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COOLING HISTORY OF SOUTH INDIA AS REVEALED BY FISSION TRACK STUDIES

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ABSTRACT. Fission track ages of a number of South Indian rocks containing zircon, sphene, and apatite have been determined. Two minerals of different annealing characteristics, namely zircon and apatite or sphene and apatite, were selected to determine the cooling history of the region. Corrections to the observed ages, due to partial geological annealing of fossil fission tracks, are applied by comparative study of fossil and induced fission tracks. The fission track ages fall into three age groups, that is, 1300 to 1400 m.y., 700 m.y., and 500 m.y. By means of the different annealing characteristics of these minerals, the ages are related to the thermal episodes associated with regional metamorphism. It is estimated that the temperature in the region could not have remained above 300 ± 30° for an appreciable length of time since the start of recording of fossil tracks in zircon and sphene.

INTRODUCTION

Fission track geochronological measurements have the advantage of unfolding the geothermal history of a region, if these measurements are carried out on more than one mineral. During geological time, fossil fission tracks may be annealed, a property that differs from mineral to mineral. If terrestrial minerals used in fission track age determination are arranged on a scale of increasing annealing temperature, apatite is almost at the bottom, muscovite in the middle, and sphene/zircon at the top (Fleischer and Hart, 1972; McCorkell, 1974). A thermal event accompanying metamorphism, downwarp, or crossfolding can erase fossil fission tracks in apatite, anneal partially in muscovite, and affect them marginally in zircon and sphene. By dating cogenetic or coexisting minerals with different annealing temperatures, it is possible to infer the cooling times and thermal history of rocks. Minerals like muscovite, biotite, and apatite, not differing sharply in annealing behavior, can be used to distinguish thermal events that do not differ widely in time and intensity. Nagpaul, Mehta, and Gupta (1974a) were able to interpret in terms of two thermal episodes separated by $\sim$ 200 m.y. the discordant fission track ages of muscovite, biotite, and apatite in the Nellore Mica Belt of India. Apparently the later episode recorded by the apatite was not too intense to erase the one recorded earlier by muscovite, thus suggesting an average temperature of $\sim$150°C for a period of $\sim$ 200 m.y. Similar analyses by Nagpal and Nagpaul (1974) and Nand Lal and Nagpaul (1974) gave cooling rates of a quarter of a degree centigrade and $\sim$4°C per m.y. for the Rajasthan and Himalayan regions of India, respectively. Work on the third mica belt of India, that is, Bihar, is in progress.

The present work, adopting the same technique, has dated a number of zircon, sphene, and apatite samples from seven districts of Andhra Pradesh and Tamil Nadu of South India.

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EXPERIMENTAL METHOD

The samples under study were collected from the same rock or the same geological formation, hence their coexistence was ensured. Crystals of zircon, sphene, and apatite were obtained either from pegmatite or coarse grained rocks. In most cases the crystals were well formed, capable of being handled individually. Plane surfaces of the crystals were fixed on glass slides with epoxylite resin, and $\backsim 100\mu$ thick sections were prepared. They were lapped with silicon carbide papers of about 180 to 600 grit and then polished successively by 8, 1, and 0.25 micron diamond compounds. In certain cases apatite crystals were small, and in situ determinations were made (see Nagpaul, Gupta, and Mehta, 1973). Apatite was etched for 20 to 30 sec in 5 percent HNO_3 at 25°C (Mehta and Nagpaul, 1970); 40 percent HCl at 90°C revealed sharp tracks in sphene in 30 to 90 min (Nagpaul, Mehta, and Gupta, 1974b).

Zircon is comparatively difficult to deal with, and different etching procedures have been followed by different workers (Fleischer and Price, 1964; Fleischer, Price, and Walker, 1964; Naeser, 1969; Krishnaswami and others, 1974). In the present experiment, zircon crystals of size greater than 250 microns were selected and etched in a solution of sodium hydroxide. This concentration was maintained at a boiling point throughout the etching process by the use of a water cooled jacket (Lal and others, 1968). The temperature of the boiling bath was varied by changing the normality of the sodium hydroxide solution; 50 to 150N gave a constant temperature ranging from 140° to 300°C. The etching conditions in terms of time and temperature varied widely from sample to sample. Whereas purple Precambrian zircon was etched in 15 to 30 min at 140°C, pink and light yellow colored Precambrian zircon was etched in 2 to 4 hrs at 220°C. It was also noted that in general samples with larger fossil track densities required shorter time and lower temperatures for etching as compared with the samples with small track densities. A similar effect has also been observed in plastic detectors (Nagpal, Nagpaul, and Mehta, 1973) and in zircon by Krishnaswami and others (1974). This indicates that intensive radiation damages either surmount the energy barriers with storage of energy or weaken the lattice structure of the solid state track detectors.

In each case, a rough check of fossil track density distribution in the crystals was made. To assess the density distribution in the vertical direction, the crystal was polished to 10 to 15 microns, etched, and track density again measured. The crystals that showed clusters of tracks or sharp track density gradient in the horizontal or the vertical sections were not taken into consideration for age determinations.

The samples, before they were dispatched for thermal neutron irradiation, were heated overnight at 700°C to erase fossil tracks in the three minerals. In order to measure the neutron dose, pieces of standard dosimeter glass were irradiated in the same capsules as the specimens. After the irradiation, the upper surface of the crystal was ground to 15 to 20 microns, and the new surface was polished and etched. The induced tracks were measured in the same crystal as the fossil fission tracks.

The fission track ages were computed by means of the following relation (Mehta and Nagpaul, 1970, 1971):

$$T = 6.57 \times 10^9 \log\left(1 + 9.25 \times 10^{-18} \frac{\rho_s}{\rho_i} \phi \right) \text{yrs} \qquad (1)$$

where T is the observed fission track age of the mineral, ρ_s, ρ_i are fossil and induced track densities, and ϕ is the thermal neutron dose.

The measured fission track ages were corrected, by comparative study of fossil and induced track lengths described elsewhere (see, for example, Storzer and Wagner, 1969; Gupta, Nagpaul, and Mehta, 1971). The main problem in determination of the correction factor is the accurate measurement of track length. The optical contrast, which is normally poor, can be considerably improved by decorating the tracks with silver (Macdougall and others, 1971). The full length of the tracks due to fission fragment was measured by using 'TINT' (track in track) and 'TINCLE' (tracks in cleavage) techniques (Lal, Ranjan, and Tamane, 1969; Bhandari and others, 1971).

The following criteria were kept in mind while making length measurement.

1. The track should start below the upper surface of the sample.
2. It should be rounded at two ends.
3. Its diameter should be greater than 1 micron.

To ensure etching the full length of the tracks, measurements were repeated after an additional etch. No discrepancy was observed except in cases where the diameter at the center was less than 0.5 micron, or track tip was not central. In case of TINTS, all tracks, long or short, were included for measurements. But in case of TINCLES, tracks shorter than 5 microns were not included, because width cleavage or fracture could contribute a significant error to their measurements. In spite of varying conditions of etching of different samples, range distribution of fission fragments was found to be normal in each case. Their lengths in each zircon sample were concordant and sharply peaked as compared to the other two minerals.

Uranium concentration C_u was calculated with the help of ρ_i, ϕ, and range R_0 of combined fission fragment in the minerals. It is given by the relation

$$C_u = K \times 10^3 \frac{\rho_i}{\phi} \text{ atom/atom} \qquad (2)$$

where constant K has been calculated to have a value of 3.9, 4.1, and 4.2 for apatite, sphene, and zircon respectively.

RESULTS

For each mineral, age determinations were made on three crystals, and the average age computed. The ages for seven different places of the region are shown in column 3 of table 1. Errors indicated are only statistical counting errors. In order to assess the annealing correction, a comparative study of the range of fossil and induced fission fragments in the crystal is made in each case. From the knowledge of annealing characteristics of minerals (see Nagpaul, Mehta, and Gupta, 1974b) the reduction in track length is transformed into the reduction of track density, which gives the percentage of correction factor, indicated with the measured value of fission track age in column 3 of table 1. The corrected fission track ages are given in the next line, just below the measured age. In case of Khamam zircon samples (no. 2) observations were made on two separate crystals. Mean values of these observations are also given in table 1.

Mean value of uranium concentration computed with the help of relation (2) is shown in column 4 of table 1.

Part of the age data has already been reported (Nagpaul and Mehta, 1974).

DISCUSSION

The sample collection region is in the Charnockite-Khondalite group of the South Indian Peninsula and extends along the Eastern Ghats to the southern extension of Tamil Nadu. (Narayanswami, 1970). Its geological formation, adopted from the Geological Survey of India Map edited by Roy and others (1962), is shown in figure 1; the locations of the collected samples are shown in the same figure. The region has a long and complex metamorphic history, which has generated a lot of controversy. Recent radiometric age determinations and analyses have shed light on this (see Holmes, 1955; Vinogradov and others, 1964; Aswathanarayana, 1964; Crawford and Compston, 1967; Crawford, 1969; Balasundaram and Balasubrahmanyan, 1973) suggesting the following sequence of events in the region.

1. The oldest gneisses, schists, and some charnockites have been dated by whole rock Rb-Sr and K-Ar methods, which give the basement rock a minimum age of $\backsim$ 3000 m.y.

2. A number of rock and mineral samples have yielded ages between 2600 and 2100 m.y. by isotopic methods. These ages correspond to multiple tectonic, metamorphic, and migmatic activities in the region.

3. Lead isotopic and Rb-Sr ages of 1600, 1300, and 500 m.y. determined from whole rock or separated minerals are considered to be associated with major Eastern Ghats metamorphism, emplacement of granites, and Indian ocean orogeny respectively.

4. Measurements of ages around 1100 and 700 m.y. have also been reported by Venkatasubramanian and Krishnan (1969) and Dean and Powell (1968) respectively.

In the present work there is no evidence of ages older than about 1400 m.y., indicating that up to that time the region had been thermally unstable to such an extent that even tracks in zircon were completely annealed. Maximum ages ranging between 1300 to 1400 m.y. have been

TABLE 1
Fission track ages of coexisting minerals of South India

1 Sample no.	2 Sample location with description of specimen	3 Mean fission track ages m.y. Measured (% of annealing correction) Zircon	 Sphene	 Apatite	4 Mean uranium concentration atom/atom × 10^{-6} Zircon	 Sphene	 Apatite
1.	Vishakapatnam Andhra Pradesh Pegmatite	1320 ± 10 (0) 1320 ± 10*	—	530 ± 20 (5) 560 ± 20*	3.2	—	1.8
2.	Khamam Andhra Pradesh	(i) 570 ± 20 (0) 570 ± 20*	—	520 ± 40 (10) 570 ± 40*	24		
	Pegmatite	(ii) 580 ± 20 (0) 580 ± 20*	—		30	—	0.21
3.	Arcot Tamil Nadu Carbonatite/albite	1330 ± 40 (0) 1330 ± 40*	1210 ± 30 (10) 1330 ± 40*	620 ± 40 (11) 690 ± 50*	1.0	1.3	0.13
4.	Salem Tamil Nadu Pegmatite	—	1280 ± 30 (10) 1410 ± 30*	510 ± 20 (7) 550 ± 20*	—	2.6	1.5
5.	Coimbatore Tamil Nadu Syenite	720 ± 20 (0) 720 ± 20*	710 ± 20 (0) 710 ± 20*	—	2.7	1.0	—
6.	Madurai Tamil Nadu Pegmatite	510 ± 10 (0) 510 ± 10*	—	450 ± 10 (13) 510 ± 10*	25	—	0.6
7.	Kanya Kumari Tamil Nadu Pegmatite	480 ± 10 (0) 480 ± 10*	—	430 ± 20 (10) 470 ± 20*	10	—	1.0

* Corrected.

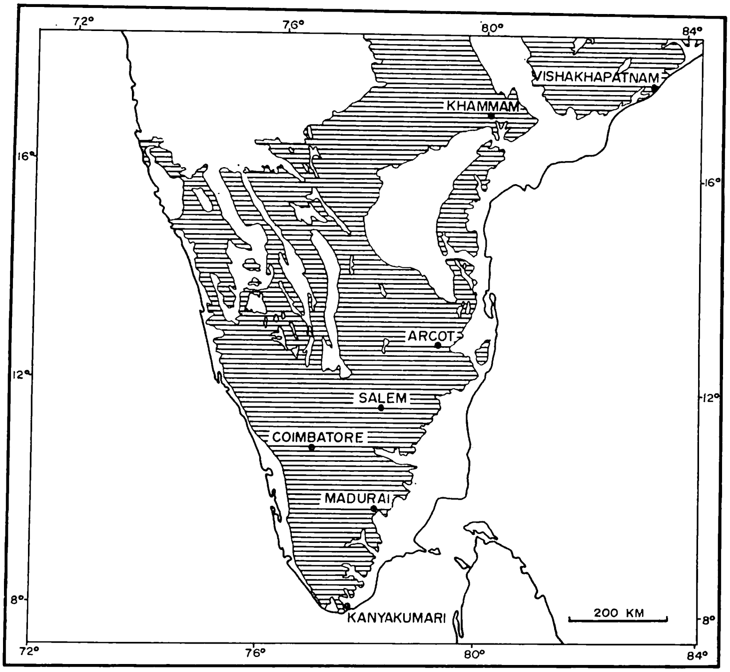

Fig. 1. Archean Formation (Charnockite-Khondalite Group) of South India.

given by zircon and sphene samples from Vishakapatnam, Salem, and Arcot districts. These ages denote the closing phase of a major metamorphic event of 1300 m.y. associated with the emplacement of charnockites and granites in the Eastern Ghat rocks (Aswathanarayana, 1968). The next event, of 700 m.y. age, is given by apatite of the Arcot district and zircon and sphene of the Coimbatore district. This age corresponds to local pegmatitic activity and regional lineament observed in the Peninsular Shield. The last age group, around 500 m.y., given by the rest of the samples, corresponds to the Indian Ocean Orogenic Cycle occurring in Eastern Ghat, South India, and Ceylon.

Measured ages in some of the coexisting minerals are concordant, whereas in others there is a large variation. Concordance or discordance of the ages depends on the rate of annealing of fossil tracks in the minerals. Each mineral is annealed in its own temperature range. The annealing time and temperature for fission tracks in apatite, sphene, and zircon (shown in table 2) are based on laboratory experiments of Nagpaul, Mehta, and Gupta (1974b), Fleischer, Price, and Walker (1965), and Fleischer and Hart (1972).

In table 2, zircon data is based on the results of Fleischer, Price, and Walker (1965), who used phosphoric acid as the etchant. A comparative study of the annealing property of zircon using different etchants could not be made. The mean measured range (11.0 ± 0.8 microns) of fission fragments in different crystals of zircon etched in varying conditions in the present work is the same as that obtained by Krishnaswami and others (1974), whose observations on annealing characteristics differ in the time-temperature range from those of Fleischer, Price, and Walker (1965). An upper limit of uncertainty of temperatures, because of varying etching conditions of zircon, is $\sim$10 percent, which is less than over all uncertainty in fission track dating technique.

Apatites coexisting with zircon of Vishakapatnam and also from pegmatite of Salem have given ages of $\sim$550 m.y., which are within the period of cross folding and regional metamorphism of the Eastern Ghats (Aswathanarayana, 1968). The measured ages of zircon and sphene are higher, 1300 to 1400 m.y. The last thermal event of $\sim$550 m.y. did not effect the tracks stored in zircon, as the fossil tracks in it show no significant shrinkage. However, the event had some effect on sphene, where measured ages were corrected by 10 percent. Thus, it can be inferred from the annealing behavior of zircon that it remained below the annealing temperature during its entire history of record of fossil tracks and the upper limit for the temperature in the region is estimated at 300 ± 30°C.

Zircon and apatite samples from Kanya Kumari, Madurai, and Khamam have almost concordant ages of $\sim$500 m.y. The last thermal episode at these places was severe enough to anneal completely earlier spontaneous fission tracks in all the minerals, which suggests that for a long period regions witnessed temperatures above 300 ± 30°C.

The thermal severity of the 500 m.y. episode shows steep fall in the Arcot region of Tamil Nadu. Cogenetic zircon and apatite samples from a carbonatite rock have given ages of 1330 and 700 m.y. respectively. The zircon age is supported by the ages of sphene derived from albite rock in the same region. A correction of 11 percent for track shrinkage applied to apatite age indicates that the 500 m.y. episode had little effect in this region, and the temperature remained below 60°C during the last $\sim$700 m.y. — the age of apatite.

A temperature limit can also be put on the 700 m.y. event recorded by apatite. It had only a marginal effect on sphene, for which a correc-

TABLE 2

Annealing time and temperatures for fission tracks in apatite, sphene, and zircon

	Annealing temperature °C		
Annealing time	Apatite	Sphene	Zircon (calculated)*
1 hour	350	600	720
1 day	290	560	660
1 yr	210	500	550
100 yrs	165	460	490
1 m.y.	130	390	380
100 m.y.	100	350	340

* From data of Fleischer, Price, and Walker (1965); Fleischer and Hart (1972)

tion of 10 percent was applied for length reduction, and had no effect on zircon. An average temperature of 300°C for a million years could have produced this effect. But the temperature should have remained above (300 ± 30)°C for an appreciable length of time, as it would have annealed all damages in sphene and zircon.

Cogenetic zircon and sphene from a pegmatite of a Coimbatore district have given an almost concordant age of 700 m.y. This age indicates a severe thermal event around this period in the region. The temperature during the event must have remained above 300 ± 30°C for long periods to erase the effect of all earlier events. No apatite was dated from this region, but the temperature during the subsequent thermal events could not have been high, as there was negligible shrinkage of tracks in sphene.

CONCLUSIONS

1. The uranium concentration is found to vary from mineral to mineral; zircon shows the highest concentration, which in turn shows wide variation among samples of different localities and origins. Among the samples studied, zircon from the Khamam, Madurai, and Kanya Kumari areas of South India have higher concentrations of uranium than the samples separated from carbonatite and pegmatite rocks of other areas.

2. The fission track age determinations point out the occurrence of 450 to 550 m.y., ∽700 m.y., and 1300 to 1400 m.y. events in the Charnockite-Khondalite region of South India.

3. The region is characterized by complex and large local variation in thermal intensity during geological time.

4. A more detailed study of systematically collected cogenetic zircon/sphene and apatite samples, especially from the other two well marked geological regions, that is, Dharwar and Peninsular Gneiss of Cuddapah, Kaladgi, Bhima, and Phakhal Basins, coupled with the information obtained in the present work, may help in locating centers of thermal activity in the region.

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