Geol. Bull. Univ. Peshawar, Vol. 37, pp. 127-138, 2004

Recognition of emplacement time of Jambil carbonatites from NW Pakistan: constraints from fission-track dating of apatite using age standard approach (the ζ method)

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ABSTRACT: *A group of alkaline igneous complexes, the Peshawar Plain Alkaline Igneous Province (PAIP), is exposed in an arcuate fashion north of the Peshawar Plain in NW Pakistan. The PAIP, which extends for about 150 km, from Tarbela in the east up to Loe-Shilman near the Pakistan-Afghanistan border in the west, consists mainly of granites, syenites, gabbros, ijolites and carbonatites. The carbonatites are present in Loe-Shilman, Sillai-Patti, Jawar, Jambil, Koga and Tarbela. The Jambil carbonatite deposit occurs as small isolated bodies and plugs of carbonatites and fenites exposed in Jambil area, about 10 km SE of Mingora in lower Swat. Here the carbonatite bodies intrude the Swat granitic gneisses and Manglaur Formation. Conduction of fission-track dating studies on the apatite crystals using the external detector method and age standard approach (the ζ method) yielded a pooled age of 29.3 ± 1.2 Ma and an average age of 29.5 ± 1.2 Ma for the Jambil carbonatite of lower Swat area. These ages are concordant with the fission track age of 32.1 ± 1.9 Ma on zircon from the Sillai Patti carbonatite, fission track age of 29.1 ± 1.9 Ma on apatite from the Jawar carbonatite, K-Ar dates of 31 ± 2 Ma on biotites from the Loe-Shilman and Sillai Patti carbonatites, U-Pb age of 29.26 ± 0.12 Ma on zircon from one of the alkaline pegmatitic dykes of lower Swat area and Ar-Ar age of 28.4 ± 1.1 Ma on muscovite from the same dyke of the earlier workers. This relationship confirms that the fission-track apatite age of this study is the emplacement age. This strongly suggests the occurrence of an Oligocene alkaline magmatic episode within the region.*

INTRODUCTION

Fission-track dating depends upon the ability of minerals to record the linear trails of radiation damage caused by the spontaneous fission of ^{238}U (Fleischer et al., 1975; Durrani & Bull, 1987). These radiation damages known as 'fission tracks' are formed from the passage of highly energetic fission fragments through the crystal lattice of the host mineral. The fission tracks in minerals are chemically highly reactive compared to the surrounding undamaged lattice and can therefore be enlarged by a simple chemical etching treatment until they can be seen under an ordinary optical microscope. When fission tracks are first created in a particular mineral, they are all similar in length. These tracks are stable over geological time, but only at relatively low temperatures. At raised temperatures the damage is gradually repaired or annealed as the disordered atoms along the tracks gradually diffuse back into a more ordered state. Ultimately the fission tracks cease to be preferentially etchable, so that they can no longer be viewed.

Temperature is the only environmental factor to have any appreciable influence on the annealing of fission tracks. The term 'closure temperature' or 'effective track retention temperature' of cooling fission-track system has been referred by Dodson (1973) to the temperature at which 50% of the fission track is retained (the temperature of the cooling system at the time given by the fission track age). Fission track dating of minerals, particularly of apatite frequently gives ages, which are significantly younger than the independently known age of the host rock. Only very rarely the measured fission track age will be related to the age of formation, or geological age of the mineral due to the phenomenon of fission track annealing. The fading of fission tracks in minerals can, therefore, be used as a sensitive geological thermochronometer. It has been observed that fission-track ages determined for different minerals from the same rock are not always the same. It is because of the fact that annealing behavior is different for different minerals.

Depending upon the nature of the thermal history experienced there are essentially three different kinds of ages recorded by the thermochronological systems: 1) Event or formation ages, 2) Cooling and uplift ages and 3) Mixed ages (Wagner, 1981; Wagner & Van den haute 1992; Gleadow & Brown, 1999).

Formation or event ages are commonly observed for volcanic rocks, shallow intrusive bodies and impactites. In this situation, temperatures at which fission tracks are preserved are reached soon after rock formation. Slow cooling is characteristic of plutonic rocks, rocks undergoing uplift/denudation, crystalline basements and sedimentary rocks. Temperatures at which spontaneous fission tracks are preserved are reached long after rock formation. A complex cooling history with a thermal overprint event is characteristic of various geological processes such as subsidence, metamorphism, heating of rocks by nearby intrusions and extrusions and meteoric impact. The measured fission track ages in this case represent the net balance of track accumulation against erasure and the age interpretation may become very complex.

In order to conclude if a fission track age is formation (event) or cooling age, several criteria can be used. One criterion is to compare the fission track age with the high temperature fission track and other radiometric ages of the co-existing minerals within a rock or the minerals in the similar rocks in the immediate vicinity. Concordant fission track as well as other radiometric ages on such minerals are indicative of event or formation ages. In the case of cooling ages (type 2) the fission track as well as the other radiometric ages on co-existing minerals are usually discordant and decrease systematically in the order of their decreasing effective track retention temperatures. The association of a fission track age with any given geologically meaningful event is the objective of its geological interpretation.

No geochronological studies have been conducted on the Jambil carbonatites (a newly discovered carbonatite deposit) of lower Swat area till now (Fig. 1 & 2). We, therefore, applied the technique of fission track dating to date mineral apatite separated from the rock samples of this carbonatite deposit. The aims of this study are: 1) to know if this age is formation or cooling age, 2) to know about the low temperature thermal history of the area and 3) to develop additional data points for refining the regional cooling patterns identified by Zeitler et al. (1982) for northern Pakistan. The results of the fission-track data from this carbonatite body has been compared with the age data of Sillai Patti carbonatite of Le Bas et al. (1987) and Qureshi et al. (1991) in order to get information on the petrogenetic relationship between the two complexes. The low temperature fission track apatite age data has been compared with the available medium and high temperature data from the nearby carbonatite and alkaline rocks to put constraints on the timing of carbonatitic and alkaline magmatic activities within the Peshawar Plain Alkaline Igneous Province (PAIP) of the northern Pakistan.

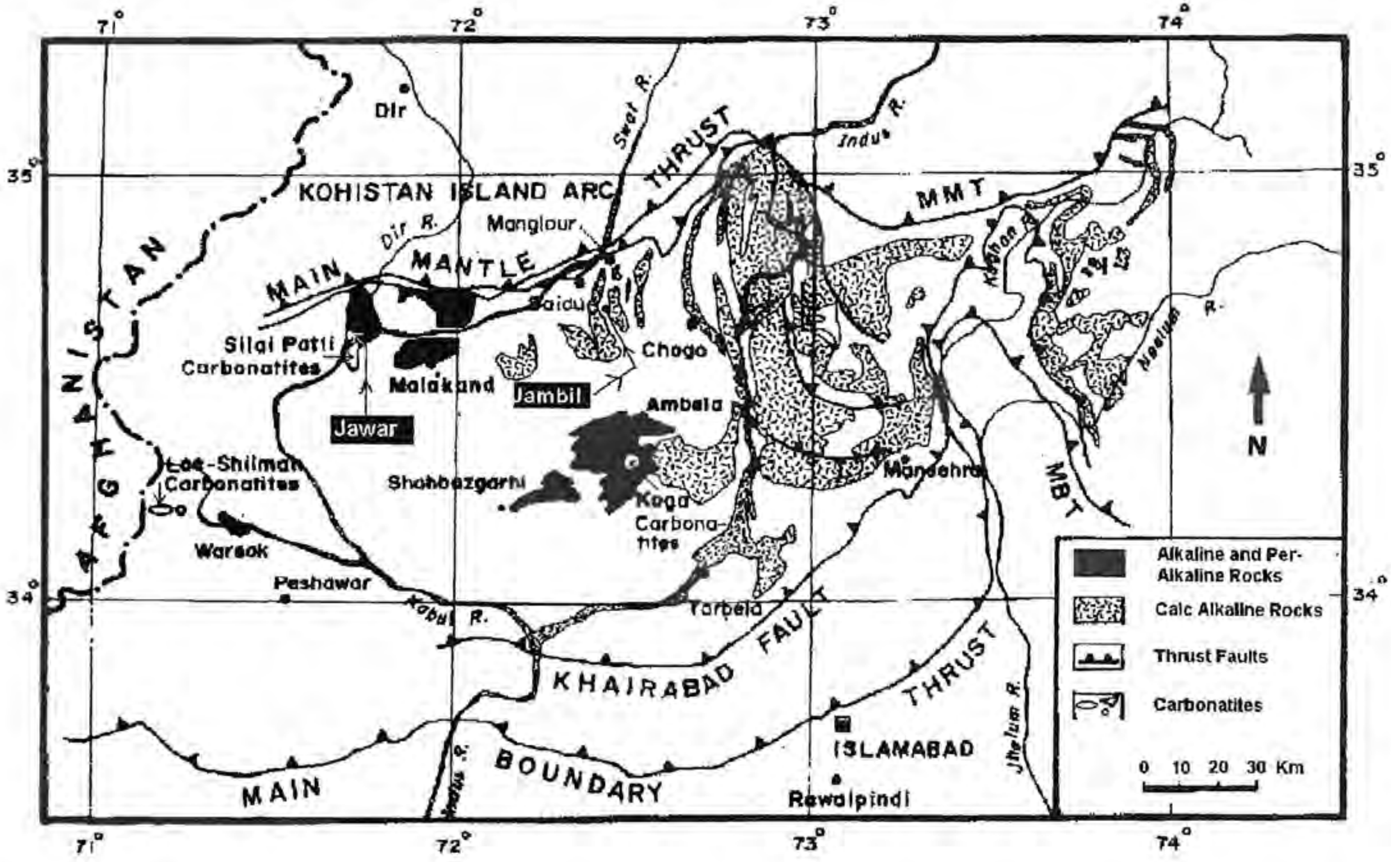

Fig. 1. Map showing locations fo the carbonatites and alkaline complexes of the northern Pakistan (After Khattak et al., in press)

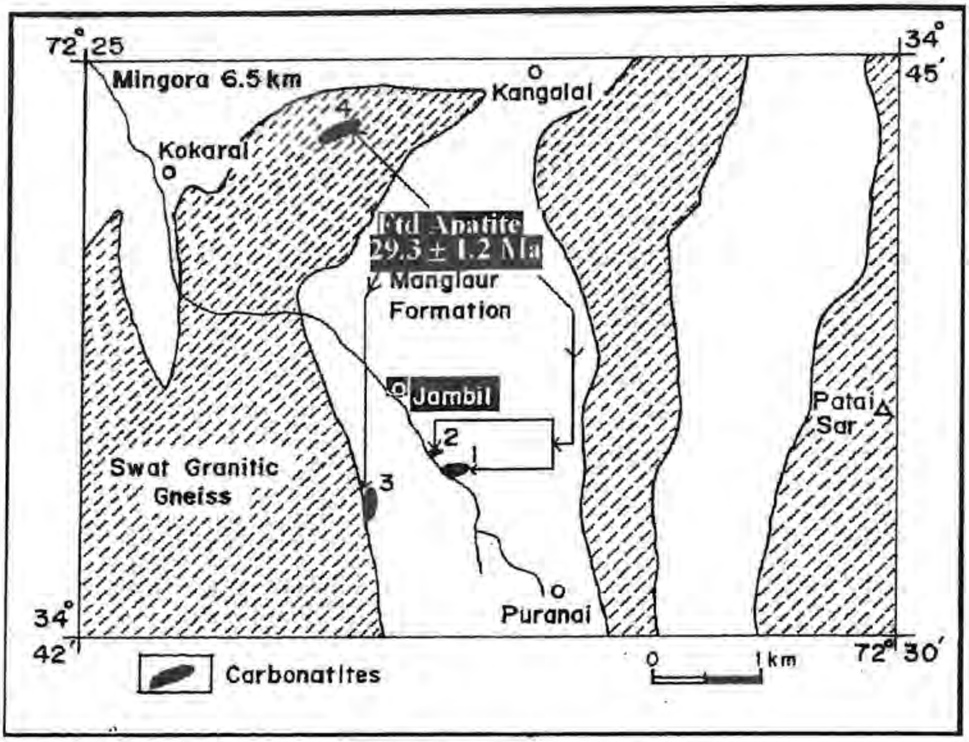

Fig. 2. Geological map of the Jambil area showing the location of different carbonatite bodies within the associated country rocks (modified after Jan et al., 1999).

GEOLOGY OF THE AREA

The Peshawar Plain Alkaline Igneous Province (PAIP) occurs along the northern side of the Peshawar valley and is comprised of alkaline granites, syenites, albitites and carbonatites (Fig. 1). The occurrence of the alkaline rocks in the northern Pakistan was first reported by Kempe and Jan (1970; 1980). The alkaline rocks are emplaced along fault zone in Early Paleozoic metasediments over a 150 km long belt extending from Afghanistan in the west, through Khyber Agency, Mohmand Agency, Warsak, Sillai Patti, Shewa-Shahbazgarhi, Koga, Tarbela, and perhaps further across the River Indus to Mansehra area in the east. Occurrence of the alkaline province is limited by the Main Mantle Thrust (MMT) in the north and by the Main Boundary Thrust (MBT) in the south. Within the alkaline belt, the carbonatite complexes are present in various places such as Sillai Patti in the Malakand Agency (Ashraf & Chaudry, 1977); Koga in Swat (Siddiqui et al., 1968); Loe-Shilman in Khyber Agency (Jan et al., 1981b); Jambil in Swat (Butt et al., 1986); Tarbela (Kempe, 1973; Jan et al., 1981a) and Khungai in Mardan (Khattak et al., 1984). Recently carbonatites were discovered in the Jawar area about 4 km to the north west of the Sillai Patti carbonatite complex by Khattak et al. (in press).

Small isolated sill like bodies and plugs of carbonatites and fenites intruding the Swat granitic gneisses and Manglaur Formation are exposed in Jambil area, about 10 km SE of Mingora in lower Swat (Fig. 2). Alkali metasomatism (feintization) around the carbonatite bodies is well observed. Because of having high albite content, these bodies can be termed as fenite or fenitized carbonatite. The Manglaur Formation hosting the carbonatites is extensively fractured, sheared, and folded. The nature of the exposures gives the appearance of a minor shear zone. Although deformation can be attributed to the Eocene-Oligocene Himalayan Orogeny, however, some is likely to be due to the Carboniferous intrusion of the Swat granitic gneisses (DiPietro, 1991). The Jambil carbonatites are generally medium-grained undeformed rocks. They show uneven distribution of mafic minerals with local crude banding. These rocks consist of 80% calcite and some clinopyroxene and traces of apatite and sphene. These can be classified as calcite carbonatite according to the classification scheme of Woolley and Kempe (1989). Fenites are usually present adjacent to the carbonatites, however, independent bodies of fenitic rocks are also noticed. These rocks may be related to larger carbonatite bodies, occurring at depth. The carbonatite is unevenly distributed as irregular patches within fenite giving the rock a spotty look.

METHODOLOGY

Fresh samples of carbonatite, collected from Jambil area, were pulverized and subjected to heavy mineral separation with the help of heavy liquids. Clear apatite grains were separated from the available heavy mineral concentrates using a binocular microscope. A large crystal of Durango apatite, used as a standard, was also crushed, washed and sieved in order to get grains of ideal size for the determination of zeta factor (ζ) for subsequent use in determining the age of the Jambil apatite. Apatite grains of the standard and the unknown samples were mounted on "sampl kwick" mounting material. Three mounts (M-9, M-10, and M-11) were prepared from the apatite grains separated from the heavy mineral concentrate of the Jambil carbonatite, while one mount (M-8) was prepared from the grains of the Durango apatite of known age. All the samples were polished and etched in 5% HNO_3 for 35 seconds. In all the mounts the spontaneous fission-track densities were counted in relatively clear apatite crystals, where as the induced track densities were calculated using the external detector method. For the induced track density determination, mounts of the Jambil and Durango apatite were irradiated along with the standard reference materials (SRM-612) in the Pakistan Research Reactor-1 (PARR-1). SRM-612 were irradiated along with lexan as external detectors. The mount of Durango apatite (M-8) was irradiated in the rabbit station-2 (RS-2) for 80 seconds along with lexan as an external detector at 10 MW power while the mounts of Jambil apatite (M-9, M-10 and M-11) were irradiated in the same station along with lexan detectors but for 50 seconds. After irradiation the lexan detectors separated from all the mounts of apatite and SRM-612 were etched in 6.5 N NaOH for 45 minutes at 50 °C and examined under the transmitted light microscope for the induced track density determination. The track counting was done under the Zeiss transmitted light microscope.

RESULTS

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 & Van den haute, 1992):

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

Where, ζ is the zeta calibration factor, λ_D is the total decay constant of ^{238}U, t_s is the age of the standard used, $(\rho_s/\rho_i)_s$ is the ratio of spontaneous to induced tracks of the standard, G is the geometry factor (G is = 0.5 or 1 depending upon the geometry of the surface investigated) and ρ_m is the 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 in the mounts of Jambil carbonatite were then determined from the following equation (Hurford, 1990; Wagner & Van den haute, 1992):

t_u (age in years of unknown sample)

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

Where, t_u is the fission-track age in years of the unknown sample, $(\rho_s/\rho_i)_u$ is the ratio of spontaneous to induced track density of the unknown sample, G is the geometry factor (G is = 0.5 or 1 depending upon the geometry of the surfaces investigated), ρ_m is the fission track density of the glass monitor and ζ is the zeta calibration factor of the age standard used.

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

Pooled zeta (ζ) value of 317 82 ± 10.5 and average zeta (ζ) value of 320.88 ± 10.6 for the Durango apatite was obtained. The zeta values of the individual grains of the Durango apatite and its average and pooled zeta values have been presented in the Table 1.

Using the pooled zeta (ζ) value of 317 82 ± 10.5 in the above age equation a pooled age of 29.3 ± 1.2 Ma and an average age of 29.5 ± 1.2 Ma for the Jambil carbonatite of lower Swat area was obtained. The ages of the individual apatite crystals and the average and pooled ages of all the mounts of the Jambil carbonatite are presented in the Table 2.

DISCUSSION

Two schools of thought exist about the origin of the carbonatite complexes and their associated alkaline rocks of the Peshawar Plain Alkaline Igneous Province.

1. Idea of two magmatic episodes

Le Bas et al. (1987) suggested that all the carbonatites and the associated alkaline rocks of the PAIP have been emplaced at least in two alkaline magmatic episodes such as (i) Carboniferous and (ii) Tertiary (Oligocene). According to them emplacement of the Koga carbonatite took place during the Carboniferous alkaline magmatism, while emplacement of the Loe-Shilman and Sillai Patti carbonatite complexes took place during the Tertiary (Oligocene) alkaline magmatic episode. This supposition is based on the K-Ar dates of 31 ± 2 Ma on biotite from the Loe-Shilman and Sillai Patti carbonatites, and Rb-Sr dates of 315 ± 15 Ma and 297 ± 4 Ma on whole rock from syenite and ijolite of the Koga igneous complex. They suggested that the PAIP is not related to the Himalayan collision, and that there is no evidence of rifting at least in the case of Loe-Shilman and Sillai Patti carbonatite complexes of Tertiary (Oligocene) age.

TABLE 1. APATITE AGE STANDARD ANALYSIS FOR SYSTEM CALIBRATION BY THE ZETA APPROACH USING EXTERNAL DETECTOR METHOD

Standard	Crystal No.	No. of field of views	Spont. Tracks		Induced Tracks		P (X^2) (%)	ρ_s / ρ_i ± 1α	Glass Dosimeter		ζ ± 1α
			No. of tracks (N_s)	Track Density ρ_s (× 10^4)	No. of tracks (N_i)	Track Density ρ_I (× 10^4)			Track Density ρ_D × (10^4)	No. of tracks (N_D)	
Durrango apatite	D-2	6	(565)	16.00	(876)	24.82					352.24 ± 20.3
//	D-3	6	(300)	8.50	(414)	11.73					313.52 ± 24.6
//	D-4	6	(932)	26.41	(1192)	33.78					290.56 ± 14.0
//	D-5	6	(474)	13.43	(679)	19.24					325.44 ± 20.6
//	D-7	6	(413)	11.70	(606)	17.17					333.35 ± 22.3
//	D-10	6	(670)	18.98	(902)	25.56					305.85 ± 16.8
//	D-11	6	(516)	14.62	(732)	20.74					322.29 ± 19.6
//	D-12	3	(216)	12.24	(315)	17.85					331.31 ± 30.0
		45	(4086)		(5716)		22.3 %	0.708 + 0.0148	27.71 ± 0.56	(2445)	
									Pooled zeta (ξ)		317.82 ± 10.5
									Average zeta (ξ)		320.88 ± 10.6

1. Time of irradiation = 80 Seconds
2. Station = RS-2
3. SRM = 612 (^{238}U = 37.38 ± 0.3 ppm, ^{235}U = 0.2392 atom %)
4. Independent age of Durango apatite = 31.4 ± 0.5
5. $\lambda_D = 1.55125.10^{-10}$ a^{-1}
6. 2π/4π geometry correction factor = 0.5

TABLE 2. FISSION-TRACK AGES OF APATITE FROM JAMBIL CARBONATITES USING EXTERNAL DETECTOR METHOD AND AGE STANDARD APPROACH

Sample Locality	Mount /Crystal No.	No. of field of views	Spontaneous		Induced		P (X^2) (%)	ρ_s/ρ_i (± 1α)	Glass Dosimeter		Age ± 1 (Ma)
			ρ_s	(N_s)	ρ_i	(N_{ii})			ρ_d	(N_d)	
Jambil	M-9 D3	1	81.43	(479)	84.49	(497)					31.6 ± 2.4
//	D4	1	38.08	(224)	39.95	(235)					31.3 ± 3.2
//	D5	1	96.05	(565)	119.17	(701)					26.5 ± 1.8
//	M-10 A1	1	81.16	(480)	89.42	(526)					30.0 ± 2.2
//	A2	1	68.00	(400)	75.99	(447)					29.4 ± 2.3
	A3	1	59.67	(351)	66.47	(391)					29.5 ± 2.5
//	A4	1	61.37	(361)	68.51	(403)					29.4 ± 2.4
//	A5	1	85.00	(500)	94.69	(557)					29.5 ± 2.1
//	M-11 B3	1	73.27	(431)	82.28	(484)					29.2 ± 2.2
//	B4	1	82.11	(483)	91.63	(539)					29.4 ± 2.2
//	B7	1	34.85	(205)	39.44	(232)					29.0 ± 3.0
//	B8	1	53.72	(316)	61.88	(364)					28.5 ± 2.5
//	B9	1	91.63	(539)	102.17	(601)					29.5 ± 2.1
//	M-11 C1	1	84.49	(497)	92.90	(560)					29.1 ± 2.1
//	C2	1	67.15	(395)	73.44	(432)					30.0 ± 2.4
		15		(6226)		(6969)	97.5	0.897 ± 0.0092	20.71 ± 0.41	(2558)	
										Average age	29.5 ± 1.2
										Pooled age	29.3 ± 1.2

1. Track densities (ρ) are as measured and are (10^4 tr cm^{-2}); number of tracks counted (N) shown in bracket.
2. Analysis by external detector method.
3. Mount No. M-9 ,M-10 and M-11 were irradiated in RS-2 for 50 Sec.
4. Ages calculated with ζ (zeta) = 617.82 ± 10.5 (yr cm^2/tr).
5. Ages were calculated using the age equation $T(\text{Age in years}) = \frac{1}{\lambda_D}\ln[(\lambda_D)(\rho_s/\rho_i)\rho_d G\zeta + 1]$ where λ_D = total decay constant of ^{238}U = (1.55125×10^{-10}), ρ_s/ρ_i = spontaneous/induced fission track ratio, ρ_d = track density in the glass dosimeter (or the adjacent detector), G = the initial geometry ratio (g_i/g_s) of the surfaces investigated counting the spontaneous and induced tracks and normally = 0.5 or =1 depending upon the dating procedure that is used and ζ = zeta calibration factor.

2. Idea of one magmatic episode

Butt et al. (1989) and Jan and Karim (1990) suggested that all the carbonatite complexes and their associated alkaline rocks of the PAIP have been emplaced during the Permo-Carboniferous tensional rifting and break-up of the Gondwanaland. Butt et al. (1989) supported their idea on the basis of the presence of the mineral epidote in the rocks of Sillai Patti carbonatite complex. They stated that the Sillai Patti carbonatite and the associated country rocks have been metamorphosed upto greenschist or epidote amphibolite facies of regional metamorphism. From this, they concluded that K-Ar dates of 31 ± 2 Ma on biotite from the two complexes represent reset ages and that the carbonatites and related rocks in these areas were of pre-Himalayan origin. They correlated these rocks with the Carboniferous carbonatite (Koga carbonatite) of the region. According to Jan & Karim (1990) the alkaline rocks and their 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 single-grain U - Pb dating studies on zircon from the Swat granitic gneisses north of the Loe-Sar dome (near Saidu) yielded a Permian age of 268 + 7/- 3 Ma while the Choga granitic gneisses east of Alpurai gave a U - Pb zircon age of 468 ± 5 Ma (Anczkiewicz et al., 1998). The Swat granitic gneisses may, therefore, be of lower or upper Paleozoic age and can thus be equated with the Sillai Patti, Malakand and Mansehra granitic gneisses. Some alkaline granitic rocks are, however, intruding these granitic gneisses in the Loe-Sar dome area of lower Swat. Anczkiewicz et al. (2001) have also dated single zircon from one of the alkali granite dykes intruding the Swat granite gneisses of Paleozoic age near the Jambil carbonatite of lower Swat area and obtained a $^{206}Pb/^{238}U$ mean age of 29.26 ± 0.12 Ma. A concordant Ar-Ar muscovite age of 28.4 ± 1.1 Ma was also obtained from the same dyke. It has been further documented by Anczkiewicz et al. (2001) that this concordant age postdates regional mica cooling ages and indicates a lack of any younger regional events capable of resetting the K-Ar system in mica. These workers have considered these alkaline dykes as part of the PAIP. As these two dates ($^{206}Pb/^{238}U$ zircon age of 29.26 ± 0.12 Ma and Ar-Ar muscovite age of 28.4 ± 1.1 Ma) of Anczkiewicz et al. (2001) are concordant with the K-Ar biotite dates of 31 ± 2 Ma of Le Bas et al. (1987), it is strongly suggested that the K-Ar biotite dates of 31 ± 2 Ma of Le Bas et al. (1987) reflect the formation rather than cooling ages. Fission-track age of zircon of 32.1 ± 1.9 Ma of Qureshi et al. (1991) from the Sillai Patti carbonatite also supports the episode of alkaline and carbonatitic magmatic activity in the Tertiary (Oligocene).

The fission-track dating on the apatite crystals from the Jambil carbonatite complex of Sillai Patti area conducted during this study, yielded a pooled age of 29.3 ± 1.2 Ma. This age is quite similar with the fission track age of 32.1 ± 1.9 Ma on zircon from the Sillai Patti carbonatite (Qureshi et al., 1991), K-Ar dates of 31 ± 2 Ma on biotites from the Loe-Shilman and Sillai Patti carbonatites (Le Bas et al., 1987) and $^{206}Pb/^{238}U$ age of 29.26 ± 0.12 Ma on single zircon and Ar-Ar muscovite age of 28.4 ± 1.1 Ma from one of the alkali granite dykes intruding the Swat granite gneisses near the Jambil carbonatite (Anczkiewicz et al., 2001). Wagner and Van den haute (1992) have pointed out that occurrence of concordant fission-track as well as other radiometric ages on co-existing minerals reflect formation ages. The strong resemblance of the fission-track apatite ages of this study with the fission-track as well as other high temperature radiometric age data from different localities of the alkaline belt strongly suggests that this date may also be the formation age. If such, it provides a strong proof for the occurrence of an Oligocene alkaline magmatic episode within this region of the northern Pakistan. Therefore, we also strongly support the idea of Le Bas et al. (1987) of emplacement of all the carbonatites and the associated alkaline rocks of the PAIP of the northern Pakistan in two alkaline magmatic episodes such as (i) Carboniferous and (ii) (Tertiary) Oligocene.

This comparison shows that the Loe-Shilman, Sillai Patti, Jawar and Jambil carbonatites of the PAIP have been emplaced during the Tertiary (Oligocene) alkaline and carbonatitic magmatic episode and, therefore, negates the idea of the earlier workers of emplacement of these carbonatites in the Carboniferous episode. All these four carbonatite deposits have probably been formed from a carbonatitic magma intruded to a shallower level within the upper crust just about 2-3 km deep from the Earth's surface.

Our opinion about the presence of the mineral epidote in the Sillai Patti carbonatite complex and the associated silicate rocks is different from that of Butt et al. (1989), who consider its formation in response to the involvement of the complex in the Himalayan metamorphic and orogenic episode. Epidote is also a product of weathering of various minerals like feldspars, micas, pyroxenes, amphiboles and garnet (Kraus et al., 1959; The 1911 Edition Encyclopedia). Epidote's formation can also take place at 150 °C during the greenschist facies metamorphism (Wallendahl & Treiman, 2004). This temperature seems to be significantly lower than the blocking temperature of K-Ar in biotite and, therefore, may not be capable of resetting the K-Ar clock in the mineral biotite.

CONCLUSIONS

The following conclusions have been drawn from the fission-track apatite ages study and its comparison with the other higher temperature radiometric ages:

1. The carbonatitic magmatic activity within the PAIP occurred in at least two episodes (i.e., Carboniferous and Tertiary (Oligocene). The Koga carbonatites were emplaced in the Carboniferous, while the Loe-Shilman, Sillai Patti, Jambil and Jawar carbonatites were emplaced in the Oligocene.

2. The mineral epidote in the Sillai Patti carbonatite may possibly have been formed at a temperature 150 °C. This temperature is significantly lower than the blocking temperature of K-Ar in biotite and, therefore, may not be capable of resetting the K-Ar clock in the mineral biotite.

3. The fission-track apatite age of the Jambil and the fission-track zircon age of the Sillai Patti carbonatites are formation ages of these complexes.

4. As emplacement of the Loe-Shilman and Sillai Patti carbonatite complexes took place at the end of the Himalayan metamorphic episode the emplacement of the Jambil carbonatite may also have taken place at the same time.

Acknowledgments: The authors are highly thankful to Pakistan Science Foundation (PSF) for providing financial support for carrying out the present research under a Research Contract No. PSF/Res/ C-PINSTECH/EARTH (69). The help of Mr. Ashiq Hussain, Sr. Technician, in irradiating the samples and Mr. Qamar Abbas, Draftsman, in drawing the maps and figures are also acknowledged.

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