Reports

Archean Rocks in Antarctica: 2.5-Billion-Year Uranium-Lead Ages of Pegmatites in Enderby Land

Abstract. *Uranium-lead isotopic data indicate that the granulite-facies Napier complex of Enderby Land, Antarctica, was cut by charnockitic pegmatites 2.5 billion years ago and by pegmatites lacking hypersthene 0.52 billion years ago. The 4-billion-year lead-lead ages (whole rock) reported for the Napier complex are rejected since these leads developed in three stages. Reconstructions of Gondwanaland suggest that the Napier complex may be a continuation of the Archean granulitic terrain of southern India.*

Soviet geologists have divided the Precambrian rocks of Enderby Land, Antarctica, into the Napier and Rayner complexes (Fig. 1) (*1*, *2*). The Napier complex consists of pyroxene granulite, orthopyroxene-quartz-feldspar gneisses, quartzites, and garnetiferous gneisses. This complex has been metamorphosed under pyroxene granulite-facies conditions with the regional development of sapphirine-quartz, sillimanite-orthopyroxene, and osumilite (*3*, *4*). We report uranium-lead concordia ages of the Napier complex, which could be one of four Archean provinces in East Antarctica (*5*, *6*). Published radiometric data are potassium-argon dates of 0.54 to 0.62 billion years (B.Y.) (*2*), a 2.12-B.Y. ^{206}Pb-^{207}Pb age, and lead-lead isochron ages of about 4 B.Y. (*7*). The 4-B.Y. ages have not been generally accepted because of ambiguities in the interpretation of the lead-lead isochron data.

The Rayner complex consists of similar rocks, but in this complex metamorphism occurred in the hornblende-granulite facies (*4*, *8*). Charnockite at Molodezhnaya Station (Fig. 1) yields a rubidium-strontium isochron age of 1 B.Y. (*8*). Metamorphism and plutonism 0.8 to 1.1 B.Y. ago have been documented in the terrain south and east of Mawson Station (*6*, *9*).

Two generations of pegmatites cut the Napier complex. Discordant charnockitic pegmatites (whose essential constituents are quartz, feldspar, and hypersthene) at Mount Charles (sample 2098A), near Mount Torckler (2125A), and at Rippon Glacier (2006D, L, and M in Fig. 1) form crosscutting planar veins a few centimeters to 1 m wide or irregular masses, some of which are associated with boudinage. These pegmatites do not alter the country rock. At Forefinger Point (2105C and 2109A in Fig. 1), discordant pegmatite veins as thick as 4 m and lacking hypersthene have altered the granulite-facies country rocks.

Perrierite (*10*, *11*) and zircon from the charnockitic pegmatites and sphene and allanite from the pegmatites at Forefinger Point were analyzed for uranium and lead concentrations and lead isotope ratios [Table 1; the analytical methods are given in (*8*)]. To the best of our knowledge, perrierite has not previously been reported in Antarctica nor has it previously been used for radiometric age dating (*11*). Common lead corrections (*12*) were made by assuming an age of 2.5 B.Y. for the charnockitic pegmatites. The sphene and allanite ratios were corrected by using the ratios of lead in a potassium-feldspar sample from the same pegmatite as the sphene (Table 1). The perrierite and zircon data lie on a chord that intersects concordia at 2.5 and 0.6 B.Y. (Fig. 2). One perrierite (2098A) is concordant. Isotopic ratios recalculated from the data of Atrashenok *et al.* (*13*) on "metasomatic" chevkinite (4343 in Fig. 1) from a fissure in charnockite also lie along this chord. The sphene and allanite are nearly concordant at 0.52 B.Y.

The 2.5-B.Y. age appears to be the age

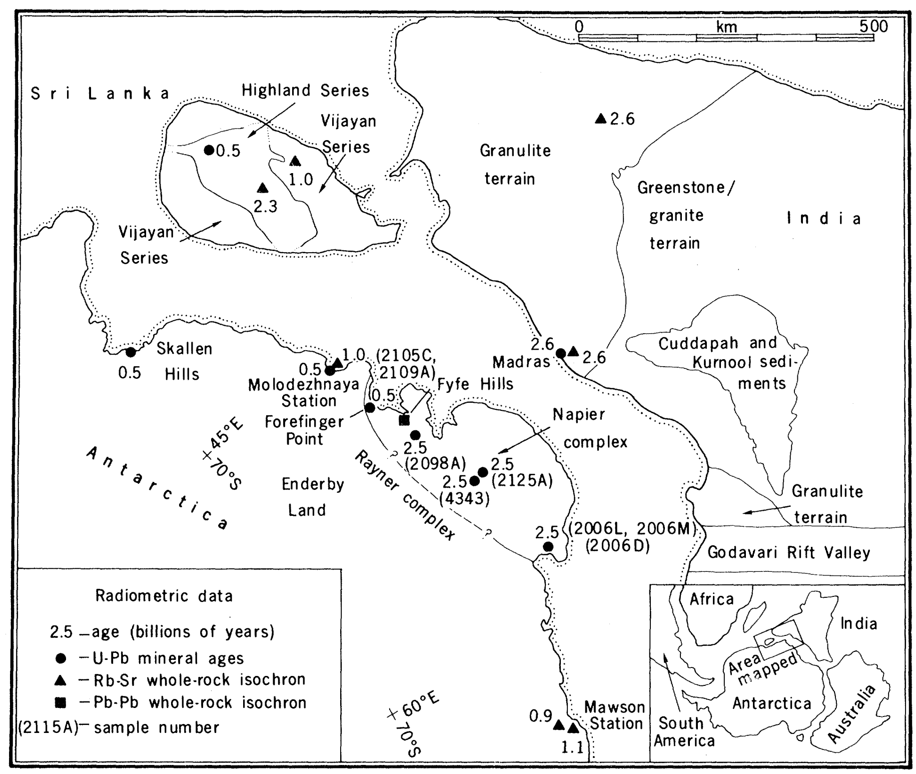

Fig. 1. Geological sketch maps and selected geochronologic data for Enderby Land and adjacent parts of East Antarctica (*1*, *2*, *6–9*, *13*, *14*), Sri Lanka (*19–21*), and southern India (*22*). Relative positions of Antarctica and India–Sri Lanka were determined by visually fitting the 2000-m bathymetric contours (*18*). Radiometric ages are rounded to the nearest 100 million years. Localities in the Napier complex are Forefinger Point (2105C and 2109A), Mount Charles (2098A), unnamed nunatak 2 km south-southwest of Mount Torckler (2125A), unnamed nunatak at confluence of Rippon and Seaton glaciers (2006D, 2006L, and 2006M), and Mount King [4343 in (*13*)]. All place names in Antarctica except Mount King have been accepted by U.S. Board on Geographic Names. Location of sampling site for the rubidium-strontium isochron age determination of 2.3 B.Y. in Highland series of Sri Lanka is not known; consequently, its position on the map is arbitrary. Location of map area relative to Barron *et al.*'s (*18*) reconstruction of Gondwanaland is shown in the inset. This map differs from maps by Ravich and Grikurov (*1*) and Kamenev (*2*) in that we have included Rippon Glacier, Forefinger Point, and the coast of Enderby Land in the Napier complex.

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at which crystallization of the charnockitic pegmatites and the chevkinite occurred; this event appears to have been simultaneous over a large portion of the Napier complex (Fig. 1). The sequence of geologic events observed in the field suggests that the granulite-facies metamorphism of the Napier complex is nearly coeval with these pegmatites and thus that its age is close to 2.5 B.Y. The 0.52-B.Y. age of the sphene and allanite is interpreted to be the age at which crystallization of the pegmatites at Forefinger Point occurred. These pegmatites appear to be contemporaneous with similar crosscutting 0.5-B.Y.-old pegmatites at Molodezhnaya Station (*8*) and Skallen Hills (*14*) (Fig. 1).

Sobotovich *et al.* (*7*) calculated the 4-B.Y. age on the basis of six whole-rock lead values that are linear on a $^{206}Pb/^{204}Pb$-$^{207}Pb/^{204}Pb$ diagram. However, the line connecting these points does not intersect the single-stage growth curve for terrestrial lead and thus cannot be a true secondary isochron. Such an isochron must intersect the growth curve at two points, the isotope ratios of modern lead and of terrestrial lead at the time the secondary system formed. Consequently, 4 B.Y. is not a valid age. Nonetheless, since the reported $^{207}Pb/^{204}Pb$ ratios range from 16.1 to 21.5, the leads were probably derived from parental material formed very early in the earth's history—at a time before much ^{235}U, the relatively short-lived parent of ^{207}Pb, had decayed (*15*).

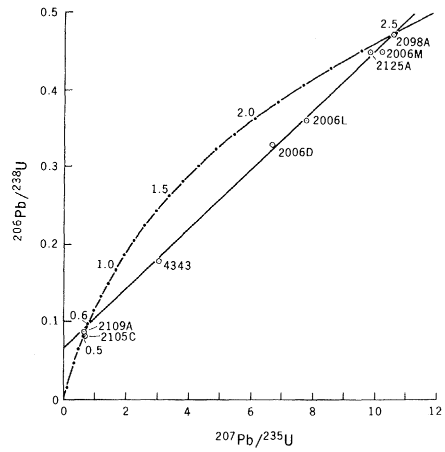

Fig. 2. Concordia diagram for pegmatite minerals from Enderby Land, Antarctica. Ages are in billions of years.

Considering the evidence for formation of the parental rocks of the Napier complex in the early Archean, and their subsequent metamorphism under granulite-facies conditions 2.5 B.Y. ago in the late Archean, development of the whole-rock lead values should be regarded as a three-stage process. It is well established that granulite-facies metamorphism severely disturbs the uranium-lead system (*16, 17*), so the reported alignment of data points (*5*) must be fortuitous. Jacobsen and Wasserburg (*17*) describe a similar case in which the considerable time interval between rock formation and subsequent metamorphism under granulite-facies conditions led to a misinterpretation of the whole-rock lead data.

The $^{207}Pb/^{204}Pb$ ratio of 16.32 in potassium feldspar from Forefinger Point (Table 1) is within the range of $^{207}Pb/^{204}Pb$ ratios reported by Sobotovich *et al.* (*7*) from Fyfe Hills. This high ratio suggests that the country rocks at Forefinger Point had a history similar to that of those at Fyfe Hills and that the Forefinger Point pegmatites are anatectic.

Some reconstructions of Gondwanaland (*18*) place the Napier complex in Enderby Land adjacent to the coastal granulite-facies terrains of southern India (Fig. 1). The Napier complex appears to be an extension of the Indian Archean terrain into Antarctica. Correlation of the Rayner complex with the Vijayan series in Sri Lanka is suggested by their proximity in the reconstruction (Fig. 1) and the 1.0- to 1.15-B.Y. ages reported for the Vijayan series (*19*).

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Table 1. Uranium and lead concentrations (parts per million), lead isotope ratios, and ratios of radiogenic lead to parent uranium isotopes for pegmatite minerals from Enderby Land, Antarctica.

Mineral (sample)	Concentrations		Isotopic ratio				
	U (ppm)	Pb (ppm)	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{207}Pb$	$^{206}Pb/^{208}Pb$	$^{206}Pb^{*}/^{238}U$	$^{207}Pb^{*}/^{235}U$
Perrierite (2006D)	2339	5327	2.61×10^3	6.558	0.1472	0.3291	6.704
Zircon (2006L)	944	391	6.5×10^3	6.268	7.201	0.3605	7.842
Zircon (2006M)	3978	1974	8.5×10^3	6.031	14.80	0.4553	10.31
Perrierite (2098A)	274	3777	134.9	3.899	0.03475	0.4737	10.67
Zircon (2125A)	1031	776	2.87×10^3	6.072	1.306	0.4499	9.943
Sphene (2105C)	260	33.2	263.8	8.565	1.898	0.08342	0.6805
Allanite (2109A)	468	425	75.96	3.913	0.1280	0.0866	0.6507
Chevkinite† (4343)	201	298	1.89×10^3	7.621	0.1820	0.179	3.059
Potassium feldspar (2105)	0.017	77.9	19.06	16.32‡	39.94§	N.D.‖	N.D.

*Radiogenic lead. †Isotopic data uncorrected for common lead (*13*). ‡$^{207}Pb/^{204}Pb$. §$^{208}Pb/^{204}Pb$. ‖Not done.

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15. In principle, it is possible to obtain a minimum value for the primary age of the rocks from the intersection of the growth curve with the line drawn through 2.5-B.Y. lead and the least radiogenic rock lead. If this rock had lost all of its uranium, the true age would be given. When treated in this manner, the data of Sobotovich *et al.* (7) yield a minimum age of 3.5 B.Y. for the parental premetamorphic rocks.
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Magnitude of Shear Stress on the San Andreas Fault: Implications of a Stress Measurement Profile at Shallow Depth

Abstract. *A profile of measurements of shear stress perpendicular to the San Andreas fault near Palmdale, California, shows a marked increase in stress with distance from the fault. The pattern suggests that shear stress on the fault increases slowly with depth and reaches a value on the order of the average stress released during earthquakes. This result has important implications for both long- and short-term prediction of large earthquakes.*

The magnitude of the shear stresses acting on the San Andreas fault is a subject of considerable controversy. The conspicuous absence of a localized heat flow anomaly near the fault implies that the average shear stress is less than several hundred bars (*1*, *2*). Although this is relatively consistent with estimates of stress reductions of 1 to 100 bars during earthquakes, laboratory experiments with accepted earthquake analogs (such as stick-slip frictional sliding) suggest that the shear stress level is several kilobars (*3*). Resolution of this uncertainty is essential for understanding the mechanics of the fault system and the nature of large earthquakes such as the 1857 and 1906 events.

Because direct measurement of stress at midcrustal depths is not economically feasible, we estimated the magnitude of shear stress on the fault at those depths by measuring the variation of shear stress with distance from the fault at comparatively shallow depths. In an attempt to penetrate rocks near the surface, where joints and weathering may have led to stress relief, the stress measurements were made in wells by using the hydraulic fracturing technique (*4*), in which a section of a vertical well is hydraulically isolated and the fluid pressure increased until a tensile fracture is produced. A vertical fracture should form parallel to the direction of maximum horizontal compression. The least and greatest principal horizontal compressive stresses are determined from the manner of fracture initiation and extension (*5*); the direction of maximum compression is determined from the fracture azimuth. It is presumed that one of the principal stresses is vertical and caused only by the weight of overlying material (*6*). An ultrasonic borehole televiewer (*7*) is used to determine fracture azimuth. A televiewer survey prior to hydraulic fracturing enables one to determine the distribution of natural fractures in the well and allows selection of initially unfractured intervals for the hydraulic fracturing tests.

To make the stress measurements, four wells, each about 250 m deep, were drilled in the western Mojave Desert near Palmdale, California (Fig. 1). Three of the wells were north of the San Andreas fault and were drilled into Cretaceous quartz monzonite; the fourth was south of the fault and was drilled into a Tertiary sandstone.

Numerous fractures and joints were encountered in the wells, and stress measurements could be attempted only at about six intervals in each well (a 4-m interval of unfractured rock is required for each measurement). The results of successful measurements are presented in Fig. 2. As a measure of the reliability of these determinations, note that when two measurements are made at similar depths, the same results are obtained. Also, the magnitude of both horizontal compressive stresses exceeds the lithostat (*8*).

The manner in which stress varies

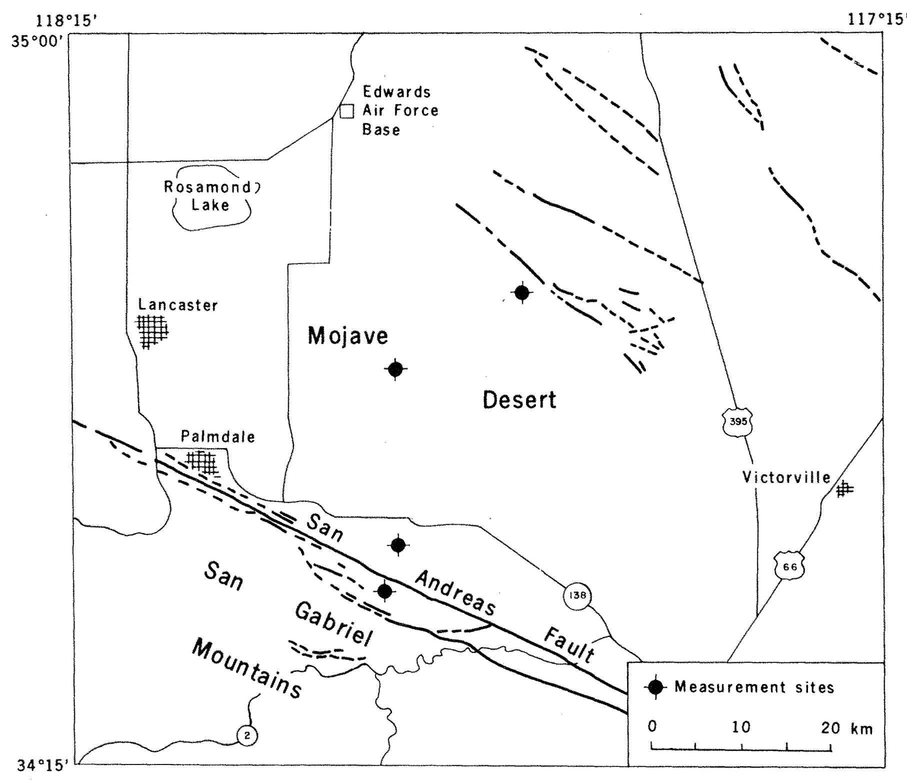

Fig. 1. Location of the four wells in which the stress measurements were made.