Fission Track Analysis and its Applications

Ming-Hung Kao
Taipei Astronomical Museum

ABSTRACT

Fission track analysis (FTA) is a very useful method in the thermal history study and dating impact/geological events. Fission track data provide not only numerical information of specific samples but also their thermal history. The FTA method has been applied widely in the following fields: (1) meteoroid impacts; (2) archaeological dating; (3) paleotemperature indicator; (4) tephrochronlogy; (5) sea-floor spreading; (6) tectonics; and so on.

The FTA principles, methodology, and techniques have been established in many papers. The main aims of this article are to discuss the FTA application and to provide one FTA example of tectonic study in Taiwan Orogeny. A constant denudation rate (~3.0 mm/yr) can be derived from fission-track data and other dating data of biotite K-Ar, and biotite Ar-Ar. The fission-track method may be compiled with different dating methods and extended its application in other fields.

Keywords: Fission track analysis, dating, meteoroid impacts, Taiwan Orogeny, biotite K-Ar, biotite Ar-Ar

1. Origin of latent fission tracks

The Decay of heavy radioactive elements (e.q. ^{232}Th, ^{235}U, and ^{238}U) will cause heavy charged particles to pass through insulating materials and leave trails of radiation damage within them (Silk and Barnes, 1959; Price and Walker, 1962a). Price and Walker (1962b) discovered that the damage trails could become stable and enlarged by chemical etching until they could be observed under an ordinary optical microscope (see Appendix I). Fleischer et al. (1965) defined that a latent track is a path of ionization-produced defects prevailed by vacancies and displaced atoms that reside in interstitial sites. The number of latent fission tracks (fossil tracks) in a uranium-bearing mineral depends on the mineral age and its uranium concentration. Because ^{235}U is less abundant than ^{238}U, (^{235}U/^{238}U) ≈ (1.3/137.8), latent fission tracks could be considered as resulting chiefly from the production of the spontaneous fission of ^{238}U.

2 Fission track dating

2.1 Identification of fission tracks

Fission tracks can be identified by these characteristics under microscopic observation. Differentiation between fission tracks and non-fission-tracks pits is very important in fission track dating. Fleischer and Price (1964) stated five key properties of etched fission tracks: (1) Etched fission tracks must be straight. (2) Etched fission tracks have a limited length; the maximum track length ranges between 10-20 μm. (3) Fission tracks should be randomly oriented, having no preferred relationship to a crystallographic direction. (4) Unetched fission tracks have limited thermal stability. (5) The distribution of spontaneous tracks should be statistically the same as that of induced tracks.

2.2 Fission track age equation

The fission track age equation is similar to that for other radiometric dating techniques. The density of fission tracks in a random cut surface through apatite or zircon depends on the uranium concentration of crystals, age and track length. When the thermal neutron fluence, spontaneous track density, and neutron-induced track density are confirmed, a fission track age of a sample can be determined by an age equation (Hurford and Green, 1983). In the determination of the fission track age, several dating procedures have been created and discussed in some publications (Fleischer et al, 1975; Naeser, 1979; Gleadow, 1981; Hurford and Green, 1982; Storzer and Wagner, 1982; Van den haute, 1986; Van den haute and Chambaudet, 1990).

2.3 Fission track annealing

Price and Walker (1963) discovered the phenomena of track-fading and noticed that both the number and mean length of fission tracks were reduced by heating. The annealing of fission tracks is a valuable characteristic in geologic dating. Because of fission track annealing, thermal history can be reconstructed according to the information recorded in the track lengths. In general, different minerals have different closure temperature". For example, the temperature of totally annealed apatite fission tracks ranges from 105°C to 150°C (Naeser, 1981); the temperature of totally annealed zircon fission tracks lies around 240 ± 40°C (Hurford, 1986).

2.4 Annealing factors

Fleischer et al. (1965) showed that track fading is essentially a function of temperature, with pressure, plastic deformation and highly ionizing radiation at upper crustal levels having little effect. It had been confirmed that a large dose of ionizing radiation has no effect on track annealing. Green et al. (1986) used confined fission track lengths to study the thermal annealing of induced fission tracks in a single fluorapatite crystal (Durango apatite). They concluded that the anisotropic characteristics of annealing, crystallographic orientation, chemical composition, and temperature are important factors in apatite fission track annealing. Clearly, the annealing process depends on temperature, chemical composition, and crystallographic orientation, and to a lesser extent. There is no doubt that temperature is the dominant control on fission-track annealing. Gleadow and Duddy (1981) showed that the temperature of apatite fission track annealing is significant between ~70°C and 125° C.

3. Application of fission track analysis

The application of the fission-track analysis would be described in this section. Many fission-track papers (Gleadow et al., 1983; Green et al., 1989a; Kamp and Green, 1990; Tippett and Kamp, 1993; Kamp et al., 1996; Kao, 2001,2002) have been published and can be refereed.

3.1 Meteoroid impacts

Fission-track dating is a suitable method for dating impact events. In the cases of many dated sites, impact glasses were usually used as fission-track recording material. The fission-track ages of the dated impact sites are given range from 4 ka to 300 Ma. In addition to the dating of impacts, fission-track studies can also reveal the thermal history of the rocks which were affected by the impact. This approach uses the degree of track annealing by the impact's heat as a geothermometer.

In principle, one has to distinguish three cases of possibilities with regard to the effect which an impact has on the pre-existing fission-track systems in the target rocks. For the first case, the temperatures are raised, but not high enough to cause any fission-track annealing. For the second case, the temperatures become high enough to cause partial track fading. For the third case, the temperatures become sufficiently high in order to cause complete track annealing. If the annealing characteristics of the fission-track systems under consideration are known and valid assumptions on the duration of heating can be made, the first possibility allows the assessment of an upper temperature limit, the second possibility allows the evaluation of the actual temperature reached and the third possibility allows - in addition to the determination of the impact's age - the assessment of a minimal temperature reached during the impact. When using different fission-track systems, such as apatite, zircon, and sphene from the same rock sample, the fission-track method enables the reconstruction of the thermal history in the temperature range between 100 and 500°C (Wagner and Haute, 1992)

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3.2 Archaeological dating

It is not difficulty to date obsidian with fission-track ages as low as a few thousand years. Minerals found in ceramics and burnt stones (archaeological samples) with a high uranium content can be used for fission-track dating. These minerals include zircon, monazite, sphene, epidote and apatite. Calcite crystals extracted from narrow cavities of bones found in African hominid-bearing breccias, turned out to be free of fossil fission tracks. This was ascribed to complete track fading at ambient temperatures (MacDougall and Price, 1974).

A glass-shard collected from mortar in the wall of a Gallo-Roman bath at Chassenon near Limoges was dated. Its fission-track dating gave AD 150 which is consistent with the time of the bath's construction, although this glass-shard has only a counting precision of 20%.

3.3 Paleotemperature indicator

Apatite Fission Track Analysis is a useful tool for the study of thermal history analysis in sedimentary basins. Green et al. (1989b) stated five temperature-sensitive fission track parameters obtained in the Otway basin as the guide to the paleotemperature and thermal histories. The five temperature-sensitive parameters are: the fission track ages, variation of apparent fission track age with depth, distribution of single grain ages, variation of mean confined track length with depth, and distribution of confined fission track lengths.
The samples of the Otway Basin have experienced a simple thermal history and are near or at their maximum temperature. The patterns in the five fission tracks parameters obtained for the Otway Basin can be applied to other basins if the samples contain a similar spread of apatite compositions, and the basin has a similar (rift-passive margin) tectonic history.

3.4 Tephrochronology

A volcanic explosion would produce tephra deposits which consist of pyroclastic materials. ephra beds can provide some important information of marker horizons for stratigraphic correlation, particularly of Quaternary and Tertiary sections (Westgate and Gorton, 1981). Fission-track dating is ideally qualified for tephrochronology. Firstly, tephra commonly contain glass shards and minerals which are suitable for track revealation. Secondly, these materials have sufficient uranium content for applying the technique. Thirdly, fission-track dating is grain-discrete, since each individual grain is routinely scanned under the microscope.

In fact, fission-track dating has recently become the most frequently used dating technique in tephrochronological studies (Seward 1976; Westgate and Briggs, 1980; Naeser and Naeser, 1984). Glass shards are the most preferred material in tephrochronological fission-track applications. Besides glass, zircon is the other tephra fission-track dating. Zircon has the advantages over glass of being less susceptible to track annealing and of having a higher uranium content. An early example of fission-track tephrochronology is the study by Seward (1974) on the Wanganui Basin, Norlh Island of New Zealand. The Pleistocene marine sediments of this basin contain many lephra layers and pumice-rich horizons with good stratigraphic and paleological control.

3.5 Sea-Floor Spreading

Basaltic glass occurs on the margins of pillow lavas. The glass forms when the surface of the hot extruding lava is quenched by the cold seawater. Since, thereafter, the glasses spent all their geological history at ambient sea-bottom temperatures around 4°C, no track fading can be expected and, thus, the fission-track age should give the time of glass formation (Fisher, 1968; Fleischer et al., 1968; Aumento, 1969).

The concept of sea-floor spreading indicates that the oceanic crust is formed in a dynamic volcanic regime at the axial zone of the mid-ocean ridges. In the vicinity of top of the diverging lithosperic plates, the newly created crust moves away from mid-ocean ridges. For the reason of this movement, the age of the basaltic oceanic crust would increase with distance from the axial zone and reveal the spreading rates. The concept of sea-floor spreading has been proven by the magnetic time scale of the magnetized basalts. The fission-track dating method has been a suitable candidate for young deep-sea basalts (Fleischer et al., 1968b).

3.6 Tectonics

Measurement of uplift rates in tile Central Alps by means of apatite fission-track dating (fission-track tectonics by Wagner and Reimer, 1972) demonstrated for the tectonic potential of the fission-track method. With this new application, the method ceased to be purely an 'age-determination' technique and developed into a unique thermo-tectonic tool. In the meantime, the technique has been further refined - in particular by the introduction of track length analysis and has been applied to many young orogenic belts. At present, fission-track analysis is an established technique for reconstructing the tectonic evolution of active mountain belts. It is also unique, since it provides depth-time paths for rocks during their upward movement through the upper kilometers of the Earth's crust. Such data are of fundamental importance for understanding mountain building processes.

Additionally, fission-track dating is occasionally used to study the amount and timing of vertical tectonic displacements along faults. This application is particular importance for crystalline basements in which faults are usually difficult to detect from field evidence. A regional pattern for apatite fission-track ages from a basement might be correlated with differential uplift. The fission-track ages are offset across a visible fault line. In practice, one is frequently confronted with a regional pattern in which an area with similar fission-track ages is separated from another one with different ages.

4. Application of FTA in Taiwan Orogeny

Fission-track ages and other geochrono logical data of Taiwan Orogeny range from ~0.25 to ~2.3 Ma (Table 1.). By using the assumption of a constant denudation rate for the Taiwan Orogeny and 1-D conduction of heat, both the "initial" geothermal gradient (G) and denudation rate (D) can be derived from reported age data of fission-track, biotite K-Ar, and biotite Ar-Sr (Kao and Yui, 2002). In this paper, the inferred P_e values (Peclet number) for the Nanao and Chipan areas (Fig.1) are >1.0 and <1.0, respectively. These values suggest that heat conduction during orogeny in the Nanao area has been mainly influenced by advection process since the late Pliocene; but in the Chipan area diffusion process played a role. Both areas have a nearly constant value of P_e, implying that the tectonics of heat conduction probably has been steady since the late Pliocene.

For the Nanao area, six assumed G values (30, 35, 38, 40, 42, and 50 ℃/km) are used for the numerical modeling of 1-D heat conduction. By comparison of the assumed and calculated G values, D = ~3.0 mm/yr is obtained to be the best-fitting value for the "initial" conditions. Similar calculation processes are also applied for the Chipan area. Six assumed G values (25, 30, 40, 45, 50, and 60 ℃/km) are used. The best-fitting value of D is ~3.1 mm/yr. According to the estimated results of Ds of Nanao and Chipan areas, the assumption of constant denudation rate for the Taiwan orogeny since the late Pliocene seems to be appropriate.

5. Summary

Fission track analysis (FTA) is a useful method not only in the thermal history study but also in dating impact/geological events. Fission track data consist of numerical information of specific samples as well as their thermal history. The FTA method can be applied in many fields

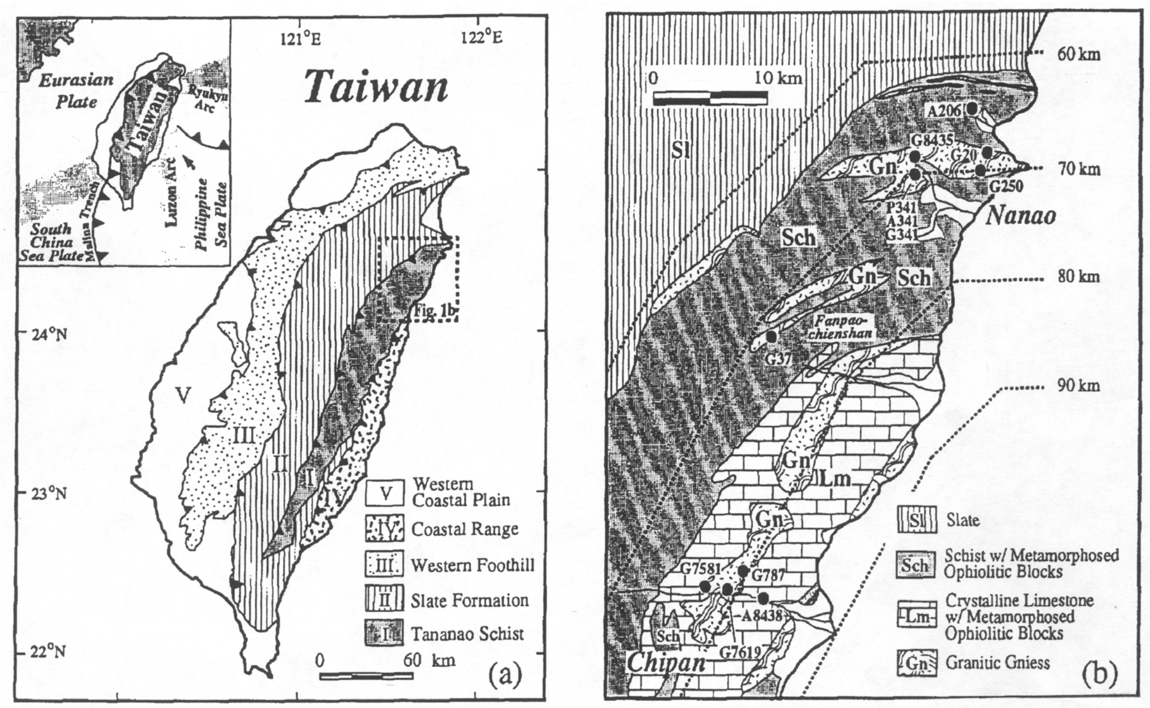

Figure 1. Locality of geochronological data

Table 1. Geochronological data of Taiwan Orogeny.

Locality	Rock type	Mineral	Dating method	Age (Ma)
Nanao	granite	apatite	Fission-track	0.25 ± 0.06
Nanao	granite	zircon	Fission-track	0.85 ± 0.10
Nanao	granite	sphene	Fission-track	0.99 ± 0.13
Nanao	shist	biotite	K-Ar	2.30 ± 0.30
Chipan	granite	patite	Fission-track	0.25 ± 0.06
Chipan	granite	zircon	Fission-track	1.31 ± 0.04
Chipan	granite	microcline	Ar-Ar	1.60 ± 0.20

Fission track ages and other geochronological data are obtained from Kao and Yui (2002).

(e.q. astronomy, tephrochronology, geology, and tectonics). The goals of this article are to indicate the FTA application and to provide one FTA example of tectonic study in Taiwan Orogeny. By using the principles of 1-D conduction of heat, a constant denudation rate (~3.0 mm/yr) can be derived from fission-track data and other dating data of biotite K-Ar, and biotite Ar-Ar. The application of the fission-track method may be further extended after its combination with other methods.

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Appendix I

In this appendix, a fission-track sample of apatite (Fig. 2) indicates the following characteristics of tracks: (1) etched fission tracks are straight. (2) etched fission tracks have a limited length (< 20 μm). (3) fission-tracks are randomly oriented, having no preferred relationship to a crystallographic direction.

Figure 2. Fission tracks of an apatite grain (~150 μm).