment, probably marginal marine, with substantial terrigenous input. The progression from stromatolitic to sandy carbonates may record a shallowing of the basin.

Volcanic rocks

Intercalated with the pelites at a few localities in the central part of the outcrop belt are thin mafic igneous layers, from 1 m to 5 m thick (Fig. 2). They are not voluminous. The rare, isolated layers within the pelites are always found close to the contact with quartzites, and may represent a single fragmented flow unit. They are fine-grained metabasites, occasionally with well-preserved quartz and epidote-filled vesicles and pipe vesicles, and we interpret them as flows within the sedimentary sequence. The presence of pipe vesicles suggests subaerial or shallow subaqueous eruption. They have been hydrothermally altered, but retain a ferro-basaltic compositional signature (Table 1). Their extreme rarity underlines the tectonic quiescence of the Itremo Group depocentre.

Depositional environment and tectonic setting of the Itremo Group

The Itremo Group sediments are interpreted as a passive margin sequence. The lithological association of quartzites with carbonate and pelitic rocks is characteristic of continental shelf associations, and there are several lines of textural and compositional evidence that the sediments were dereived from a continental or cratonic source area and deposited in shallow water. The suite of sedimentary structures, the clean, well-sorted nature of the deposits and the association with stromatolites suggest that the Itremo Group sediments were deposited on a shallow continental shelf or continental platform, close to a landmass.

Detrital zircon geochronology

Forty-seven grains from two quartzite samples (MAD 113 and MAD 125) were analysed. Fifty-five analyses (including multiple analyses of six grains) are reported in Table 3. Sample locations are shown on Fig. 1, and GPS coordinates are given in Table 3. MAD 113 was collected on Kiboy Mt near the eastern margin of the outcrop belt (Fig. 1), where the Itremo Group is in apparent thrust contact with granitic gneisses. MAD 125 was collected at Saronara Mt on the margins of a ductile shear zone.

Significance of zircon morphology

The zircons from both the MAD 113 and MAD 125 samples are rounded and show the effects of extensive mechanical abrasion, with all original facets and faces destroyed. They are highly variable in terms of colour, transparency and size ranging from clear, light-coloured, structureless grains on one end of the spectrum to a distinctive sub-population of grains in sample MAD 113 which are either milky white or dark red/brown and totally opaque. Such opaqueness in zircon normally indicates advanced structural damage through radiation, but in fact these zircons do not have unusually high abundances of Th or U (Table 3). SEM imaging shows that these dark zircons are riddled with Fe-oxide-filled cavities and channels (Fig. 3a) which may account for their colour and lack of transparency. The surfaces of these zircons (as well as some of the clear zircons) are extensively pitted and also have deep cavities and channels. The holes and channels and some of the delicate external projections could not have survived mechanical abrasion during transport, and are interpreted to have formed by post-depositional dissolution.

A number of the zircons from both samples display another unusual feature which is only apparent through SEM imaging. Although the grains are highly rounded and the surfaces are extensively pitted, small platelets of new zircon growth are present (Fig. 3b). In some cases these are isolated patches of new growth, but in a few grains this growth can be seen to have started on a number of places on the original detrital grains, following what appear to be original crystallographic orientations. This new growth shows no sign of any abrasion and in fact covers pre-existing pitted surfaces and thus must have formed *in situ*.

The variable dissolution and re-precipitation of zircon as metamorphic overgrowths has been described elsewhere, and in fact the dissolution features observed in some of the zircons from the Itremo quartzites are remarkably similar to those described from the amphibolite-grade Hope Valley Shear Zone, Massachusetts, USA (Wayne *et al.* 1992) and probably indicate an enrichment of HF (or some other corrosive medium) in the vapour phase during metamorphism. Clearly Zr, Si and probably U, Th, Pb and other trace elements were mobile during metamorphism, and with different or changing conditions (such as a lowering of temperature) new zircon was precipitated onto the detrital grains. If this process had continued the original grains would have been preserved as cores within an enveloping sheath of metamorphic zircon, a feature commonly observed in high-grade metamorphic rocks, but in this case the process was arrested very early on and only limited new zircon growth was preserved. It is possible that the process may have gone to completion at other locations where the metamorphic grade is higher.

Upper age limit of the Itremo Group: source rock ages

Concordant SHRIMP ages identify several age sub-populations with a total range from 2732 ± 12 Ma to 1855 ± 11 Ma (Fig. 4). We interpret these to represent the crystallisation ages of the zircon grains in the sediment source rocks, or in protoliths to the sediment source rocks. The youngest concordant ages form a tight cluster at around 1.85–1.88 Ga (Table 3, Fig. 4). Based on these data, the maximum possible age for the Itremo Group is about 1.85 Ga.

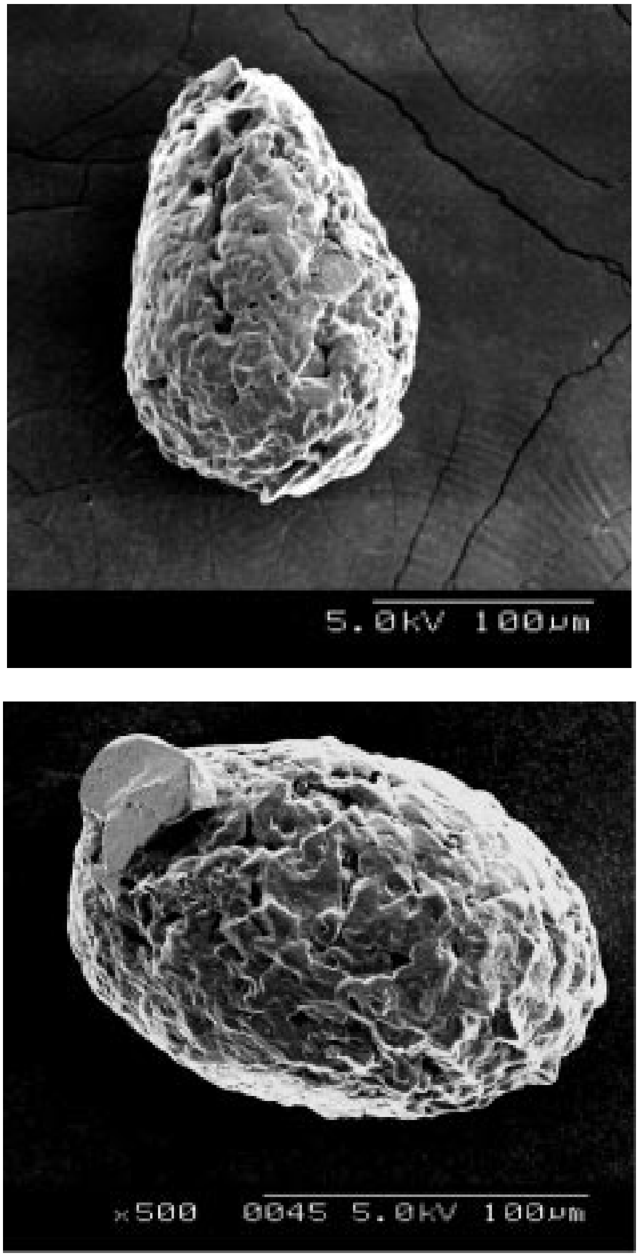

Fig. 3. (**a**) Rounded detrital zircon grain showing pits and channels indicative of post-depositional dissolution. (**b**) SEM image of detrital zircon showing platelet of new zircon growth.

Lower age limit: age of deformation and metamorphism

Numbers of grains from all age sub-populations show radiogenic Pb-loss, a significant part of which appears to be Late Proterozoic, presumably reflecting lead loss and zircon growth during metamorphism and deformation associated with Gondwana assembly. Analysis of the small metamorphic

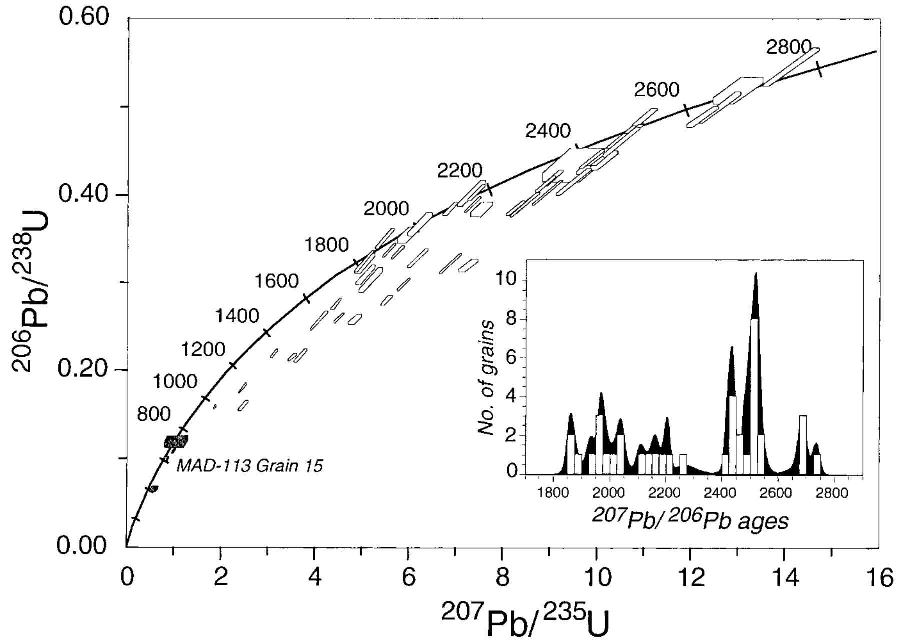

Fig. 4. Concordia plot of detrital zircon analyses from two samples of Itremo Group quartzite. Polygons represent 95% confidence limits on ages for single-grain analyses. Inset histogram shows the frequency distribution of ages. Multiple analyses of MAD 113 Grain 15 are shown in the dark stipple.

overgrowths found on some grains would provide a direct determination of the time of metamorphism but unfortunately these overgrowths have thus far been too small to analyse and special analytical procedures will have to be devised to achieve this.

The Pb-loss is most severe in the opaque corroded and pitted zircons. Of these, the grain which showed the most severe Pb-loss (MAD 113, Grain 15; Fig. 4) was analysed several times in different areas in order to try and establish the time of alteration. In section this opaque zircon is a patchwork of holes and Fe-oxide inclusions and gives a blotchy cathodoluminescence image with no hint of any igneous or original internal structure. The four analyses on this grain all have relatively high common Pb contents and have variable U/Pb ages (Table 3), plotting along the concordia curve between 800 and 400 Ma (Fig. 4). A weighted mean $^{207}Pb/^{206}Pb$ age calculated on these four points gives 833 ± 112 Ma (2σ), this being equivalent to regressing the data and assuming zero-age Pb-loss.

The authors are divided on the interpretation of these data. One of us (L. D. Ashwal) believes that the Pb-loss event is unrelated to the metamorphism of the metasediments. Two of us (R. Cox and R. A. Armstrong) interpret this date to represent the time of metamorphism of the rocks and the time at which the zircon was altered, both structurally and isotopically. This date thus provides an imprecise lower limit on the age of the sedimentary sequence.

Other geochronological data support the latter interpretation. The metasediments have been intruded by several large plutons that are interpreted as late syntectonic intrusions based on field relations. They contain a weak subsolidus foliation, probably imposed during emplacement, which is sub-parallel to the regional foliation in the strongly deformed country rocks. In the aureoles of these bodies, contact metamorphic minerals overgrow the regional metamorphic fabric. Isotope dilution U–Pb analyses of zircons from these cross-cutting granitoids have yielded crystallisation ages of 797 ± 5 Ma, 795 ± 8 Ma and 787 ± 14 Ma (R. D. Tucker, unpublished data).

Two of us (R. Cox and R. A. Armstrong) interpret the granitoid ages to approximate the age of deformation and metamorphism of the Itremo Group because the plutons appear to be syntectonic. These ages are consistent with the mean $^{207}Pb/^{206}Pb$ age calculated from the altered zircons. The other of us (L. D. Ashwal) believes that the U–Pb ages from the granitoids provide a precise lower limit on the depositional age of the sedimentary sequence, but disagrees that those ages or the Pb-loss age from the detrital zircons are related to the regional deformation event.

The data show that deposition of the Itremo Group sediments must have occurred in the interval 1850–800 Ma. We are unable thus far to bracket it more closely, as the Itremo Group lacks datable volcanic rocks.

Sediment provenance

The sedimentology of the Itremo Group is consistent with continental shelf deposition, probably in a passive-margin tectonic setting. Detritus in such environments should have a cratonic or recycled orogen provenance signature.

Quartzite petrology

The Itremo Group quartzites are very pure, and contain >95% quartz on average. However, petrological evidence indicates that some of these quartzites are diagenetic rather than primary quartz arenites. The predominance of quartz reflects, in part, diagenetic loss of other constituents. At some localities, quartzites have anomalously high porosities and are extremely friable, with oversized pore spaces partially occupied by phyllosilicates and oxides. This interstitial material does not represent primary matrix because the arenites are well-sorted and current-structured and it is therefore unlikely that they contained appreciable fine-grained or muddy interstitial material when deposited (Visher 1969).

We interpret the interstitial pseudomatrix as remnants of altered and dissolved detrital material. The effects of diagenesis on immature sandstones are well-documented (e.g. Helmold 1985). The 'missing' detrital material probably consisted of labile detrital sand grains such as feldspars or rock fragments, and it seems likely that the Itremo Group included arkoses and/or lithic arenites at the time of deposition. The clear evidence for net mass transport of material means that provenance interpretations for the Itremo Group may not be based on quartzite compositions.

Mudrock chemistry

The chemical composition of pelitic rocks is known to record their provenance and general tectonic setting (Garver *et al.* 1996; Prame & Pohl 1994; van de Kamp & Leake 1985). Mudrock trace element ratios from the Itremo Group confirm a continental source and demonstrate that the tectonic setting was a passive margin.

XRF bulk rock analyses of Itremo Group pelites (Table 4) are rich in Al_2O_3 and K_2O, and poor in Na_2O, K_2O, MgO and CaO. On the weathering discrimination diagram of Nesbitt & Young (1984), they plot on the Al_2O_3–K_2O join, in the position of granite-derived muds (Fig. 5). This is suggestive of a continental source, although the possibility of diagenetic alteration of the major element composition, particularly potassium metasomatism (Fedo *et al.* 1995; Nesbitt 1992), cannot be excluded.

Rare earth element data also support a continental source. Low-solubility trace elements are far less subject to diagenetic flushing than are the major elements, and the ratios of such elements in pelitic sediments have been shown to relate to their source rocks and tectonic setting (Taylor & McLennan, 1985; Bhatia & Crook, 1986; Condie & Wronkiewicz, 1990*a*, *b*). Relative to chondrites, the samples are enriched in the light rare earths and show marked europium anomalies (Fig. 6). Eu/Eu* values range from 0.59 to 0.70 and average around 0.65 (Table 2), which is the approximate value for the average upper continental crust (Taylor & McLennan, 1985), and also the value for the North American Shale Composite (calculated from data in Gromet *et al.*, 1984).

Trace element data for the Itremo Group pelites (Table 4, Fig. 7) also support a continental origin. Values for Th/Cr, Th/Sc and La/Sc cluster around those of the North American Shale Composite (NASC) (Gromet *et al.* 1984) and calculated average values for the upper continental crust (Taylor & McLennan, 1985; Krauskopf & Bird 1995), indicating a continental source terrane. In general, average trace element ratios are close to the average value for passive margin sediments. Some individual samples have low values for La/Sc, possibly indicating a mafic volcanic source in some areas (Fig. 7). This is consistent with the evidence for some basaltic volcanism mentioned previously. However, this is a very minor component of the sedimentary package. We conclude that the sediments represent a continental platform environment, with very slight igneous activity.

Geochronological evidence for provenance

Clues to the palaeogeographic affinity of the Itremo Group are provided by the detrital zircon $^{207}Pb/^{206}Pb$ dates (Fig. 4, Table 3), which range from Archaean to mid-Proterozoic. To examine these data for age groupings, we used the mixture-modelling techniques of Sambridge & Compston (1994), which were designed to de-convolve datasets combining ages from multiple populations. This exercise included only those analyses which were more than 80% concordant and which had minimal common Pb (i.e. $f\,^{206}Pb(\%)<1\%$, see notes for Table 3). The results suggest seven distinct populations are significant (Table 5, Fig. 4).

Likely source areas for the Itremo Group include the Tanzanian craton in Africa and the Dharwar craton of India, and these possibilities can be tested by examining the match between the detrital zircon ages and the basement ages.

There is a marked difference between the largely Archaean ages of the Dharwar Craton and the predominantly Proterozoic ages of the East African basement (Table 5). In particular the Indian data do not include Early to Mid-Proterozoic basement ages, both of which are very prominent in the Itremo Group detrital zircon population. Most of the published ages for the Tanzanian and Dharwar cratons are Rb–Sr isochron ages, and may not represent crystallization ages in all cases; but they provide information about the thermal and tectonic history of the basement. Although it is clearly important to recognize the limitations of this approach, the differences in age groupings between the two cratons is distinct, and it is reasonable to expect that difference to be reflected in the ages of zircon populations shed into the sedimentary system.

The distribution of age populations in the Itremo Group quartzite (2700–1860 Ma) overlaps significantly with the distribution of ages for the Tanzanian Craton (3100–2050 Ma) but bears little resemblance to recorded ages from the Dharwar craton (3300–2600 Ma) (Table 5). This suggests a source for the Itremo Group in Africa rather than India, although the robustness of this correlation remains to be tested.

Additional support for this hypothesis comes from Nd model ages. Model ages from the Dharwar (Karnataka) craton are all Archean, with no ages less than 2600 Ma. Proterozoic model ages are found only in the far south of India, in the Madurai Block (Harris *et al.* 1994, 1996). In contrast, all model ages for the Tanzanian craton and Mozambique Belt are less than 2800 Ma, and the vast majority are Proterozoic, with clusters at about 1800–1500 and 2500–2300 Ma (Maboko 1995; Maboko & Nakamura 1996). These age clusters are very close to some of the detrital zircon age clusters for the Itremo Group.

The lack of Mid- to late Proterozoic Kibaran ages in the detrital zircon population suggests that deposition of the Itremo Group may predate 1400 Ma. However, more data are needed to address this hypothesis.

Correlation with Gondwana sequences: review of possible stratigraphic equivalents

The U–Pb data suggest an African provenance, implying that lithostratigraphic correlatives may be found in the Mozambique Belt. The similarity of the Itremo Group lithologies and structural style to those of deformed metasedimentary rocks preserved in Kenya, Tanzania and Mozambique (Sacci *et al.* 1984; Mosely 1993; Pinna *et al.* 1993) has previously prompted the suggestion that the central Madagascar rocks are part of the same sedimentary and tectonic zone (Shackleton 1986; Pinna 1993; Pinna *et al.* 1993; Rogers *et al.* 1995). However, although the lithological similarities among late Proterozoic shelfal sequences in the East Gondwana fragments may be compelling, the geochronology is currently inadequate to constrain correlations.

With this in mind, we identify a series of units that are candidates for lateral correlatives of the Itremo Group. We

Table 4. *Major and trace element compositions of pelitic rocks of Itremo Group*

	Pelite samples															
	94-1	94-2	94-11	94-14	94-23	94-25	94–28	94-29	94-44	94-47	94-48	94-69	94-71	149	151	161
Oxides: weight %																
SiO_2	6.63	81.95	72.66	57.19	75.68	67.80	60.19	61.70	65.62	65.56	76.03	61.46	67.23	72.44	72.83	59.47
TiO_2	0.50	0.50	0.57	0.55	0.59	0.63	0.62	0.80	0.64	0.74	0.63	0.67	0.84	0.69	0.67	0.58
Al_2O_3	11.53	10.49	12.04	12.12	11.11	17.08	15.87	17.22	18.25	18.87	18.13	17.61	15.77	13.79	13.54	11.06
Fe_2O_3 (t)	1.98	0.96	4.90	21.67	3.61	4.58	9.19	6.81	5.06	4.91	4.79	6.82	5.82	2.96	3.19	0.76
MnO	0.03	0.01	0.03	0.03	0.01	0.02	0.04	0.03	0.02	0.01	0.02	0.02	0.02	0.00	0.00	0.00
MgO	0.28	0.30	1.61	0.00	0.75	1.22	2.58	2.62	1.25	1.18	0.92	2.45	1.26	0.59	0.84	0.28
CaO	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
Na_2O	0.18	0.11	0.08	0.01	0.23	0.17	0.12	0.10	0.19	0.20	0.23	0.11	0.03	0.13	0.12	0.17
K_2O	3.09	3.03	5.92	0.00	2.82	5.95	9.35	8.57	6.09	6.36	5.58	7.28	1.09	3.95	3.89	4.40
P_2O_5	0.11	0.08	0.04	0.58	0.15	0.05	0.02	0.03	0.05	0.10	0.03	0.06	0.04	0.13	0.09	0.04
H_2O-	0.11	0.10	0.10	0.35	0.22	0.07	0.10	0.05	0.06	0.05	0.05	0.13	0.77	0.08	0.09	0.09
LOI	5.28	2.18	1.76	7.32	4.43	2.10	1.72	1.98	2.26	2.18	2.37	3.16	6.98	5.22	4.58	23.27
Total	99.78	99.71	99.71	99.82	99.60	99.67	99.80	99.91	99.49	100.16	99.78	99.77	99.85	99.98	99.84	100.17
Trace elements: ppm																
Zr	111	107	138	236	164	169	170	185	150	149	188	136	186	132	136	154
Sr	26	104	21	80	23	96	27	20	99	66	60	28	11	48	46	25
U	5	7	<5	20	6	<5	<5	5	<5	<5	5	5	<5	9	5	7
Th	12	14	19	28	16	13	27	29	11	19	21	20	13	11	14	13
Cr	194	128	104	132	148	115	101	148	92	107	103	130	147	153	143	88
V	301	218	62	405	314	109	63	75	146	176	145	91	261	465	444	83
Ba	433	380	480	123	516	657	608	469	978	1098	694	492	371	540	422	391
Sc	13	13	15	63	14	12	9	15	16	13	15	22	30	16	17	9

Analysis of concurrently run standard shown in Table 1.

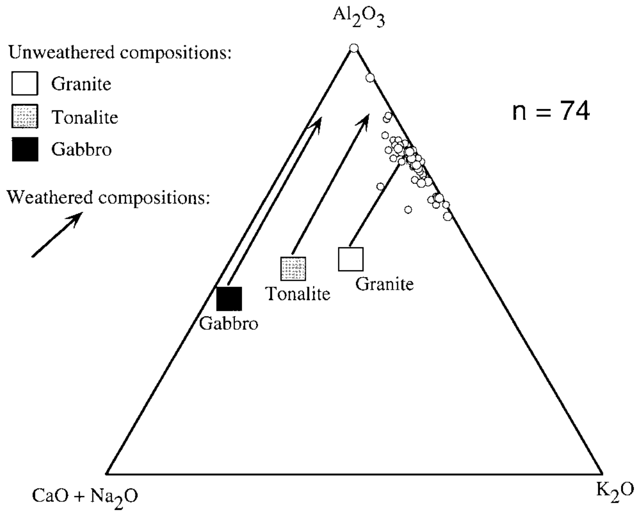

Fig. 5. Itremo Group pelite analyses shown on a major elements molar proportions plot. The diagram is modified after Nesbitt & Young (1984): total CaO is plotted because none of the samples was calcareous. Values for average gabbro, tonalite and granite are from Nesbitt & Young (1984). Petite analyses are from this study (Table 2) and from Moine (1974).

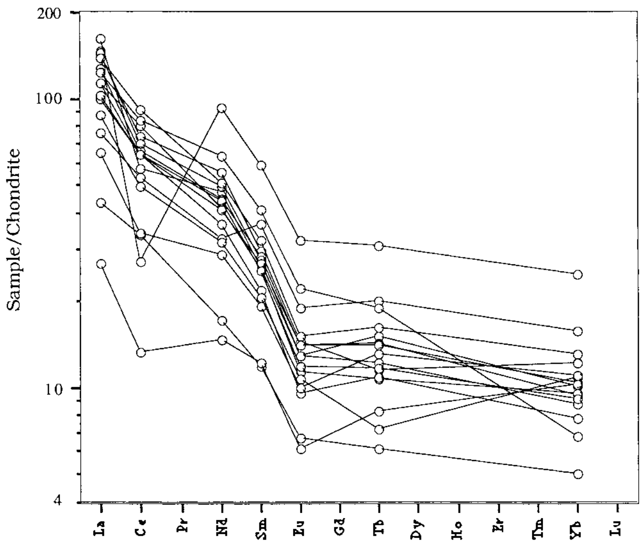

Fig. 6. Chondrite-normalized rare earth element analyses for Itremo Group pelites. Normalizing factors are those of Evensen *et al.* (1978).

wish to stress that the ages of all of these sequences are very poorly known, as has been pointed out in summaries by Cahen (1982) and by Goodwin (1991, 1996). Any or all of them might be unrelated. Their age brackets as currently understood, however, overlap with that of the Itremo Group, and their tectonic settings are broadly similar. They represent conceivable associations within the context of the Proterozoic palaeogeography of the Gondwana fragments. We stress the word 'conceivable': this represents a hypothesis to be tested.

Proterozoic sequences in east Africa

In Africa, possible correlatives include the Katangan Supergroup of Zaire and Zambia; the Usagaran Supergroup of

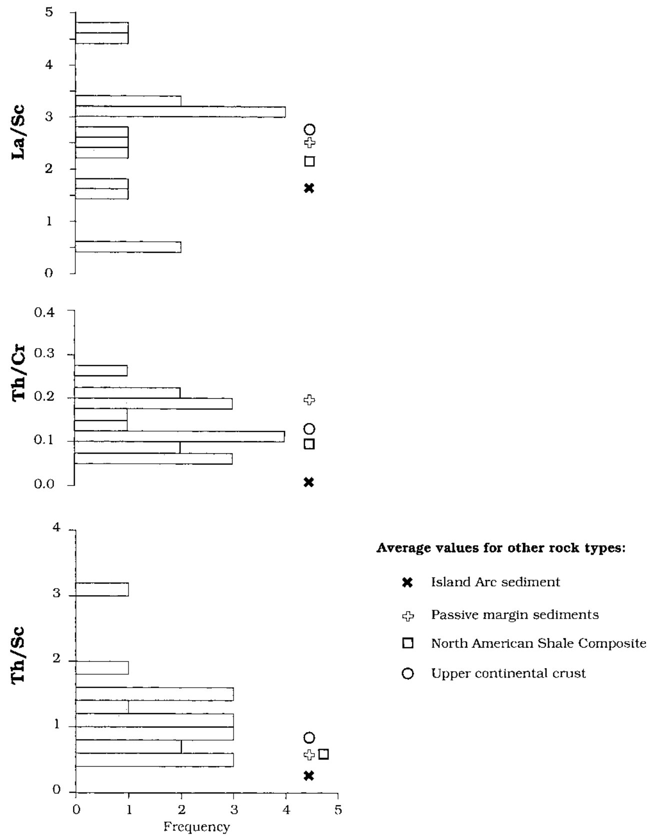

Fig. 7. Histograms of trace element ratios for Itremo Group pelites. Sources for comparative data include Krauskopf & Bird (1995), Taylor & McLennan (1985) and Gromet *et al.* (1984).

Tanzania; the Bukoban Supergroup of Tanzania; the Kisii Group of Kenya and the Ikorongo Group of Tanzania; the Umkondo Group of Mozambique and Zimbabwe; and the Lurio and Chiure Supergroups of Mozambique (Fig. 8).

The Katangan Supergroup of Zaire and Zambia (Fig. 8) is a mixed arenite–carbonate–shale sequence with some glaciogenic sediments and rare volcanic rocks. A younger age limit of 570–560 Ma for the deposition of this sequence is provided by recent U–Pb data from cross-cutting granitoids (Hanson *et al.* 1993). Glacial deposits within the sequence have been related to the late Proterozoic glaciations (Goodwin 1991), suggesting deposition between about 950 and 550 Ma.

The Usagaran Supergroup of Tanzania (Fig. 8) transgresses the Tanzania craton. The rocks are strongly deformed and metamorphosed, and consist of pelitic and psammitic gneisses with subordinate marble. They are overlain by a succession of intermediate and felsic volcanic rocks and by the quartzites and pelites of the Ndembera Group. The age of this succession is unclear. Rb–Sr ages ranging from 1900–1800 Ma on lavas and cross-cutting granitoids have been reported (Gabert & Wendt 1974), but these are difficult to interpret given that amphobolite and granulite grade metamorphism affected these rocks at about 715–650 Ma (Maboko *et al.* 1985; Muhongo & Lenoir 1994).

The Bukoban Supergroup in Tanzania (Fig. 8) consists of quartzites, shales, stromatolitic carbonates and intercalated basaltic flows. It rests unconformably on the Archaean craton (Mosely 1993), and also appears to overlie rocks affected by Kibaran-aged (1310 Ma) deformation. It is overlain by the

Table 5. *Comparison of ages from Itremo Group detrital zircons (this study) with basement ages from the African and Dharwar cratons (from summaries in Goodwin 1991, 1996*

Age (Ma)	Itremo quartzite detrital zircons (U–Pb)	African craton (Rb–Sr)	Dharwar craton (Rb–Sr)
3400			
3200			3300–3100 various gneisses
		3100 Pegmatites	
3000			
2800			3000–2600 Dhawar-Kola belts
	2700 (11%)	2700 Migori granite	
2600		2600 Dodoman orthogneiss	2600 Closepet granite
	2503 (32%)	2500–2450 Granite plutons	
	2428 (15%)		
2400			
2200	2180 (11%)		
	2032 (9%)	2050 Deformation and metamorphism	
2000			
	1957 (14%)	2200–1800 Ubendian basement	
	1860 (8%)	1900–1800 Luapula volcanics	
1800			

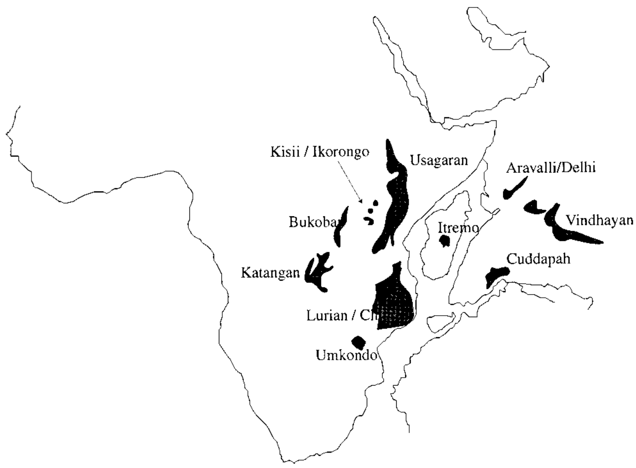

Fig. 8. Gondwana reconstruction after de Wit *et al.* (1988), showing the location of major Proterozoic sedimentary sequences.

Gagwe lavas, which have given a K–Ar age of 815 ± 14 Ma (Cahen & Snelling 1974).

The Kisii Series of Kenya (Fig. 8) unconformably overlies the Archean (Mosley 1993). It contains pelitic rocks, cherts, arenites and conglomerates, and volcanic rocks ranging from basaltic to felsic in composition. The corresponding Ikorongo Group of Tanzania consists of quartzite, siltstone and slate. The Kisii Series has been correlated with the Bukoban Supergroup (e.g. Shackleton 1986). However, since this correlation is based mainly on the presence of basaltic rocks in both units but paleomagnetic data from these basalts are quite different (Meert 1993; Meert *et al.* 1995), it is unlikely that they are correlative (J. G. Meert pers. comm.). Basalts within the Kisii Group have given K–Ar ages ranging from 1221–546 Ma (Briden *et al.* 1971), but more recent attempts to date these rocks using Ar–Ar have demonstrated that the presence of excess argon renders the ages meaningless (Meert 1993). Palaeomagnetic data from the rocks place them on the African APWP at 1000 Ma and 530–525 Ma (Meert 1993, pers. comm.).

The Umkondo Group of Zimbabwe and Mozambique (Fig. 8) consists of pelitic rocks, limestones and sandstones, with intercalated basic lavas. It has been dated at approximately 1100 Ma based on Rb/Sr analyses of mineral separates and whole rock samples of penecontemporaneous dolerite sills (Allsopp *et al.* 1989).

The metasediments of the Chiure Group in the Lurio Belt of Mozambique (Fig. 8) include marbles, quartzite, conglomerate and graphitic pelite associated with a variety of metavolcanic rocks (Pinna *et al.* 1993). Rocks of the Molocue or Rio Molocue Group, which is tentatively correlated with the Chiure Group (Pinna *et al.* 1993), include lithologies of possible ophiolitic affinity (Sacci *et al.* 1984). These metasediments have yielded whole-rock Rb–Sr errorchrons between 950 and 100 Ma (Sacci *et al.* 1984; Pinna *et al.* 1993), interpretation of which is not straightforward.

There is no consensus as to the stratigraphic relationships among these units. It has been suggested that many of them may be broadly coeval (Mosely 1993); however, it has also been proposed that they represent several different tectonosedimentary packages, with ages ranging from >2000 to 550 Ma (Key *et al.* 1989; Pinna *et al.* 1993; Sacci *et al.* 1984; Shackleton 1986). Several scenarios have been presented. Pinna (1993) hypothesized that the Bukoban, Katangan, and Umkondo units are substantially younger (upper Proterozoic) than the older Usagaran, Chiure, and central Madagascar sequences (Pinna *et al.* 1993). Sacchi *et al.* (1984) considered the Katangan Group to be youngest (‘Pan-African cover’), and grouped the Usagaran and Umkondo sequences together with the Wadela Group of Ethiopia as greater than 1100 Ma, and possibly coeval with the metasediments in the Lurio Belt. Shackleton (1986) acknowledged the chronological uncertainties, but proposed that the Bukoban, Ikorongo, and Kisii rocks could be coeval at about 1375–1000 Ma, and younger than the 2000 Ma Usagaran. Key *et al.* (1989) correlated the Kisii and Bukoban sequences and inferred that they were deposited during a period of crustal extension at about 840–766 Ma. This wide range of postulated relationships reflects the chronostratigraphic confusion in the Mozambique Belt and adjacent areas.

Proterozoic continental sequences in India

In India, there are few Proterozoic supracrustal sequences preserved. However, there are a few lithologically similar Proterozoic cover sequences that may be correlatives or tectonostratigraphic equivalents of the Itremo Group. These include strata of the Cuddapah Basin and the Vindhyan Supergroup, in west-central and north-central India respectively.

The fill of the Cuddapah basin consists of a series of sandstone–shale–carbonate sequences, separated by unconformities. Quartzites within the succession have been interpreted to represent a shallow marine shelf and beach environment (Rao *et al*. 1987; Reddy *et al*. 1990). Mafic and intermediate volcanic rocks occur throughout the sequence, and probably represent episodic tectonic disturbance, possibly associated with rifting (Kale & Phansalkar 1991). Age estimates based on Rb–Sr isotopic analyses (Crawford & Compston 1973; Miejerink *et al*. 1984) indicate that the depositional history of the basin lasted from 2000–500 Ma. A well-constrained whole rock-mineral isochron gives a Rb–Sr age of 1817 ± 24 Ma for a mafic sill in the lower part of the succession, indicating that the earliest phases of sedimentation predate 1.8 Ga (Bhaskar Rao *et al*. 1995).

The Vindhyan Supergroup is a shallow-marine succession (Kale & Phansalkar 1991) which consists of limestones, sandstones, conglomerates and shales with some felsic volcanic rocks. It is estimated to range in age from 1550 to 910 Ma, based on biostratigraphic evidence (Raha & Sastry 1982). As is the case in Africa, the stratigraphic relationships are unclear.

The uncertainty about stratigraphy stems from the lack of reliable geochronology. As has been noted by previous workers (e.g. Malisa & Muhongo 1990) the Rb–Sr dates which dominate the existing database are difficult to interpret and are often misleading, in part because of resetting and incomplete homogenization in complexly deformed and metamorphosed systems, but also because they are commonly based on small numbers of data points. Much work is needed to establish reliable age brackets before any meaningful regional and international correlations can be established.

Conclusions

The Itremo Group records sedimentation in a stable continental setting. The Itremo basin was closed and deformed during the late Proterozoic, possibly around 800 Ma, although one of the authors (L. D. Ashwal) disagrees on that point. The location and nature of the basin edges are unknown, and therefore we cannot establish whether it was part of a continental shelf passive-margin succession or a more local restricted basin. It is likely to have been part of a regional sedimentation system associated with the margin of a pre-Pan-African Mozambique ocean, possibly correlative with Proterozoic shelf sequences in Africa.

The current database suggests a link between the Itremo Group and mainland Africa, indicated by the closer match between the Itremo Group detrital zircon ages and the distribution of available dates for tectono-thermal events in East Africa (Table 5). The implications of this interpretation are that the sediments in central Madagascar represent the western passive margin of the pre-Mozambique Belt ocean, which was deformed during the assembly of East Gondwana. If this is the case, then much of the Madagascar basement may have been part of the present-day Tanzanian craton, and the suture with the Dharwar craton should be sought to the east of the Itremo Group outcrop belt.

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