Exhumation History and Tectonics across Purulia – Bankura Shear Zone: Constraints from Apatite Fission Track Analysis.

Amal Kumar Ghosh
Department of Physics, Bhagwant University, Ajmer – 305 004
Email: ghosh.971@gmail.com

Abstract
The Purulia-Bankura Shear Zone (TPSZ) is a ductile- to-brittle-ductile, tectonically disturbed narrow zone of nearly 150 Km with a WNW-ESE trend. Two different rock assemblages, the Chhotanagpur Gneissic complex and rocks of the Shinbhum Group (SG) Occur on opposite sides of this shear zone. The TPSZ borders the Meso-Proterozoic greenschist facies litho-package of the SG, which is comprised of meta sedimentary rocks, felsic volcanics, mafics/ultramafics, granitoids and an alkaline/carbonatite suite of rocks. The Chotanagpur Gneissic Complex contains amphibolites to granulite facies in the north mafic-ultramafic suites of rocks that are in close proximity to felsic volcanics, suggesting a bimodal character of magmatic episodes. The TPSZ was subjected to a compressional regime, and its development is attributed to thrusting and wrenching. The area initially underwent rifting, volcanism, granite plutonism, and shallow sedimentation followed by shearing. The possible reactivation and exhumation history of the area was analyzed using apatite fission tracks (AFT). Offset of AFT ages between the two rock assemblages occur on the two sides of this shear zone, indicating that reactivation occurred due to over-thrusting at approximately 500 Ma, which is further supported by the results of thermal history models. The youngest AFT age of 260 Ma means that this age is a result of the entire thermal history of the sample. Furthermore, samples from Sushina hills indicate AFT ages decreasing towards Beldih via Chirugora. We interpret this to be an effect of motion along this shear zone. The thermal history indicates that the samples were rapidly exhumed at 600 Ma, given that the samples were cooled rapidly and subsequently re-heated; therefore, a cooling-only history is impossible. Denudations are predominantly controlled by tectonic processes and to a lesser degree, by erosional processes. Most of the sample ages are in the 200-to 300 Ma range, but their track-lengths are quite short, providing thermal history information before 600 Ma.

1. Introduction
A state of stress may influence a development of the basins, especially intraplate stress. This stress could be compression stress which could produce relative uplift of the basin flank, subsidence at the basin centre, and seaward migration of the shoreline. Increasing the level of tensional stress however, induces widening of the basin, subsidence of the basin flank, and thus causes landward migration of the shoreline (Kooi and Cloetingh, 1992).

Therefore, a rifting activity which involves crustal stretching by tensional stress either acceleration of subsidence would certainly give effects to the basin flank and shifting of the shoreline. Continental rifting cannot be solely regarded as a responsible factor for repeated faults reactivation and uplift. Another factor which triggers the faults reactivation may be derived by the latest phase of pre-drift extension (Redfield et al. 2005).

Subduction carries fluids, sediments, oceanic crust, and offscraped continental crust towards the Earth’s interior, and may cause accretion and magmatic activity. These processes lead to forearc deformation, faulting, mountain building, and ultimately to continental growth and destruction. In addition, all continental margins also experience erosion, which is controlled by climate, tectonic uplift, and the development of morphology (Burbank 2002, Bonnet and Crave 2003).

Erosion is a mechanism that enables exhumation and, more generally, vertical movements of rocks within the crust (Ring et al, 1999, Willet et al. 2003). Thus, for a full understanding of margin dynamics, information on the timing and kinematics of deformation from the rock record has to be linked with quantitative constraints on exhumation histories of individual geologic units within a marginal basin.

A shear zone is regarded as a planar zone of concentrated, dominantly simple shear deformation and accommodates, partly or wholly, an imposed regional or local strain rate, which the country rock cannot accommodate by bulk deformation (Ramsay, 1980; Ramsay and Huber, 1983, 1985). The shear zone is thus a general term for a relatively narrow zone with sub-parallel boundaries in which shear strain is localized. Most shear zones rise from depth commonly taking the basement rocks up to the surface.

The Singhbhum Group of rocks and the Chhotanagpur Gneissic Complex (CGC) that belong to distinct geological domains are in contact with each other along a tectonically distributed dislocation zone, viz. Purulia-Bankura Shear Zone or the Tamar-Porapahar Shear Zone (TPSZ), located to the north of Singhbhum Shear Zone (Fig. 2). A marked tectonic control is evident in the disposition of this shear zone as they are restricted to the peripheral zones of the
cratonic area (CGC) bordering the Singhbhum Group of rocks. The WNW-ESE lineament is marked to have extended from Porapahar in the East in the district of Bankura to Tamar in the West in the district of Ranchi through Sushina, Chirugora, Kutni, Mednitar and Beldih in the district of Purulia.

The tract of TPSZ is exposed in the surface by almost continuous signature of cataclastic movement resulting in brecciation, grinding, fracturing, shearing, mylonitisation indicating the nature of disturbance along this zone. At places, this shear zone passes either through rocks of Singhbhum Group or Chhotanagpur Gneissic Complex. Several parallel (sympathetic) shears are developed between the Dalma volcanic and the Tamar Porapahar Shear Zone. The formations north of Archaean cratonic margin (Singhbhum Granite Complex) and south of the Chhotanagpur Granite Gneissic Complex are now referred as ‘North Singhbhum Mobile Belt’(NSMB), which evolved during Proterozoic.

The five well-developed zones in the Eastern Singhbhum lose their identity in the western part. The Chaibasa Formation and Dhalbhum formation are folded into overturned ‘Singhbhum Anticlinorium’ and Dalma Synclinorium’ with E-W trending sub-horizontal axis. The southern (overturned) limb of the anticlinorium is sheared and overthrust upon the younger rocks of Iron Ore Group in the south. This overthrusting has given rise to a major shear zone which is termed ‘Copper Belt Thrust’ or Singhbhum Shear Zone’. The area adjoining the shear zone throughout the belt are affected by three phases of deformation. This shear zone consists of number of thrust planes with variable upward displacement of the northern block (Naha, 1994 Lind references therein). A number of cross faults are also known to have displaced the shear zone.

From the structural pattern worked out in different parts of Chhotanagpur Granite Gniess Terrain, it is seen that the rocks of the area bear imprints of three generations of deformations producing distinctive folds and related linear and planar fabrics. The rocks of CGC have witnessed several period of magmatism, tectonism, sedimentation, metamorphism, partial melting and mineralization.

Thus, the intense deformation in CGC and SSZ and the thrust sense of movement of northern block(CGC) towards south over southern block(Singhbhum Group) point to a complex exhumation history. Again, the rocks of TPSZ had suffered brecciation, grinding, deeper fracturing and intense shearing. The development of the basin may be attributed to the thrusting and wrenching (A. Acharyya et al.,2006). Hence, it is unknown to what extent the TPSZ
was affected by the intense deformation in the area adjoining this shear zone and how this might have been influenced by the number of cross faults which have displaced the SSZ.

Thus, TPSZ is a particularly well-suited area to study long term margin evolution and mass transfer patterns. The present fission-track reconnaissance study in the TPSZ addresses several key topics of current interest. The core aims of this study are to understand the burial and exhumation history of Purulia - Bankura Shear Zone (TPSZ). It is also attempted to determine the timing of possible vertical movement of the TPSZ. The possible reactivation could be reflected by an offset of Apatite Fission Track (AFT) ages between two tectonical rock assemblages. Another objective of this study is to unravel the thermal histories of the rocks in the study area, to obtain new insight in the exhumation history. To meet these we conducted an apatite fission track thermochronology study because fission track analysis yields age information on low-temperature increments of the cooling history of rocks. Given the thermal history of the upper crust is well constrained, fission track ages may provide quantitative estimates on erosional and tectonic exhumation, on tectonic movements at fault zones, and on the thermal evolution of sedimentary basins (Gallaghar et al. 1998 and references therein).

2. Geological setting

The Eastern Indian shield is well known for the Archean cratonic batholith of Singhbhum granite (3.2 – 2.7 Ga) encircled in the north by Dalma greenstones (1.6 Ga, Sakar & Saha, 1962), which is a part of the 200-km long, 50-km wide, North Singhbhum Mobile Belt (Fig.1). The North Singhbhum Mobile Belt (NSMB) is delimited in its southern periphery by the famous Singhbhum Shear Zone (SSZ) that is characterized by intense ductile shearing/thrust with rich copper-uranium mineralization. The thrust belt affects a host of rock types, including the Singhbhum Group, the Iron Ore Group (IOG), and the Dhanjori volcanics. The NSMB in its northern margin has a tectonic boundary with the Chhotanagpur Gneissic Complex (CGC) along the Tamar-Porapahar (TP) lineament/South Purulia Shear Zone. The lithological assemblage south of the CGC represents suites of the Singhbhum Group (Fig. 1). In the Purulia and Bankura districts, the CGC is composed largely of migmatites, granite gneiss, psammite, calc-granulite, amphibolite, and metadolerite with small granulatic patches of khondalite, charnockite and anorthosite, which in turn is intruded by granite and mica pegmatites of later ages. Along the shear zone alkaline, alkaline ultrabasic rock and carbonatite occur intermittently for approximately 35km. indicating their close genetic relationship (Roy, 1941; Inogradov et al. 1964; Gupta et. Al., 1971, Bhattacharya, 1976; Roy Burman
and Nandi, 1978; Ghosh Roy and Sengupta, 1988; Banerji, 1988; Majumdar, 1988; Bhattachayra and Das Gupta, 1992).

The presence of quartz-kyanite and kyanitic rocks near both the shear zones signify that there were clay-rich horizons. However, Sarkar et al. (1988) supported that the tectonic evolution of the CGC occurred as a consequence of the subduction of the oceanic lithosphere of the Singhbhum micro-plate and the process continued up to the Late Proterozoic. (2300 Ma – 850 Ma). The subducted block experienced subsequent prolonged geodynamic and geochemical processes. In these metallogenic domains, zones of rifting and upward movement of mafic melts to the surface with or without strong vertical displacement and horizontal compression led to the emplacement of Fe, Mn, Cr, V, Ti, Au and asbestos (Banerjee, 1988; Deb and Roy, 1988). Gorumaheshani volcanics and associated Banded Iron Formation occur in faulted blocks within the Singhbhum granite. These features are extensively intersected by dikes of doleritic composition and intruded by V-Ti rich gabbro anorthosites. A resemblance to the ophiolitic composition of Sukinda, Nausahi, Bonai and Jujobatu volcanics (Banerjee 1988), and the anorthosite gabbro and granophyre intrusives in Singhbhum suggest the occurrence of rifting.

During the Archean to the Early Proterozoic, mantle-derived metallogenic phase was dominant, which changed over to a rust-derived metallogenic epoch towards the Middle Proterozoic in Singhbhum and adjoining parts of West Bengal (Banerjee, 1988). The available geochronological data suggest that polymineralization occurred in stages mostly in the Early-Mid Proterozoic times approximately 1600 Ma (Fruncheteau et al. 1979; Bostrom and Peterson, 1965; Scott et al., 1974). Geochronological data are scarce from this Shear Zone. Felsic volcanics from Ankro (approximately 8 km south of the SPSZ) has been dated to be1500 Ma by the Rb-Sr whole rock method (Sarkar and Ghosh Roy, 1999) and the same rock near Chandil, north of the Dalma Volcanics, yielded a Rb-Sr whole rock age of 1484 ± 44 Ma (Sengupta et al. 2000). Gabbro-Pyroxenite rock north of Dalma was dated to be 1619 Ma (Rb-Sr date, Roy et al. 1999) near Kunchea.

The nature of the Shear Zone has been described as ductile to brittle-ductile (Pyne, 1992, Bhattacharya,1989,Acharyya and Ray, 2004). Shearing has been demonstrated to be syn to post-kinematic to F1 folds with concomitant development of mylonitic fabric. Mylonitic foliation has been found to act as the form surface of F2 folds. Micro-structural study revealed a thrust sense of movement of northern block (CGC) towards the south over the southern block (Singhbhum Group).
2.1 Structural Features

Quartz-reef/quartz-breccia/quartzite–mylonites are linearly arranged in low-lying as well as elevated ridge-forming expressions (near Sarberiya) demarcating the pronounced lineament of the TPSZ. The composite S1 – S2 foliation and mylonitic foliation are the dominant structural grains in the area. S1 parallels the mylonitic foliation, which also acted as a form of surface to F2 folds, producing regional antiform and synform E-W axial trace. Shear Zones had been developed syn to post-kinematic to F1. The entire packet of litho-assemblage from augen gneiss of CGC in the north of the quartz mica-schist of the Singhbhum Group in the south bears imprints of ductile shearing. Shear indicators such as C-C'/S-C-C' fabric are identified, in addition to downdip stretching lineations. The ductile shear zone represents a pronounced thrust type of the movement tectonics demonstrated by clear-cut downdip stretching lineation on the S1/mylonitic foliation plane in quartzite-mylonite, Biramdih gneiss, Felsic volcanics. A wide area along the zone is markedly dominated by voluminous felsic volcanics, which were earlier described as phyllites and schist. The mode of deposition of the facies A, B, or C might be due to the pyroclastic process, but compositional homogeneity is a notable feature pointing against an admixed epiclastic process. The repetitive layers of the tuffaceous volcaniclastic (Facies A) represent the variation in the pyroclastic facies B and C. In the course of geological evolution of the lithopackage of this shear zone, successive emplacement of felsic volcanism and granite plutionism was eventually followed by deposition of sedimentary litho-units such as quartzite mica-quartz schist and metagreywacke.

After the rocks came into place, the basin started closing with an F1 folding deformation, which, during its culmination stage, produced the shear zone. The shear zone is characterized by downdip stretching lineations on the S1 foliation surface. Shear indicators present in ignimbrite quartzite and mylonite indicated thrusting of the northern block towards the south over the southern block. The near horizontal fabric in the augen gneiss and granite mylonite might suggest an additional tectonic component. The variation in tectonic fabric (downdip versus near horizontal) may be explained as combining ductile thrusting and wrenching during progressive shortening of the area (Lagardo and Michard, 1986). In the subsequent folding deformation event, the mylonitic fabric became folded and S1 foliation crenulated during F2 when regional antiform synforms with the E-W axial plane developed in the region.

A transition from the continental rift, developing into the incipient oceanic crust with continued lithospheric stretching, may be suggested (A. Acharyya et al. 2006). There have been a number of tectonic models advocated for NSMS (Sarkar, 1982, Sarkar et al. 1992; Bose; 1992). Bose (1992) opined that the entire setting resembles an
ensialic back arc basin. Gupta and Basu (2000) refuted the idea of back arc setting and indicated that it only takes into account the second stage of Wilson’s cycle without any reference to the first stage. It appears that the intracratonic rifting and ensialic orogeny model proposed by Sarkal et al. (1992) and Basu (2000) for the mobile belt (NSMB) also applies for the TPSZ. A. Acharyya et al. (2006) advocated that the migmatized mica schist occurring as a marker all along the contact of CGC and SG might be representing an intracratonic crustal sag deposit. The Manbazar schist belt also represents a Trans-dalma low grade supracrustal that branches off the SPSZ (toward the northeast of Sindri) and again imply a crustal sag deposit (Mahadevan, 1992), which might have acted as a failed arm for later rifting sequel. The Manbazar Schist belt remained protected most likely for the reason that it was completely confined within the cratonic realm of the CGC. The crustal sags are suited for lithospheric weakness in the Proterozoic crust. Rifting could be initiated in such locales of pre-existing weakness (Dunbar and Sawyer, 1988). The presence of high volume of magmatization along this shear zone, the arcuate shape of the lineament following quartz reef, distinct tourmalinite, bands, absence of dyke, swarms etc. are all indicative of the rupture of the crust. This Shear Zone is approximately 30km north of the Spine of the Dalma Volcanics. Litho-characters of the Dalma range are typical of deep ruptures of a rift where oceanic crust had formed (report of pillow lava, agglomerate, felsic tuff etc. are common). The margins of the rift should be shallower where silicic volcanism abounds. A. Acharyya et al. assumed that the entire rift zone spans from the northern limit of the SPSZ to the southern limit of the SSZ, with the Dalma range representing the deepest axis of the rift. Records from similar settings in other parts of the world are also encouraging. In the Proterozoic Mid-continental Rift, U.S.A., the flows are chiefly felsic ignimbrite and basalt (Allen et al. 1995). Even in a modern day rift setting, ignimbrites are the predominant rock type (60% by volume), as recorded in the Oslo-rift (Neumann et al. 1995). The range of felsic ignimbrite in the present setting includes dacite, andesite and rhyolite. In a similar trend, the San Pedro volcanic craton produced multiple voluminous, heterogeneously mingled units (dacite-andesite, dacite-basalt-andesite-rhyolite) indicating that shallow silicic magma chambers were repeatedly established and then intruded by new inputs of mafic magma (Dungan et al. 2001). This behavior also implies that rifting was operative at the site of ignimbrite ponding. Integrating the sequence of events along this Shear Zone, it essentially involves an initial crustal sagging for the deposition of supracrustal, which is followed by the initiation of rifting in an ensialic resident crust with the formation of narrow basin, primarily ponded with felsic volcanics and granites. This sequence was followed by development of deeper fractures and pouring of mafic/ultramafic rocks, with the subsequent tapping of
syenites, alkali feldspar granites and carbonatites. The granite plutonism, felsic volcanism, boron effusion and pouring of ultramafic extrusive/intrusive happened to be the early phase of crustal tectonic activity, followed by shallow sedimentation (at places volcanogenic, epiclastic) occurring as veneers over igneous suites. The basin was then subjected to the compressional regime, and the development of the Shear Zone (TPSZ) may be attributed to the thrusting and wrenching along this lineament.

Hence, a total sequence of basin initiation by rifting, volcanism, granite plutonism, sedimentation followed by shearing at the close of the basin is preserved in this setting. It would be appropriate to reconcile the Central Indian Tectonic Zone (CITZ) as presenting a magma-event in the Meso-Proterozoic of Indian peninsula.
3. Method and sampling strategy

Every solid material, once it is penetrated by nuclear particles, will obtain linear trails of disrupted atoms, which also reflect damage on the atomic scale. Fission tracks are such a damage feature. The emerged features are produced by spontaneous fission of $^{238}\text{U}$ (Gallagher et al., 1998). In general, fission track dating is similar to the other dating methods that rely on the same equation of radioactive decay, i.e., estimating the abundance both of the parent and the daughter isotope. In fission track analysis, the age corresponds to the number of $^{238}\text{U}$ atoms and the number of spontaneous tracks per unit volume. To obtain the number of spontaneous tracks, we simply count the number of spontaneous fission tracks on a given surface of a mineral grain. Meanwhile, the abundance of $^{238}\text{U}$ can is determined by irradiating the samples with low energy thermal neutrons to induce fission of $^{238}\text{U}$. By controlling the thermal neutron flux, we obtain the number of ‘induced tracks’, which also signified the abundance of $^{238}\text{U}$. Because the ratio of the $^{238}\text{U}/^{238}\text{U}$ is constant, we are able to estimate the abundance of $^{238}\text{U}$ (Gallagher et al. 1998).

Fission tracks are meta-stable features, i.e., the tracks can fade or be annealed. The annealing of the tracks can cause the tracks to shorten. Therefore, length track distribution is a fundamental parameter in the fission track analysis. Several factors that influence annealing are temperature, time, pressure, chemical composition and ionizing radiation (Fleischer et al., 1965b). However, temperature combined with time is the greatest contributing factor for the annealing. Therefore, the track length distribution contains information of the thermal history of the analyzing samples (Gallagher et al., 1998). Recently, applications using fission track analysis are widely known to solve geological problems. This thermo-chronology method is rather exceptional compared to other methods, whereas the temperature dependence of the annealing of the fission tracks provides information of the thermal history. Various geological problems can be unraveled by this method, such as the thermal history of sedimentary basins, sedimentary provenance, the structural evolution of orogens, the continental margin development, and long-term denudation on continents (Gallagher et al. 1998). Based on the kinetic indicators, AFT ages and track length data, the thermal histories of seven samples were modeled using HeFTy (Ketcham, 2013, Version 1.8.1). Forward modeling was used to test the possible time-temperature paths indicated by the AFT ages and the track length distribution. The start of the thermal history models for all samples considered was set to a nearly high temperature...
constraint (near 600 Ma) keeping in mind a particular hypothesis to be tested. We took samples from two rock assemblages that occur on the two sides of the shear zone, targeting a possible reactivation to be revealed. The samples of BAP(S), BAP-20, and BAP-168, were collected from Beldih; CAP was collected from Chirugorah; and SAP was collected from Sushina (Fig. 2). These samples belong to the Singhbhum Group of rocks. The samples of BAN-1 and BAN-2 were collected from Mochrakend, Majhia and Bangalipara, Majhia, respectively (Fig. 2). These samples belong to the West Bengal part of the CGC block. We took samples along the shear zone, e.g., BAP(s), Bap-20, Bap-168, CAP and SAP to understand the effect of motion of the shear zone. A few general observations can be made about the application of the approach to understanding exhumation. First, the evolution of exhumation is best evaluated when samples are collected from a well-dated stratigraphic section that spans the exhumation event. Second, a condensed section from the perimeter of the basin is most likely to preserve unrest detrital grains and therefore provide provenance information. This problem is especially acute for apatite. Third, during erosion, the removal of cover rocks or a ‘deadzone’ precedes the exposure of rocks with young cooling ages. Fourth, fast exhumation results in a short lag time and slow exhumation results in a long lag time. In this study, a rapid exhumation is exhibited by almost all of the thermal history models.

![Supplementary Geospatial Data](image_url)

**Figure 2: Location map of the studied area**
4. Discussion and Interpretation.

Five samples from the Singhbhum Group of rocks and two samples from the Chhotanagpur Gneissic block were analyzed, and the results are shown in table 1 (see also Appendix A). Seven thermal history models are also discussed. Here, a possible exhumation history along this shear zone is proposed based on the AFT ages and the thermal history. A minimum of 15 grains were selected to achieve a satisfactory age measurement. The large age errors, e.g., 14.25%, 12.76%, 11.05% and 10.85%, are found in samples SAP, BAP(s), BAN-1 and CAP, respectively. As already known, low Uranium samples present a problem because of low induced track densities. The P (X²) test was performed to measure the Uranium variation in the samples. A value of P(X²) larger than 5% means that the grains are assumed to be a single age. Four samples, BAP(s), SAP, CAP and BAN, failed the X² test, which may indicate bimodal distributions for the samples. Track length measurements were performed for seven samples: five samples from Singhbhum Group (BAP(s), CAP, SAP, BAP-20 and BAP-168) and two samples from Chhotanagpur Gneissic Complex (BAN-1 and BAN-2). The sample ages from the Singhbhum Group are in the 200-300 Ma range, but the MTLs are quite short, so samples contain information on the thermal histories before 600 Ma (Richard Ketcham, personal communication). The short track lengths indicate a possibly more complex thermal history. The value of D par are dominated by low values in the range of 1.15-1.49 µm. Carlson et al. (1999) affirmed that the D par value of less than 1.75 µm anneals rapidly, which is also typical for the near-end members of calcian-fluorapatites. The fluorapatites member has been known to be less resistant to anneal than cl-apatite (Gleadow & Duddy, 1081). According to Kelcham et al. (1999) the fission track with D par = 1.5 µm, cl = 0 wt%, experience a total loss of tracks in the range of 100⁰C-110⁰C in the geological environment. Hence, it can be inferred that these samples approximately have the properties of low Cl and OH, high F content and rapid annealing and are most likely typical for Calcian-fluorapatites.

By applying apatite fission track analysis, the possible reactivation of the TPSZ was attempted to be revealed, which could be reflected by an offset of the Apatite Fission Track (AFT) age between the two rock assemblages that occur on the two sides of the shear zone. Seven thermal history models were also developed to unravel the thermal histories of the rocks in the study area.
The AFT ages exhibit a significant difference between the two block, where as the samples that were taken from the Singhbhum Group of rocks have AFT ages in the range from 260 Ma- 535 Ma, with a weighted mean age of 325.67 Ma (Carboniferous). Meanwhile, from the West Bengal part of the Chhotanagpur Gneissic Complex block is obtained AFT ages in the range of 453.22 Ma -407.034 Ma with a weighted mean of 430.13 Ma (late Silurian-Early Silurian time). Fault movements, which postdate the formation of particular profile of apparent fission track age with depth, will disrupt and offset the apparent fission track ‘stratigraphy’. Discontinuities may then be observed in the regional pattern of the apparent ages, which will reveal the presence of such fault movements and place constraints on the timing of the movement. The time represented by the youngest apparent age so revealed will place a maximum constraint on the time of the fault movement. Quite apart from the time constraints, the observed fission track pattern may provide valuable structural information, especially in rocks where no clear structural markers exist (Gleadow). Interpreting the AFT age is very seldom a straightforward process. The youngest age “will place a maximum constraint” on the timing and not provide an estimate for that timing (Richard Ketcham, personal communication). In the case of all of my samples, the track lengths are shortened, which reduces the fission-track age compared to a sample that has gone through no partial annealing. Thus, even though the youngest age of the sample is 260 Ma, the event that offset it from rocks across the shear zone and/or brought it into the temperature regime that allows fission tracks to be retained could have been much earlier. In our HeFTy models, seldom is an “event” found that corresponds to the youngest age (260 Ma); in all cases where the lengths are substantially shortened, the age (260 Ma) is a result of the entire thermal history of the sample, not just one instant in time. The oldest mean AFT age indicates that the reactivation of TPSZ occurred due to over-thrusting near 500 Ma (Late Cambrian time), which is further supported by the results of the thermal history models. For the reactivation corresponding to near 500 Ma, the event that resulted in these rocks cooling enough to start retaining fission tracks could have been much earlier. Further, the samples from Sushina hills exhibit an AFT age decreasing towards Beldih via Chirugora. We interpret this behavior as an effect of motion along this shear zone. The result of the thermal history model indicates that almost all of the forward models have rapid cooling from high temperature to a surface temperature near 600 Ma. A very rapid cooling mainly subsequently occurred due to volcanic activity, hydrothermal activity (Duddy et al. 1998), dyke displacement, faulting or meteorite impact (Miller & Wagner, 1979), and volcanic activity (Ketcham, personal communication). It is inferred that Exhumation caused reactivation
of this shear zone at 600 Ma due to volcanic activity. Samples are then re-heated near 500 Ma, which is referred to
as a burial event; it may also reflect over-thrusting near 500 Ma.

This age is in good accordance with the age of reactivation constrained from the AFT ages between the two rock
assemblages. As a result, the cause of reactivation may be attributed to the over-thrusting. Because the samples were
cooled and then re-heated, cooling-only history is impossible to obtain. The cooling event may be interpreted to
have occurred due to mainly a tectonic process.

In BAP-20, we have the present-day temperature at approximately 65 degrees. This sample was collected at depth
of 20m. It is most likely impossible to say definitely how many times the samples entered the PAZ. Moreover, the
hypothesis, e.g., the duration of the residence of the samples in the PAZ, cooling rate, linear or non-linear cooling,
over printing and bimodal distribution, are quite impossible to infer because the thermal history models indicate that
the samples are cooled rapidly and then re-heated. As a result, cooling-only history is impossible to determine.

5. Apatite Description

Generally, the whole samples display fair-good apatite quality. Several particular features on the apatite, however
could lead to possible errors in the counting. Typical features are; bad grain surface, wide cracks, zoning whereas
uranium is concentrated in clusters, thus the tracks are distributed unevenly on the grain, dislocations, and very low
or very high uranium content (Fig. 3)
Fig. 3: Several defect features occurred on my apatite samples. These defects lead to possible errors in the counting. They are; (a) & (c) low uranium concentration results rare fission tracks, (b) dislocation features (marked by arrow)
Fig. 4. Induced Track Imprinted on Mica Sheet
Results of AFT analyses: ages calculated using dosimeter glass IRMM-540R with 15ppm U, zeta = 250, irradiated at FRMII, calibrated by traditional zeta approach and external detector method, N=Number of grains, ρ – track densities given in 10^5 tr cm^-2, ρ_d – dosimeter track density, N_d – number of tracks counted on dosimeter, ρ_s(N_i) – spontaneous (induced) track densities, N_s(N_i) – number of counted spontaneous (induced) tracks, Pr(χ^2) – probability for obtaining χ^2 value for n degrees of freedom, where n=no. of grain – 1, MTL – mean track length, SD – Standard deviation.

6. Conclusion

The largest age error (14.52%) occurs in sample SAP. This high error is most likely due to a very low uranium concentration (0.68 ppm). As already known, low uranium samples place limits on how robust the ages could be. In low uranium samples, an exact match between the areas counted in the grains and the mica is often hard to achieve. An adjustment by eye is difficult and subjective because the outline of the induced tracks on the mica does not reflect the shape of the analyzed grain.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Rock Type</th>
<th>Depth (m)</th>
<th>No. of Grains (N)</th>
<th>Dosimeter</th>
<th>Spontaneous</th>
<th>Induced</th>
<th>Pr(χ^2) (%)</th>
<th>U (ppm)</th>
<th>Mean Age (Ma)</th>
<th>MTL (µm)</th>
<th>SD</th>
<th>No. of Tracks</th>
<th>D_est</th>
<th>Error(%) on Mean Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singhbhum Group</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BAP(S) Breccia with fibrous apatite veins</td>
<td>NA</td>
<td>15</td>
<td>19.25</td>
<td>1232</td>
<td>0.98379</td>
<td>136</td>
<td>0.88975</td>
<td>123</td>
<td>0.64</td>
<td>0.42</td>
<td>260.51</td>
<td>11.01</td>
<td>NA</td>
<td>80</td>
</tr>
<tr>
<td>CAP Apatite - Magnetite</td>
<td>NA</td>
<td>18</td>
<td>19.25</td>
<td>1232</td>
<td>1.2779</td>
<td>212</td>
<td>0.9645</td>
<td>160</td>
<td>2.23</td>
<td>0.45</td>
<td>306.96</td>
<td>10.99</td>
<td>NA</td>
<td>90</td>
</tr>
<tr>
<td>SAP Syenite</td>
<td>NA</td>
<td>15</td>
<td>19.25</td>
<td>1232</td>
<td>3.25</td>
<td>156</td>
<td>1.45833</td>
<td>70</td>
<td>0.33</td>
<td>0.68</td>
<td>535.25</td>
<td>10.75</td>
<td>NA</td>
<td>80</td>
</tr>
<tr>
<td>BAP-20</td>
<td>NA</td>
<td>20</td>
<td>18</td>
<td>19.25</td>
<td>1232</td>
<td>3.67717</td>
<td>610</td>
<td>3.35768</td>
<td>557</td>
<td>11.64</td>
<td>1.56</td>
<td>281.56</td>
<td>9.84</td>
<td>NA</td>
</tr>
<tr>
<td>BAP-168</td>
<td>NA</td>
<td>168</td>
<td>16</td>
<td>19.25</td>
<td>1232</td>
<td>1.74967</td>
<td>258</td>
<td>2.00059</td>
<td>295</td>
<td>24.63</td>
<td>0.94</td>
<td>244.06</td>
<td>10.96</td>
<td>NA</td>
</tr>
</tbody>
</table>

West Bengal part of CGC Block

| BAN-1 Granite | NA | 15 | 19.25 | 1232 | 1.552 | 215 | 1.0706 | 148 | 3.29 | 0.50 | 406.70 | 10.46 | NA | 75 | 1.29 | 11.05 |
| BAN-2 Granite | NA | 15 | 19.25 | 1232 | 3.7109 | 513 | 2.5535 | 353 | 16.20 | 1.19 | 453.22 | 10 | NA | 75 | 1.19 | 7.48 |
Track lengths were measured using a calibrated eye-piece graticule and stage micrometer with significantly poorer resolution compared to digitizing tablet. The precisions of individual fission-track length and angle to c-axis measurements are approximately 0.15µm (1σ) and 2° (1σ) respectively (Donelick 1991). Measurements of etch pit diameters were carried out both the parallel (Dpar) and perpendicular to the c-axis (Dper). However, the values of Dper are ignored because of imprecise measurements reasons. It is unlikely to obtain an accurate measurement of Dper using an optical microscope with the magnification which was used in this study.

A failure of a positive correlation between the AFT ages and the MTL occurred because the track length is determined rather by the thermal history than the fission track ages. This occurs remarkably in complex cooling histories, whereas the pre-existing tracks will be shortened in significant time. If cooling histories are more complex thus also produce more complex length distribution (Gleadow et al., 1986).

In this study, we attempted to unravel the exhumation history in the Purulia - Bankura Shear Zone (TPSZ) by means of a low temperature thermo-chronological technique, i.e., the apatite fission track analysis; we also attempted to determine the patterns and timing of possible vertical movements along the TPSZ. This possible reactivation could be reflected by an offset of the Apatite Fission track (AFT) ages between two distinct tectonical geological domains that occur on the two sides of the TPSZ in combination with the structural data and the geological data. Another attempt of this study was to unravel the thermal histories of the rocks in this study area to obtain new insight into the exhumation and uplift history of the TPSZ.

Samples taken from the Singhbhum Group of rocks have AFT ages in the range from 260 Ma – 535 Ma, with a weighted mean age of 325.67 Ma (Carboniferous). Meanwhile, the West Bengal part of Chhotanagpur Gneissic block has AFT ages in the range from 453.22Ma – 407.034Ma, with a weighted mean of 430.13 Ma (Late Silurian - Early Silurian time). The thermal histories have been modeled from seven samples: five samples from the Singhbhum Group and two samples from Chhotanagpur Gneissic complex.

The thermal history models indicate that the cooling-only history is impossible to determine. The models also indicate that samples contain information on the thermal histories before 600 Ma. The AFT ages of the samples from the Singhbhum Group indicate the effect of the motion along the TPSZ. Exhumation due to volcanic activity
caused reactivation of the TPSZ at 600Ma. Denudation was dominantly controlled by a tectonic process and to a lesser degree by an erosional process.

The youngest age of the sample (260 Ma) is a result of the entire thermal history of the sample, not just one instant in time. The reactivation of the TPSZ occurred due to over-thrusting near 500Ma (Late Cambrian time).

**Fig. 5(a). Thermal History Models from Singhbhum Group of Rocks**

<table>
<thead>
<tr>
<th>Sample Name: BAP (S)</th>
<th>Model: 261</th>
<th>Measured: 261 +74/-58</th>
<th>GOF: 1.00</th>
<th>Model: 11.49 ± 1.73 µm</th>
<th>Measured: 11.02 ± 1.72 µm</th>
<th>GOF: 0.77</th>
</tr>
</thead>
</table>

**Model**: 261  
**Measured**: 261 +74/-58  
**GOF**: 1.00  

**Model**: 11.49 ± 1.73 µm  
**Measured**: 11.02 ± 1.72 µm  
**GOF**: 0.77
Sample Name: BAP – 20

<table>
<thead>
<tr>
<th>Model</th>
<th>Measured</th>
<th>GOF</th>
<th>Model</th>
<th>Measured</th>
<th>GOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>258</td>
<td>258 +35/-31</td>
<td>1.00</td>
<td>9.75 ± 1.96µm</td>
<td>9.89 ± 1.58µm</td>
<td>0.41</td>
</tr>
</tbody>
</table>

---

**Time-Temperature History**

**AFT: Track Length Distribution**
Sample Name: BAP – 168

Model: 207
Measured: 207 +38 / -32
GOF: 1.00

Model: 10.56 ± 1.98 µm
Measured: 10.87 ± 1.68 µm
GOF: 0.73
Sample Name: CAP

Model: 311
Measured: 311 + 73/ -60
GOF: 1.00

Model: 11.66 ± 1.73 µm
Measured: 10.99 ± 1.90 µm
GOF: 0.45
Sample Name: SAP

<table>
<thead>
<tr>
<th>Model</th>
<th>Measured</th>
<th>GOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>411</td>
<td>515 ±167 / -127</td>
<td>0.11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>Measured</th>
<th>GOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.64 ± 1.47 µm</td>
<td>10.75 ± 1.47 µm</td>
<td>0.70</td>
</tr>
</tbody>
</table>
Fig. 5(b). Thermal History Models from Chhotanagpur Gneissic Complex

Sample Name: BAN – 1

<table>
<thead>
<tr>
<th>Model</th>
<th>Measured</th>
<th>GOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>336</td>
<td>340 ± 82/66</td>
<td>0.91</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>Measured</th>
<th>GOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.88 ± 2.24 µm</td>
<td>10.33 ± 2.14 µm</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Sample Name: BAN – 2

<table>
<thead>
<tr>
<th></th>
<th>Model</th>
<th>Measured</th>
<th>GOF</th>
<th>Obs</th>
<th>Model</th>
<th>Measured</th>
<th>GOF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>338</td>
<td>341 ± 54/ -46</td>
<td>0.91</td>
<td>537</td>
<td>10.41 ± 1.69 µm</td>
<td>10.00 ± 1.68 µm</td>
<td>0.85</td>
</tr>
</tbody>
</table>
Acknowledgements

I thank Prof. Barry Paul Kohn, “University of Melbourne”, Australia for his overall support and advice throughout my time as a Ph.D. student. He also sent me age standard minerals (Durango apatite) for zeta calibration, free of charge. Without his contribution, my work would have never been possible.

I thank Prof. Richard Ketcham “University of Texas”, U.S.A., who kindly reviewed my AFT models and provided valuable guidance for the improvement of the models.

Prof. Ketcham also kindly extended his help to offer the important interpretations of my AFT models and the offset AFT age. Prof. Ketcham sent me the copy of the most recent versions of the HeFTy (Ketcham, 2013, Version 1.8.1), free of charge.

I thank Prof. Paul B.O’ Sullivan, Apatite to Zircon, Inc., U.S.A., who kindly initiated my idea into the importance of obtaining the AFT data in the correct form. Prof. O’Sullivan also kindly advised me to contact Prof. Richard Ketcham.

My indebtedness to these professors knows no bounds.

I am highly indebted to the Director General of Geological Survey of India, 27, J.L. Nehru Road, Kolkata – 700 016, for his kind permission to perform my work in the laboratory of G.S.I, Kolkata.

I thank Mr. Partha Nag, Officer-in-Charge, WBMTDC, Purulia for his dedicated help with the field work.

I thank Mr. T-Ray Barman, Ex-Scientist, G.S.I, Kolkata, for his constructive advice.
Many thanks are due to the entire family of G.S.I., Kolkata, for their help and encouragement.

I thank the entire team of FRMII, Garching, Germany for providing me with use of the irradiation facility, free of charge.

**Appendix-A**

The samples for this study were processed in the laboratory of the Geological Survey of India, Kolkata, after obtaining permission from the Director General, GSI, Kolkata, West Bengal. The samples were prepared using standard separation, grinding and polishing techniques. All the samples were prepared for the external detector method. AFT mounts were etched with 70% HNO$_3$ at room temperature for 30 s and were irradiated in the thermal facilities of FRM II at Garching, Germany together with dosimeter glass IRMM-540R (15ppm). Mica sheets were etched using 48% HF at room temperature for 19 min. The fission tracks were counted under a total magnification of 1000x. The calibrated area of one grid is 0.64X 10^{-6} cm$^2$. The length and D par were measured using a stage micrometer and an ocular micrometer, with total magnification of 1000X.

Durango apatites were used as the age standard mineral, which was provided by Prof. Barry Paul Kohn, University of Melbourne, Australia. A copy of the HeFTy software was provided by Prof. Richard Ketcham, Texas University, U.S.A.

**Appendix B**

For modeling, 75 - 90 confined track lengths were used to fit the AFT data. 600 Ma is a reasonable starting point for thinking about modeling and a hypothesis we attempted to test (Richard Ketcham, personal communication).

**References**


