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Recognition of the time and level of emplacement of the Sillai Patti carbonatite complex, Malakand Division, Northwest Pakistan: Constraints from fission-track dating

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Abstract

The Sillai Patti carbonatite complex represents the second largest carbonatite body of the Peshawar Plain Alkaline Igneous Province of northern Pakistan. It is situated about 20 km west of Malakand, near Sillai Patti village. Here, the carbonatite occurs along a fault in the form of a sheet striking in the NNE–SSW direction and dipping towards south. The carbonatite body is about 12 km long and 2–20 m thick, predominantly intruded along the faulted contact of metasediments and granite gneiss but locally, within the metasediments.

A fission-track age of 29.40 ± 1.47 Ma was obtained for the Sillai Patti carbonatite complex. Close resemblance of fission-track apatite age of this study with the fission-track as well as other high temperature radiometric ages from the same and the neighboring carbonatite complexes of the alkaline belt of northern Pakistan suggests emplacement of the Sillai Patti carbonatite complex at higher crustal level and subsequent extremely fast cooling to near ambient temperatures (<60 °C) required for the complete retention of fission tracks in apatite. The age data also point out that the fission-track age of 29.40 ± 1.47 Ma of this study is the age of intrusion of the carbonatitic magma of Sillai Patti carbonatite complex to shallow, near-surface level.

Comparison of the uplift induced denudation rates of the region with the world data clearly reflects the presence of a post collisonal extensional environment in the region south of Main Mantle Thrust during Oligocene time. This strongly negates the idea of the earlier workers of emplacement of the carbonatite complexes of the Loe-Shilman and Sillai Patti areas along thrust faults during Oligocene.

Keywords: fission-track dating; age standard approach; Sillai Patti carbonatite; Durango apatite; formation age

Introduction

Fission-track dating of geological materials is possible because most geological materials including minerals and glasses contain some uranium in trace amounts and because the most abundant isotope of uranium, ^{238}U, fissions spontaneously (Durrani and Bull, 1987; Fleischer et al., 1975). Over the life span of a rock considerable numbers of fissions occur; their tracks are preserved and thus leave a record of the time elapsed since track preservation started. The number of fission tracks produced in a given volume of a geological sample depends upon the total uranium content as well as the age of the sample. It is, therefore, necessary to measure the uranium content of a sample to be dated.

Fission-track dating is superior to other radiometric dating systems in three ways. Firstly, the time span to which fission-track dating is applicable, ranges from less than about 100 years to approximately 4.5 billion years. A second useful feature is that measurements can sometimes be made on extraordinarily small specimens, such as chips of minerals or fragments of natural glass. A third useful quality is that each mineral dates the last cooling through a particular temperature (called closure or track retention temperature) below which tracks are retained permanently. Since this temperature is different for each mineral, it is possible to measure the cooling rate of a rock by dating several minerals—each with a different track-retention or closure temperature. If a rock cools immediately as in the case of a volcanic rock or a shallow igneous intrusion, the fission-track ages will date this initial cooling (Wagner, 1981; Wagner and Van den haute, 1992). If the mineral formed at depth or was deeply buried after formation,

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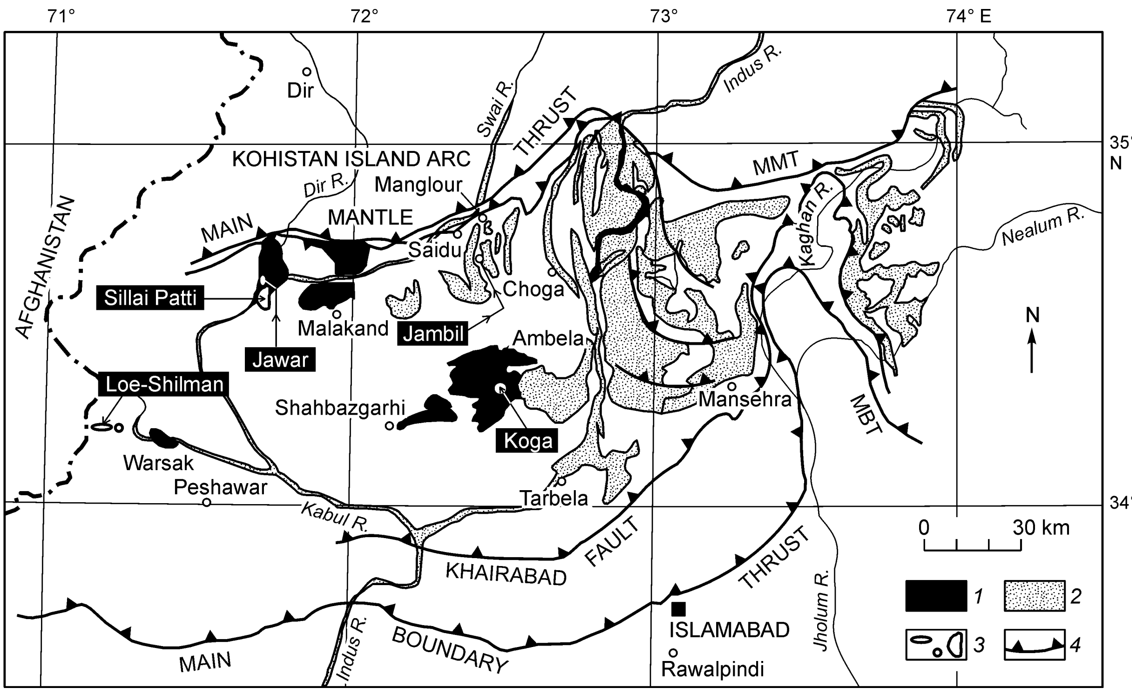

Fig. 1. Geological sketch map of northern Pakistan showing location of the Sillai Patti and other carbonatite complexes and associated alkaline rocks of the alkaline belt of northern Pakistan (after Butt, 1983; Khattak et al., 2001). *1*, Alkaline and peralkaline rocks; *2*, calc alkaline rocks; *3*, carbonatites; *4*, thrust faults.

the fission-track age will reflect this latest heating and cooling event.

The Sillai Patti carbonatite complex is situated about 60 km northeast of Loe-Shilman, about 70 km north of Peshawar, about 35 km west of Dargai and about 20 km west of Malakand, near Sillai Patti village, in Malakand Division of the Khyber Pakhtunkhwa Province (Fig. 1). This sheet-like body was first reported by Ashraf and Chaudhry (1977). It occupies a southerly dipping thrust plane (the Main Mantle Thrust) between amphibolites to the north and granite gneisses and schists to the south (Le Bas, 2008). Le Bas et al. (1987) suggested that the carbonatite body of Sillai Patti was emplaced along the fault plane of the thrust in the form of a 12 km long and 2–20 m thick sheet. Butt et al. (1989) stated that the so called carbonatite sheet at Sillai Patti has been emplaced either within the metasediments or at the contact of metasediments and granite gneiss, which appears to be a thrust fault.

The Sillai Patti carbonatite complex is the second largest carbonatite body of the alkaline belt of northern Pakistan. Emplacement time as well as the tectonic setting (compressional or extensional?) of the Sillai Patti carbonatite is controversial since long ago. This study attempts to resolve these issues using fission-track dating on apatite separated from the three carbonatite samples from the complex. The results are compared with previously published age data including K–Ar dates on biotite (Le Bas et al., 1987) and fission track age on zircon (Qureshi et al., 1991) from this carbonatite sheet and fission track as well as other high temperature radiometric ages from the neighboring carbonatite and alkaline complexes occurring within the alkaline belt of the northern Pakistan. Tectonic setting has been interpreted in the light of the uplift induced denudation rates of rock complexes within the region.

Regional geological setting

Geology of northern Pakistan is governed by collisional tectonics involving three tectonic blocks, which from south to north include; Indian plate, Kohistan island arc terrane and the Eurasian plate (Tahirkheli, 1979). The Indus Suture (termed Main Mantle Thrust—MMT in Pakistan Himalayas) separates the Indian plate from the Kohistan terrane, while, the contact between the Kohistan terrane and the Eurasian plate is marked by the Shyok Suture Zone or the Main Karakoram Thrust (MKT). The northern edge of the Indian plate, south of the MMT is included in the Himalayan internal zone (Coward et al., 1988) comprising predominantly of the Indian-plate basement rocks of Precambrian age with local preservation of Lower Paleozoic to Eocene sedimentary rocks in thrust slices. Besides predominance of metamorphic rocks, the internal zone of the Indian plate is characterized by a common occurrence of igneous rocks, which are divisible into two broad groups; Cambrian and older and Permo-Carboniferous and younger. This second group of igneous rocks includes rift-related basic rocks (e.g., Panjal volcanics and associated intrusions and dikes) as well as intrusive rocks of alkaline affinity (e.g., nepheline syenites, peralkaline granites and carbonatites), of which the later are especially concentrated in the western parts of the Indian plate to the north of Peshawar in the footwall of the MMT. Kempe and Jan (1980) included the alkaline rocks in their Tertiary Peshawar-Plain Alkaline Igneous Province (PAIP). Based on radiometric dating, Le Bas et al. (1987) divided the Peshawar-Plain Alkaline Igneous Province into two groups; Permo-Carboniferous (e.g., Koga nepheline syenites and carbonatites) and Mid Tertiary (Loe-Shilman and Sillai Patti carbonatites). This two-fold division was later supported by detailed geological evidence as well as by further radiometric age dating by several workers (e.g., Khattak et al., 2004, 2008; Qureshi et al., 1991; Tilton et al., 1998). The Sillai Patti carbonatite complex, subject of this study, is part of the younger alkaline activity in the PAIP.

Local geology

Carbonatite of Sillai Patti occurs as sheet-like intrusion along a fault plane, which is striking in the NNE–SSW direction and is dipping roughly to the south (Fig. 2). At the top of the sheet, the carbonatites are in contact mostly with Malakand granite gneiss (Butt et al., 1989; Le Bas et al., 1987). The Sillai Patti carbonatite consists of a white sheet of biotite–apatite carbotatite and a later brown and more extensive sheet of amphibole–apatite carbotatite. Fenites are found at the immediate contact of the overlying granite gneisses and as xenoliths of metasomatized granite within the carbonatites (Butt et al., 1989; Le Bas et al., 1987).

According to Le Bas (2008) the biotite carbonatite, rarely more than 20 m thick, is best developed in the east, where it has caused K-metasomatism in the overlying granitic gneiss. The gneiss adjacent to the carbotatite contact is usually medium to coarse grained, well foliated, but friable and weathered. The commencement of K-fenitization is discernible by the disappearance of the quartz and muscovite, the foliation being marked by alignment of K-feldspar, biotite and Fe oxides. The grain size increases toward the contact, with K-feldspar crystals ($Or_{88–96}$) reaching up to 2×3 cm, usually enclosed in clusters of small granules of albite (Ab_{99}).

Le Bas (2008) mentions that near the contact between granitic gneiss and the brown amphibole carbonatite sheet at Sillai Patti, veins of carbotatite cutting the K-fenitized gneiss are enclosed in aegirine prisms, indicating the passage of afterward sodic fluids. The gneiss near the carbotatite sheet is also recrystallized to fenite of syenitic composition. Nearer to the carbotatite contact, the fenites are feldspar rich, with aligned prisms and aggregates of dark green aegirine-augite. The albite and K-feldspar occur in the proportions of 2:1 in the coarser-grained fenites, with albite increasing in the finer-grained fenites to 3:1. These uneven proportions show no relationship to distance from the contact, but the field outcrops do suggest a relationship of distance to earlier joints in the gneiss, along which fenitizing fluids may be presumed to have traveled (Le Bas, 2008).

Texturally the Sillai Patti carbonatite is porphyritic to subporphyritic and consists of calcite (generally 50 to 90%), arfvedsonite, siderite, ilmenite/magnetite, vermiculite, apatite, chlorite, and K-feldspar, the minerals being unevenly distributed (Kempe and Jan, 1980). The carbonatite usually consists of fine to medium grained crystalline rocks. Calcite occurs as anhedral crystals whereas biotite and amphibole crystals are generally anhedral to subhedral (Butt et al., 1989). The carbonatite contains triple-junctioned plates of calcite, and includes rounded prismatic crystals of apatite and biotite flakes (Le Bas, 2008). Apatite tends to be euhedral and is occasionally completely enclosed in calcite (Butt et al., 1989).

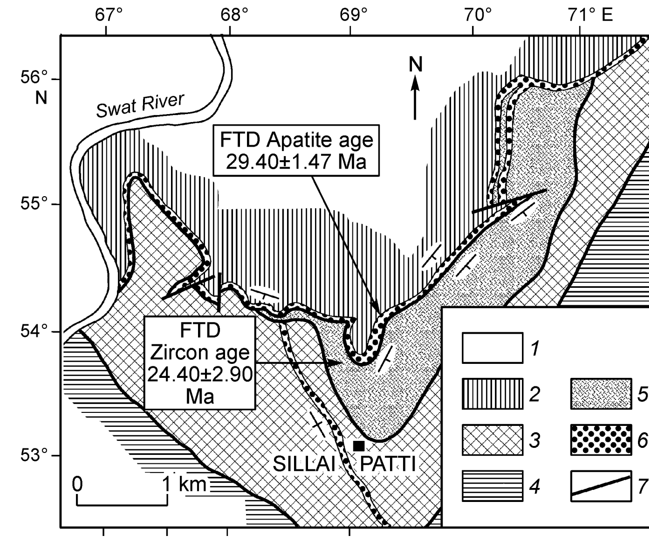

Fig. 2. Geological map of the Sillai Patti carbonatite complex, Malakand Division (modified after Le Bas et al., 1987). *1*, unmapped area; *2*, pelitic schist; *3*, psammitic schist; *4*, garnet-mica schist; *5*, granite gneiss; *6*, carbonatite; *7*, fault.

The country rocks at Sillai Patti have been subjected to at least biotite grade of regional metamorphism during the Tertiary but prior to thrusting. The peak metamorphism within the region seems to have occurred before the thrusting and, therefore, before the intrusion of the carbonatite (Le Bas et al., 1987). This view is also supported by the conclusions of Maluski and Matte (1984) who stated that the thermal peak of Barrovian metamorphism in the region occurred at about 42 ± 2 Ma, and that the thrusting postdates the regional metamorphism.

Rare earth elements study

The Sillai Patti carbonatite constitutes a very promising host for the rare earth elements. Seventeen (17) samples from the host carbonatite sheet were analyzed for the determination of their rare earth element contents using Inductively Coupled Plasma—Mass Spectrometry (ICP-MS) technique. The results have been presented in the Table 1 and indicate that the Sillai Patti carbonatite contains La (39–795 ppm, average 519 ppm), Ce (100–1354 ppm, average 915 ppm), Pr (9–153 ppm, average 97 ppm), Nd (29–493 ppm, average 314 ppm), Sm (5–52 ppm, average 35 ppm), Eu (2–19 ppm, average 11 ppm), Gd (5–50 ppm, average 34 ppm), Tb (1–6 ppm, average 4 ppm), Dy (4–21 ppm, average 16 ppm), Ho (1–4 ppm, average 3 ppm), Er (2–19 ppm, average 9 ppm), Tm (0–1 ppm, average 0.9 ppm), Yb (2–8 ppm, average

Table 1. Rare earth elements contents (ppm) in Sillai Patti carbonatite complex

Sample No.	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	ΣREEs
SP-2	586	1063	111	378	43	12	43	5	19	4	10	1	7	1	2283
SP-3	39	100	9	29	5	2	5	1	4	1	2	0	2	0	199
SP-4	134	304	27	111	17	5	16	2	4	1	4	1	3	1	630
SP-5	646	1191	123	413	46	13	17	5	21	4	10	1	7	1	2498
SP-6	636	1042	117	402	43	13	48	4	21	4	10	1	8	1	2350
SP-8	559	941	108	368	40	12	41	5	20	3	9	1	7	1	2115
SP-10	672	1285	135	460	50	14	50	6	23	4	11	1	8	1	2720
SP-13	795	177	16	59	11	2	11	2	7	1	4	1	3	1	1090
SP-15	375	722	78	197	31	9	30	4	14	2	7	1	4	1	1475
SP-17	559	1074	109	359	38	11	39	4	19	3	10	1	8	1	2235
SP-19	309	644	75	197	32	9	31	4	15	2	7	1	5	1	1332
SP-23	535	998	107	368	38	11	38	3	18	3	9	1	7	1	2137
SP-24	256	1005	101	237	35	19	36	2	17	3	8	1	6	1	1727
SP-26	631	1183	127	436	45	13	45	4	20	4	10	1	7	1	2527
SP-30	715	1275	130	433	44	13	46	5	21	4	11	1	8	1	2707
SP-32	765	1354	153	493	52	16	39	6	19	3	12	1	6	1	2920
SP-35	605	1191	123	397	29	9	36	4	18	4	19	0	5	0	2440
Average	519	915	97	314	35	11	34	4	16	3	9	0.9	6	0.9	1965

Note. Samples analyzed at Geo-science Labs, Chak Shahzad, Islamabad, with ICP-MS Technique.

6 ppm), and Lu (0–1 ppm, average 0.9 ppm). These values of some of the REEs from the carbonatite sheet of the Sillai Patti are quite encouraging and demand for further detailed work in the area in order to declare its suitability as a commercially exploitable deposit of REEs.

Fission-track dating methodology

Clear grains of apatite separated from three samples of the Sillai Patti carbonatite taken roughly at the same elevation were mounted in "sampl kwick" mounting material. Sample mounts prepared in this way were then polished and etched in 5% HNO_3 for 35 seconds to reveal the fossil fission tracks in the apatite grains. The spontaneous fission-tracks (N_s) were counted in apatite crystals, whereas the induced tracks (N_i) were counted with the help of external detector method. The spontaneous tracks (N_s) were counted first. For induced track density determination, mounts of the Sillai Patti apatite (along with a mount of Durango apatite) were co-irradiated with the standard reference material (SRM-612) in the Pakistan Research Reactor-1 (PARR-1) along with the attached lexan detectors. The irradiation was made for 200 seconds in the rabbit station (RS-2) at 10 MW power. After irradiation the lexan detectors separated from all the mounts of apatite and SRM-612 were etched in 6.5 M NaOH for 45 minutes at 50 ºC. The lexan detectors were then examined under the Zeiss transmitted light microscope at an overall magnification of 1000× for the induced track density determination.

Results

Fission-track ages of apatite grains separated from the Sillai Patti carbonatite samples were calculated with the external detector method (EDM) and the age standard approach (the ζ-method). In the age standard approach, first the zeta calibration factor (ζ) for Durango apatite was determined using the procedure of Fleischer et al. (1975) and Wagner and Van den haute (1992). The zeta calibration factor (ζ) was calculated with the following equation (Hurford, 1990; Wagner and Van den haute, 1992):

$$\zeta = \frac{(e^{\lambda_D t_s} - 1)}{\lambda_D (\rho_s/\rho_i)_s G\rho_m} . \tag{1}$$

Where,

ζ = zeta calibration factor;

λ_D = total decay constant for uranium (1.55125×10^{-10} yr^{-1});

t_s = age of the standard used (Durango apatite);

$(\rho_s/\rho_i)_s$ = ratio of spontaneous to induced track desity of the standard;

G = geometry factor (G is = 0.5 or 1 depending upon the geometry of the surface investigated);

ρ_m = fission track density of the glass monitor used.

Once the ζ-calibration factor (which is expressed in yr cm^2 tr^{-1}) was evaluated, the ages of the apatite grains of the Sillai Patti carbonatite were then determined from the following equation (Hurford, 1990; Wagner and Van den haute, 1992):

Table 2. Apatite age standard analysis for system calibration with the zeta approach using the external detector method

Standard	Crystal No.	Number of field of views	Spontaneous tracks		Induced tracks		Zeta (ζ)	Grain only SE	Total SE
			Number of tracks (N_s)	Track density ρ_s ($\times 10^{-4}$ tr cm^{-2})	Number of tracks (N_i)	Track density ρ_i ($\times 10^{-4}$tr cm^{-2})			
Durango apatite	1	20	(308)	16.03	(1317)	68.56	353.17	24.8	25.4
	2	20	(167)	08.69	(632)	32.90	312.57	28.8	29.2
	3	20	(506)	26.34	(1800)	93.71	293.81	17.2	17.9
	4	20	(257)	13.38	(1041)	54.19	334.55	25.4	26.0
	5	20	(224)	11.66	(915)	47.63	337.38	27.1	27.7
	6	20	(364)	18.95	(1458)	75.90	330.83	21.8	22.4
	7	20	(281)	14.63	(1058)	55.08	310.98	22.9	23.4
	8	20	(233)	12.13	(928)	48.31	328.96	26.1	26.6
	9	20	(431)	22.44	(1675)	87.20	320.99	19.9	20.5
	10	20	(611)	31.81	(2435)	126.27	329.16	17.9	18.7
	11	20	(501)	26.10	(1923)	100.11	317.02	18.6	19.2
	12	20	(481)	25.04	(1781)	92.72	305.82	18.2	18.9
	13	20	(501)	26.08	(1866)	97.14	307.63	18.1	18.7
	14	20	(583)	30.35	(2251)	117.19	318.90	17.7	18.4
Total			(5448)		(21080)				
Pooled zeta (ζ)							319.58	10.8	11.9
Average				20.26		78.39	320.88	10.5	11.7

Note. Time of irradiation = 200 s. Station = RS-2. SRM = 612 (^{238}U = 37.38 ± 0.3 ppm, ^{235}U = 0.2392 at %): $\rho_d \times 10^4 = 76.22 \pm 2.3$, $N_d = 1098$. Hereafter, ρ_d and N_d stand for track density of glass dosimeter and total number of tracks of glass dosimeter, respectively. $P(\chi^2) = 79.2\%$, $\overline{\rho_s/\rho_i} = 0.257 \pm 0.003$. Independent age of the Durango apatite = 31.4 ± 0.5 Ma. $\lambda_D = 1.55125 \times 10^{-10}$ yr^{-1}. 4π/2π geometry correction factor $G = 0.5$.

$$t_u = \frac{1}{\lambda_D} \ln\left[(\lambda_D)\left(\frac{\rho_s}{\rho_i}\right)_u \rho_m G\zeta + 1\right]. \qquad (2)$$

Where,

t_u = fission-track age in years of the unknown sample;

λ_D = total decay constant of ^{238}U;

$(\rho_s/\rho_i)_u$ = ratio of spontaneous to induced track density of the unknown sample;

G = geometry factor (G is = 0.5 or 1 depending upon the geometry of the surfaces investigated);

ρ_m = fission track density of the glass monitor;

ζ = zeta calibration factor of the age standard used.

χ^2-test of Galbraith (1981) was applied to both the Durango and Sillai Patti apatite samples. Samples of both the areas passed the χ^2-test (there was more than 5% probability of finding the calculated χ^2 value). For calculating errors in the zeta factor and fission-track ages the procedure of Wagner and Van den haute (1992) was followed.

Average and pooled zeta (ζ) values of 320.88 ± 11.7 and 319.58 ± 11.9 yr cm^2 tr^{-1} were obtained with manual calculation procedures for the Durango apatite. The manually calculated zeta (ζ) values of the individual grains of the Durango apatite and its average and pooled zeta values have been presented in the Table 2.

Using the pooled zeta (ζ) value of 319.58 ± 11.9 yr cm^2 tr^{-1} in the age equation of Hurford (1990), and Wagner and Van den haute (1992) an average age of 29.41 ± 1.42 Ma, and a pooled age of 29.40 ± 1.47 Ma were obtained for the Sillai Patti carbonatite with manual calculation procedures. The ages of the individual apatite crystals and the average and pooled age of all the three apatite mounts of the Sillai Patti carbonatite obtained in this way have been presented in the Table 3.

Discussion

Two rival ideas namely of single versus multiple episodes of carbonatitic magmatic activity within northern Pakistan have been proposed by two different groups of experts to explain the timings and nature of emplacement of the carbonatites and their associated alkaline rocks within the alkaline belt of northern Pakistan. The tectonic setting having prevailed during the emplacement of the alkaline complexes within the province has also remained under substantial dispute. One group of the researchers believes that the emplacement of the alkaline complexes took place along thrust faults in a compressional environment, whereas, the other group considers it to have taken place along rift zones of normal faulting.

Multiple magmatic episodes

Le Bas et al. (1987) and Tilton et al. (1998) are of the opinion that all the carbonatites and associated alkaline rocks

Table 3. Fission-track ages of apatite from Sillai Patti carbonatite using external detector method and zeta calibration approach

Sample locality	Mount /Crystal No.	Number of field of views	Spontaneous tracks		Induced tracks		Age, Ma (±1σ)
			ρ_s ($\times 10^{-4}$ tr cm^{-2})	N_s	ρ_i ($\times 10^{-4}$tr cm^{-2})	N_i	
Sillai Patti	SPN-3/1	12	20.12	(232)	82.17	(947)	29.77 ± 2.61
	SPN-3/2	12	29.93	(345)	119.30	(1375)	30..49 ± 2.35
	SPN-3/3	12	30.19	(348)	129.80	(1496)	28.27 ± 2.16
	SPN-3/4	12	21.87	(252)	87.81	(1012)	30.26 ± 2.58
	SPN-3/5	12	25.77	(297)	108.89	(1255)	28.76 ± 2.31
	SPN-3/6	12	28.33	(327)	115.75	(1334)	29.79 ± 2.33
	SPN-3/8	12	34.36	(396)	142.73	(1645)	29.25 ± 2.16
	SPN-3/9	12	29.59	(341)	121.91	(1405)	29.49 ± 2.27
	SPN-3/10	12	28.20	(325)	112.80	(1300)	30.38 ± 2.38
	SPN-3/12	12	26.98	(311)	108.81	(1254)	30.13 ± 2.39
	SPN-3/15	12	27.16	(313)	110.11	(1269)	29.97 ± 2.38
	SPN-3/16	12	34.45	(397)	143.60	(1655)	29.15 ± 2.15
	SPN-7/1	12	17.61	(203)	74.62	(860)	28.68 ± 2.63
	SPN-7/3	12	22.56	(260)	97.18	(1120)	28.21 ± 2.37
	SPN-7/4	12	20.82	(240)	87.20	(1005)	29.02 ± 2.51
	SPN-7/5	12	31.24	(360)	128.24	(1478)	29.60 ± 2.25
	SPN-7/8	12	27.77	(320)	112.36	(1295)	30.03 ± 2.37
	SPN-7/9	12	18.57	(214)	77.83	(897)	28.99 ± 2.61
	SPN-9/1	12	16.49	(190)	72.10	(831)	27.79 ± 2.60
	SPN-9/5	12	23.43	(270)	99.52	(1147)	28.60 ± 2.37
	SPN-9/6	12	20.56	(237)	85.29	(983)	29.30 ± 2.54
	SPN-9/7	12	28.02	(323)	111.84	(1289)	30.45 ± 2.39
	SPN-9/8	12	15.36	(177)	65.16	(751)	28.64 ± 2.76
Total		276		(6678)		(27603)	
Pooled age							29.40 ± 1.47
Average			25.19		104.13		29.41 ± 1.42

Note. Number of tracks counted (N) shown in parentheses. Analysis by external detector method. All the mounts were irradiated in RS-2 for 200 s. Glass dosimeter: SRM-612, ρ_d = 76.22 ± 2.30 tr cm^{-2}, N_d = 1098, $P(\chi^2)$ = 99.9%, $\overline{\rho_s/\rho_i}$ = 0.242 ± 0.001. Ages calculated with zeta ζ = 319.58 ± 11.9 yr cm^2 tr^{-1}).

of the alkaline belt of northern Pakistan were emplaced at least in two alkaline magmatic episodes during the (i). Carboniferous and (ii). Tertiary (Oligocene), respectively. They consider Koga carbonatites to have been emplaced during the Carboniferous alkaline magmatism, while the Loe-Shilman and Sillai Patti carbonatite complexes are interpreted to have been emplaced during the Tertiary (Oligocene) alkaline magmatic episode. The assumption of Le Bas et al. (1987) was based upon the K–Ar dates of 31 ± 2 Ma on biotite from the Sillai Patti and Loe-Shilman carbonatites, and Rb–Sr dates of 315 ± 15 Ma and 297 ± 4 Ma on whole rocks from syenite and ijolite of the Koga igneous complex. They further argued that the alkaline complexes of the northern Pakistan were not related to the Himalayan collision, and that there was no indication of rifting at least in the case of the Loe-Shilman and Sillai Patti carbonatite complexes of Tertiary (Oligocene) age. Tilton et al. (1998) proposed the idea of multiple alkaline and carbonatitic magmatic episodes within the northern Pakistan on the basis of the isotopic data. They argued that a striking feature for the synorogenic carbonatites of the Loe-Shilman and Sillai Patti areas is their very negative ε_{Nd} values, coupled with the high $^{87}Sr/^{86}Sr$ ratios in contrast to the positive ε_{Nd} paired with low $^{87}Sr/^{86}Sr$ values for the preorogenic Koga carbonatites.

Le Bas et al. (1987) and Mian and Le Bas (1988) stated that the Loe-Shilman carbonatite was emplaced along a northward dipping Warsak thrust between Paleozoic metasediments and dolerites to the north and Precambrian slates and phyllites to the south. Qureshi et al. (1991) are also of the opinion that the Sillai Patti carbonatite sheet was intruded somewhere in the middle of the Oligocene along a thrust fault associated with India–Eurasia plate collision. Tilton et al. (1998) also favored the idea of emplacement of the Loe-Shilman and Sillai Patti carbonatites along thrust faults at around 30 Ma (Oligocene) in a postcollisional setting.

Single magmatic episode

Tahirkheli (1980) pointed out the presence of a rift zone of semicircular shape extending from the Loe-Shilman area near the Pakistan–Afghanistan border in the west up to Tarbela area in the east on the northern side of the Peshawar valley. He suggested the alkaline activity within the rift zone to have taken place between Middle to Upper Eocene. Kempe and Jan (1980) proposed that the Peshawar Plain is an irregular rift valley extending east–west for over 200 km. They suggested a line of rifting to run from Loe-Shilman to Malakand and then to continue eastwards. They further argued that alkaline magmatism within the Peshawar Plain took place as a result of lithospheric doming caused by mantle plumes within a rift system produced by rebound' relief tension, or compression release, following the initial plate collision perhaps during very Late Cretaceous or Early Tertiary times. Later on Butt et al. (1989) and Jan and Karim (1990) floated the idea of a single alkaline and carbonatitic magmatic episode in northern Pakistan in a pre-Himalayan time. According to these workers all the carbonatite complexes and associated alkaline rocks of the northern Pakistan were emplaced in a single magmatic episode during the Permo-Carboniferous tensional rifting and break-up of Gondwanaland. The idea of a single magmatic episode was supported on the basis of the presence of the mineral epidote in rocks of the Sillai Patti carbonatite complex. Butt et al. (1989) believe that the Sillai Patti carbonatite and associated country rocks were metamorphosed up to green schist or epidote–amphibolite facies during regional metamorphism of the Himalayan Orogeny in the region and that the K–Ar dates of 31 ± 2 Ma on biotite from the two main carbonatite complexes represent reset Permo-Carboniferous ages. They correlated these rocks with the Carboniferous carbonatites (Koga carbonatites) of the region. Jan and Karim (1990) supported their idea by arguing that alkaline rocks and associated carbonatites are absent from the post Paleozoic sequence. They correlated the Loe-Shilman and Sillai Patti carbonatites with the alkaline rocks of Ambela, Malakand, and Shewa-Shahbazgarhi of Late Paleozoic age.

The Carboniferous episode of carbonatitic magmatic activity within this part of northern Pakistan has now been undoubtedly accepted by all the earlier workers. However, there has been considerable disagreement over the episode of Tertiary (Oligocene) alkaline and carbonatitic magmatic activity within the alkaline belt of the northern Pakistan.

Qureshi et al. (1991) reported a fission-track age of 32.1 ± 1.9 Ma on zircon from the Sillai Patti carbonatite. Anczkiewicz et al. (2001) have dated single zircon from one of the alkali granite dikes intruding the Swat granite gneisses of Paleozoic age and obtained a $^{206}Pb/^{238}U$ mean age of 29.26 ± 0.12 Ma. They also reported a concordant Ar–Ar muscovite age of 28.4 ± 1.1 Ma from the same dike. These workers have considered these alkaline dikes as member of the PAIP. Khattak et al. (2004) reported a fission-track age of 29.3 ± 1.2 Ma on apatite from the Jambil carbonatite occurring about 10 km SE of Mingora in Lower Swat area. Khattak et al. (2008) also reported a fission-track age of 30.0 ± 1.5 Ma on apatite from the Loe-Shilman carbonatite of Khyber Agency near Pakistan–Afghanistan border.

It has been pointed out by the earlier workers (Armstrong et al., 2003; Eby et al., 1995; Hasebe et al., 2000; Wagner and Van den haute, 1992 among many others) that concordant FT ages of zircon and apatite for an intrusive body suggest rapid cooling of the body through the zircon and apatite closure temperatures. Thus the obtained ages should represent the emplacement age for the intrusive concerned. Concordance of the FT ages of zircon and apatite with the age data by K–Ar method provides an additional evidence for the rapid cooling.

The average and pooled fission track ages of 29.41 ± 1.42 and 29.40 ± 1.47 Ma, respectively, on apatite from the carbonatite of Sillai Patti area of this study are consistent with the K–Ar date of 31 ± 2 Ma on biotite (Le Bas et al., 1987) and fission-track age of 32.1 ± 1.9 Ma on zircon (Qureshi et al., 1991) from the same carbonatite sheet. This concordance of apatite fission track (AFT), zircon fission track (ZFT) and K–Ar biotite ages for the carbonatite sheet of the Sillai Patti area, therefore, strongly suggests that they all document the age of emplacement of this carbonatite complex. Age concordance, the porphyritic textures of the carbonatites and apatite fission track modeling, all indicate rapid cooling from emplacement temperatures. For a geothermal gradient of about 35 ºC km^{-1} and assuming postintrusion temperatures of less than about 60 ºC as indicated by fission track modeling, the intrusion depth would have been as shallow as 1.0 to 1.5 km (Armstrong et al., 2003).

The fission track ages on apatite from the Sillai Patti area are also concordant with the $^{206}Pb/^{238}U$ age of 29.26 ± 0.12 Ma on zircon and Ar–Ar age of 28.4 ± 1.1 Ma on muscovite from the alkaline granitic dike of Lower Swat area (Anczkiewicz et al., 2001), K–Ar dates of 31 ± 2 Ma on biotite from the Loe-Shilman carbonatite (Le Bas et al., 1987), fission track age of 29.3 ± 1.2 Ma on apatite from the Jambil carbonatite of Lower Swat area (Khattak et al., 2004), and fission-track age of 30.0 ± 1.5 Ma on apatite from the Loe-Shilman carbonatite (Khattak et al., 2008). The strong resemblance of the fission-track apatite age of this study with the fission-track as well as other high temperature radiometric age data from the other localities of the alkaline belt of northern Pakistan also strongly documents that the Sillai Patti carbonatite complex was emplaced at high crustal level (shallow burial depths) and cooled there relatively rapidly to near surface temperatures.

According to Harrison (1994), normal erosion rates in mountainous regions are usually in the range of 0.235–0.212 mm yr^{-1} and significantly faster denudation rates require tectonic extension or lithospheric delamination. The average uplift induced denudation rates of the Mansehra and Sillai Patti granites have been computed to be $0.26 \pm 0{:}01$ and $0.27 \pm 0{:}03$ mm yr^{-1}, respectively, on the basis of zircon fission-track ages for the period between 25 Ma and the present time by Khattak et al. (2001). This indicates that the two complexes occurring south of the MMT have experienced fast and more or less identical uplift-induced denudation histories during the past about 25 Ma. Uplift induced denudation rate averaged in excess of 0.70 mm yr^{-1} has been computed by Zeitler et al. (1982) for the period from 25 to 15 Ma for the region south of the Main Mantle Thrust. Denudation rates of all these workers for the region south of MMT are significantly higher than the range of normal erosion rates of 0.235–0.212 mm yr^{-1} of Harrison (1994). This clearly indicates the presence of an extensional environment in the region south of MMT during Oligocene time which is a prerequisite for alkaline magmatism within a region. This clearly negates the idea of emplacement of the carbonatite complexes of the Loe-Shilman and Sillai Patti area along thrust faults during Oligocene. Our finding of the reactivation of the MMT as a normal fault during Oligocene time subsequent to imbrications and thrust stacking within the region is also supported by the work of several earlier researchers including Zeitler et al. (1993), Burg et al. (1996) and Anczkiewicz et al. (2001). Zeitler et al. (1993) indicated the interval of 25 to 20 Ma for the reactivation of the Main Mantle Thrust as a normal fault when the Kohistan slid down northward relative to the Indian plate subsequent to the main phase of regional metamorphism and thrust stacking within the Indian plate. Anczkiewicz et al. (2001) assigned an age range of 29–15 Ma for normal faulting which they interpreted to be coeval with the extension along the South Tibetan Detachment System (STDS) on the north side of the High Himalaya.

Besides the Sillai Patti carbonatite complex, the Loe-Shilman carbonatite complex, situated about 50 km northwest of Peshawar is also commonly considered to have been emplaced in a compressional setting. Le Bas et al. (1987), Mian and Le Bas (1988), Qureshi et al., (1991), Tilton et al. (1998) and many others stated that the Loe-Shilman carbonatite complex was emplaced along a northward dipping Warsak thrust between Paleozoic metasediments and dolerites to the north and Precambrian slates and phyllites to the south. In our view, the north dipping fault at the Loe-Shilman cannot be a thrust because it is having younger Paleozoic rocks in the hanging wall on the northern side over the older Precambrian slates in the footwall in the south. Such a situation is possible only if we assume this fault to be a north dipping normal fault along which the footwall in the south has been uplifted upward and to the south relative to the hanging wall lying on the northern side.

Conclusions

1. The FT age of 29.40 ± 1.47 Ma on apatite from the Sillai Patti carbonatite is concordant with the fission track as well as the other higher temperature radiometric ages from the same carbonatite sheet. This concordance of the ages for the carbonatite sheet of the Sillai Patti area, therefore, strongly suggests that they all document the age of emplacement of this carbonatite complex at around 30 Ma. Age concordance also reveals that the intrusion depth of carbonatite magma would have been as shallow as 1.0 to 1.5 km and that the magma cooled very rapidly soon after its emplacement to near ambient surface temperatures.

2. The FT age of 29.40 ± 1.47 Ma of this study is also concordant with the fission track as well as the other higher temperature radiometric ages from the carbonatites and alkaline granites of the neighboring areas. This concordance indicates that the episode of Tertiary (Oligocene) carbonatitic and alkaline magmatism occurred over a much widespread area extending from the Loe-Shilman carbonatite complex near Pakistan–Afghanistan border in the west up to the Jambil carbonatite of Lower Swat area in the east.

3. The presence of porphyritic to subporphyritic textures in the carbonatite sheet indicates that intrusion of carbonatite magma (s) in the Sillai Patti area took place at higher crustal levels near to the surface. The magma was then rapidly solidified soon after its intrusion at near surface shallow level.

4. The Oligocene carbonatite magmatism occurred along extensional faults rather than thrust faults as proposed by several earlier workers.

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