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Track Fading and Its Applications in Archaeology, Tectonics and Geothermal Chronology in China

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ABSTRACT: Track fading is a basic phenomenon in track science and has been the source of information in geosciences. This article summarizes the knowledge of track fading and gives some examples of successful applications of track fading in archaeology, tectonics and geothermal chronology in China. The applications of track fading are classified into 5 modes: (1) mode of complete fading (annealing); (2) mode of partial fading; (3) use of the dependence of track fading on time and temperature; (4) use of the differences of track fading between coexisting minerals; and (5) use of fading-reduced track length. Track fading mechanisms hints that scientists in geothermal chronology should adopt microprobes for quantitative elemental analysis to determine the detailed chemical compositions of each mineral grain or at least of the grains from each position of geological structures in order that one becomes well aware of the relation between the track fading behavior and chemical compositions of the mineral used.

KEY WORDS: track fading, archaeology, tectonics, geothermal chronology.

INTRODUCTION

Track fading was first recognized by Silk and Barnes (1959) when they observed fission fragment tracks in muscovite mica under transmission election microscope (Silk and Barnes, 1959). They saw that the latent tracks of fission fragments in muscovite mica began to disappear within a few seconds of electron beam bombardment due to the heating by the electron beam. Price and Walker found the way to circumvent the problem of the rapid fading of tracks in muscovite mica and stabilized and fixed the tracks by chemical etching (Price and Walker, 1962a). They enlarged the tracks continuously by etching until the tracks were observable under optical microscope. Price and Walker also discovered fossil tracks of ^{238}U spontaneous fission in muscovite mica and invented the technique of fission track dating (Price and Walker, 1962b).

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Fleischer et al. recognized that thermal fading of tracks follows Arrhenius equation (Fleischer et al., 1965; Fleischer and Price, 1964) and later many other scientists confirmed its correctness.

In the early stage of the development of fission track dating, track fading was regarded as a shortcoming, which results in smaller apparent ages. Soon after, it was noticed that not only the number of tracks is important parameter for geo-science, but also the reduced track length induced by track fading is important. It can provide powerful insight into geological processes. Track fading turned to an advantageous feature of fission track dating technique.

This article summarizes the knowledge of track fading, gives some successful examples in China in applications of track fading through various modes, and draws some important inferences from track fading mechanisms.

TRACK FADING MECHANISMS

Crystalline minerals and amorphous glasses used in geo-science are inorganic solids. The mechanism of track formation in inorganic solids is mostly accepted to be the model of ion explosion spike. The formation of tracks in this model can be divided into three main stages as described below. (1) Ionization stage. In this stage, an energetic heavy charged particle, in geo-science being mostly fission fragment, passes through the solid and ionizes the atoms along the trajectory of the particle, producing electrons and ionized atomic ions. This process takes place over a very short time. For fission fragment of spontaneous fission of ^{238}U and induced fission of ^{235}U by thermal neutrons, the time is about 10^{-17} seconds. (2) Ion explosion stage. The positively charged ions at the lattice sites formed in the ionization stage along the trajectory repel each other and repulsed into the interstitial sites of the atoms around the trajectory, forming a narrow and long hole composed of vacancies along the trajectory and a thick cylindrical shell composed of lattice and interstitial atoms around the hole of vacancies. This process lasts less than 10^{-13} seconds. (3) Relaxation stage. The formed interstitial and lattice atoms around the hole are not stable for the reason that the attractive forces between atoms in the interstitial and undamaged region pull the atoms towards the undamaged region. To diminish and balance this potential, the diameters of the hole and interstitial region become larger and the surrounding regions are strained. This process lasts about 1 second. The vacant (hole), interstitial and strained regions along the trajectory can be observed by transmission electron microscope and may be etched by chemical reagent.

The masses and energies of fission fragments from ^{238}U spontaneous fission and ^{235}U thermal neutron induced fission are very close to each other as compared below.

(1) For ^{238}U spontaneous fission, the atomic masses of light fragments A=85–105 with average mass 97; the average kinetic energy of light fragments is 97.6±0.7 MeV. The atomic masses of heavy fragments A=130–150 with average mass 139; the average kinetic energy of heavy fragments is 67.0±1.2 MeV. The total kinetic energy of light and heavy fragments is 164.6 MeV.

(2) For ^{235}U thermal neutron-induced fission, the masses of light fragments A=78–107 with peak value 95, the average kinetic energy of light fragments is 99.8 MeV. The atomic masses of heavy fragments A=118–156 with average mass 138; the average kinetic energy of heavy fragments is 68.4 MeV. The total kinetic energy of light and heavy fragments is 168.3±1.2 MeV.

The differences between average masses and between average kinetic energies for ^{238}U and ^{235}U fission respectively are not large enough to affect the track formation remarkably in the two types of fission in the same mineral or glass. For the same reason, one can neglect the difference between ^{238}U spontaneous fission and ^{235}U neutron induced fission in track fading (see below).

Track fading is a process opposite but not reversible to track formation. Track fading in inorganic solids occurs presumably by the diffusion of atoms in the damaged region (Wagner and Van den Haute, 1992; Durrani and Bull, 1987; Fleischer et al., 1975). Interstitial atoms can move to the vacant places (recombine with lattice vacancies) if the interstitial atoms get sufficient kinetic energy by heating (thermal motion of atoms). The values of activation energies of ~1–2 eV for track fading (annealing) support this conclusion (Guo et al., 2012). From thermo-dynamics, the kinetic energies of the atoms in the interstitial sites have a distribution (similar to Boltzman distribution). Some atoms may randomly gain kinetic energies (up to about 1–2 eV) and diffuse to places of lattice vacancies. The probability of this process is related to the temperature of the solids and diffusion coefficient D of the atoms. D is related to the atomic masses M of the interstitial atoms: $D \propto 1/\sqrt{M}$. The lighter the interstitial atoms, the faster they diffuse, and vice versa. Therefore, the differences of chemical compositions in minerals or glasses will give strong effects on track fading. For fluorapatite ($Ca_5[PO_4]_3F$) and chlorapatite ($Ca_5[PO_4]_3Cl$), the numbers and the masses of atoms of other elements (Ca, P, O) are the same, but the mass of F (19) is much smaller than Cl (35). Therefore, the track fading rate in fluorapatite should be faster than that in chlorapatite. Fluorapatite and chlorapatite can not be treated as the same minerals (apatite) in high-precision track fading studies.

APPLICATIONS OF TRACK FADING

Applications of track fading can be classified into 5 modes as explained below.

Mode of Complete Fading

This mode of application is adopted in age determination, in which the old ^{238}U spontaneous fission tracks formed before a heating event must be completely annealed out, new spontaneous fission tracks recorded after the heating event are counted for age determination of the event. This mode of age determination can avoid the influence of the old tracks. The starting time to record new tracks is very clear due to the heating event.

The dating of Peking Man Site at Zhoukoudian, Beijing is a good example. Archaeologists discovered that large amount of ancient ashes exist in Peking Man Site. The ashes were left by Peking Man when Peking Man were making fires. Some dust might be brought into the fires by fire-woods or by wind and the dust was heated by fire to a higher temperature for enough long time. The latent tracks of ^{238}U spontaneous fission in the dust recorded before firing might be annealed out. New track formed after the firing may be used to date Peking Man Site.

Guo et al. (1980) collected ancient ashes from Layer 10 of Locality 1 in Peking Man Site and they separated the dust from the ashes. The dust is composed of many kinds of minerals. Guo et al. picked out some gains of sphene from the dust. The sizes of the grains of sphene were about 0.05–0.3 mm. Experiments demonstrated that the spontaneous fission tracks formed before firing by Peking Man in some grains were annealed out completely during the firing. Some new tracks formed after the firing in the sphene can be etched and observed very clearly under optical microscope as shown in Fig. 1. No shortened spontaneous fission tracks can be observed on the surface of the sphene. It shows that the tracks recorded before firing were completely annealed out during the firing by Peking Man. The new tracks were counted to calculate the age of Peking Man. The calculated age of Peking Man at Layer 10 of Locality 1 in Peking Man Site is 0.462±0.045 Ma (Guo, 1982; Guo et al., 1980).

The key point in dating of Peking Man is to reject the minerals which are not completely annealed.

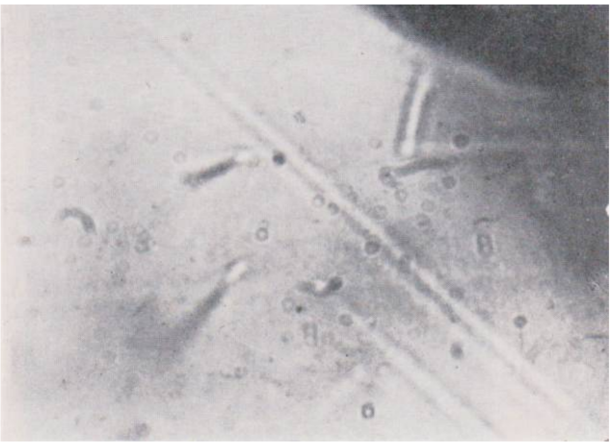

Figure 1. Microphotograph of ^{238}U spontaneous fission-fragment tracks in a sphene grain separated from ancient ashes left by Peking Man in Layer 10 of Locality 1 in Peking Man Site at Zhoukoudian, Beijing. The sphene grain was completely annealed by Peking Man when they were making fires. No crowded tracks formed before firing was left in the completely annealed grain. Only a few tracks formed after the firing made by Peking Man appear clearly on the surface of the grain. These tracks were used to date Peking Man (0.462±0.045 Ma in Layer 10 of Locality 1 in Peking Man Site).

This type of the minerals would have much more spontaneous fission tracks (about several hundred times more) than that in the completely annealed minerals. It was very easy to distinguish the grains of sphene which fell in the ashes without heating in fires by Peking Man or even heated in the fires but the tracks were not completely annealed. Figure 2 shows the tracks incompletely annealed. In this situation, one can see a batch of (crowded) shortened tracks on the surface of the sphene. These tracks were partially annealed (partially faded). This kind of sphene must be rejected in fission track dating of Peking Man.

The unique feature of fission track technique is its capability to judge the annealing degree of a single grain of mineral as the example above. This feature ensures the reliability of fission track dating in case some grains of mineral were not completely annealed by ancient heating event. The capability of judging track fading degree in single grain of mineral in fission track dating is superior to most of the other dat ing techniques that cannot judge annealing degree of a single mineral grain.

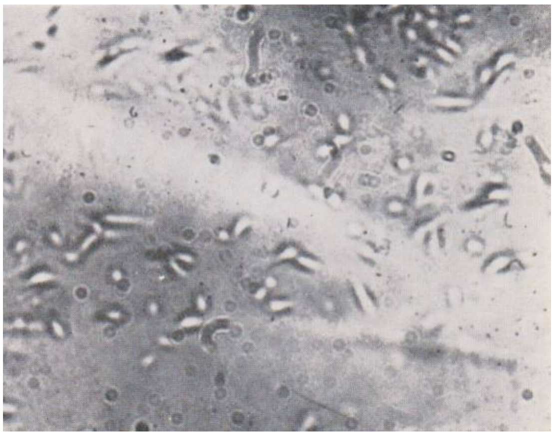

Figure 2. Microphotograph of ^{238}U spontaneous fission tracks in a sphene grain which was not completely annealed by Peking Man when they were making fires. The tracks are crowded and shortened compared with the tracks in completely annealed grain of sphene (see Fig. 1). The tracks shown in Fig. 2 were largely formed before the firing made by Peking Man but only partial fading took place during the firing. This type of incompletely annealed grain of sphene must be rejected in dating of Peking Man.

Usually, quite a number of mineral grains are used in fission track dating. Each grain reports an age. Commonly, an arithmetic mean is derived from all the grains. This calculation often hides mistakes. One way of exposing the mistakes is to make statistical analysis for the ages obtained from all the grains. If some of the age values deviate from the vast majority beyond the statistical uncertainty, the ages of those grains might have some problems. They should be rejected from the majority. The single grain feature of fission track dating has made it possible to make statistical analysis of age distribution. The base of the statistical analysis is the uranium content and the number of spontaneous fission tracks in each grain of mineral. For more details of the way of the analysis, please refer to the original paper (Guo, 1982; Guo et al., 1980).

Mode of Partial Fading

This mode of applications requires two preconditions.

(1) The mineral or glass to record tracks was formed just before the event.

(2) Track fading occurred partially in the mineral or glass due to moderate high temperature.

The first precondition was met in tektite formation. Tektites are thought to be formed when a meteorite hit on the earth. Large amount of crust materials was melted and sputtered into the sky and then cooled and fell down to the earth, forming tektites. Tektites are glassy substances, which can record tracks of spontaneous fission of ^{238}U.

Volcanic glass is another type of substance. Magma erupted from volcano and flew to the land or lakes. The magma subsequently formed volcanic glass as the temperature of the magma dropped down. Volcanic glasses can record tracks of fission fragments.

The tracks recorded naturally in tektites or volcanic glasses were often partially annealed (partial fading). The partial fading needs to be corrected in fission track dating.

One of the examples of dating tektite is the dating of ancient man in Baise Basin in South China (Guo et al., 1997). Archaeologists discovered tektites

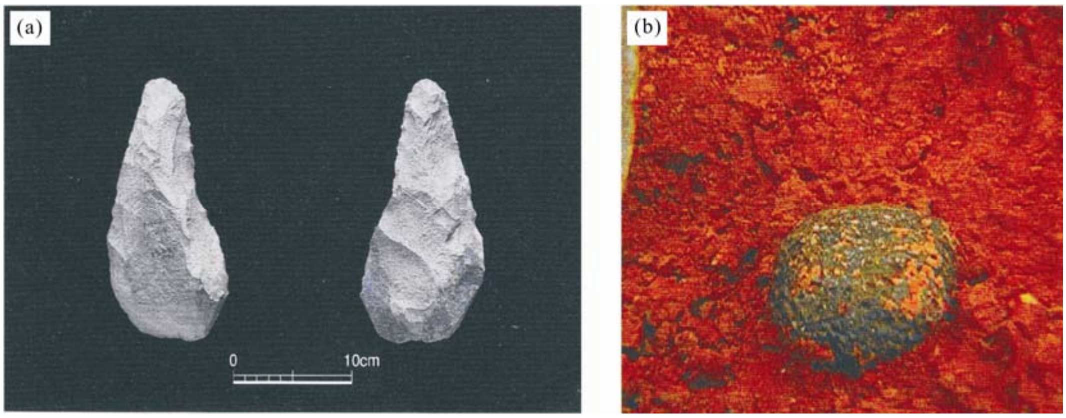

Figure 3. Photographs of (a) bifacial hand axe and (b) a tektite, both are discovered in the same stratigraphic layer in Baise Basin, Guangxi Province in southern China. (a) Photograph Showing two sides of a bifacial hand axe. Geologists and archaeologists have demonstrated that the deposition layer which contained the hand axe and the tektite was original, never moved and never disturbed. The age of the bifacial hand axe and the age of the tektite are the same. The age of the ancient man in Baise Basin who used the hand axe is the same as the age of the tektite (0.732±0.039 Ma after correction for track fading).

in an original, never moved or never disturbed layer of deposits, where they also discovered bifacial hand axes as shown in Fig. 3, which were thought impossible to have this kind of stone tools in the Far East Asia in very ancient time.

Fission track dating of the tektite obtained an age of 0.732±0.039 Ma after correction of track fading. This result of age breached the Movius Line drawn by Hallam Movius, an American paleoanthropologist more than 60 years ago (Gibbons, 1998). Movius claimed that there were no sophisticated bifacial hand axes in Far East Asia in the Early Stone Age. World archaeologists believed him more than 50 years until the line was breached by fission track dating. The breaching was also confirmed by ^{40}Ar/^{39}Ar dating a couple of year later (Hou et al., 2000).

Use of Dependence of Track Fading on Time and Temperature

The uplift rate V of a mountain can be derived from the differences of ages (t_2–t_1) of the same kind of mineral at different elevations (h_2, h_1), V=(h_2–h_1)/(t_2–t_1). That is, the ratio of elevation difference to the age difference is equal to the uplift rate if the denudation is negligible. Every mineral has a closure temperature, below which, fission tracks can be retained in the mineral for a geologic time. When a grain of mineral rises (uplifts) to an elevation beneath the surface of the earth, where the temperature is at the closure temperature, the mineral starts to record tracks. As the uplifting movement continues, a series of ages and elevations would be obtained. This way of determining uplift rate of a mountain is called height difference method.

Apatite is a mineral often used to determine uplift rate of mountains. Chen et al. (2001) determined the uplift rate of Taibai Mountains (the west part of Qinling Mountains in Central China) by fission tracks in apatite and obtained that the Taibai Mountains were formed around 40 Ma ago (according to apatite apparent age). The uplift rate was about 130 m/Ma in the first stage from 40 to 35.5 Ma. Then, the overburden on the mountains started denudation accompanying the uplift. The sum of the uplift rate plus denudation rate was 430 m/Ma from 35.5 Ma ago to nowadays (Chen et al., 2001).

Huangshan Mountains (Yellow Mountains) is a famous scenic spot in east part of China. It was included in the “Directory of World Cultural and Natural Heritage” by the UNESCO in December, 1990. Zheng et al. (2011) determined the uplift rate of Huangshan Mountains by apatite analysis. They found that three zones can be recognized in Huangshan area, each of them had different denudation intensities caused by different uplift rates of the fault blocks. The exhumation rates were measured to be 90, 104 and

167 m/Ma in different fault blocks from Early Cenozoic Era. The last phase of uplift took place from 10 Ma and the denudation rate was 156 m/Ma (Zheng et al., 2011).

Yuan et al. (2009) determined the uplift rate by apatite fission tracks of the Nimu District, South Gangdese terrane, Tibet Plateau. They found that the mean uplift rate is estimated to be 1.41–1.95 km/Ma with total uplift reaching ~5 900 m in the period 8–2 Ma.

Use of Annealing Differences between Coexisting Minerals

Apatite and zircon as two accessory minerals often co-exist in the same rock such as granites. The fading behaviors of the two minerals are different. The closure temperature for apatite is about 100±20 ℃, zircon is 210±40 ℃ (Wagner and Van den Haute, 1992).

One can use the two minerals selected from the same rock to determine the uplift rate of the rock (mineral pair method). The uplift rate is equal to

$$\left(\frac{\text{closure temperature difference}}{\text{geothermal gradient}}\right)\bigg/\text{apparent age difference}\ .$$

For the pair of apatite and zircon, closure temperature difference=110 ℃, geothermal gradient= 35 ℃/km, then, (closure temperature difference)/(geothermal gradient)=3.14 km. If zircon apparent age is 68.2 Ma, apatite apparent age=41.4 Ma, apparent age difference=26.8 Ma, then, uplift rate=117 m/Ma. It means that if one can select two kinds of minerals in one block of rock, then one can basically obtain the uplift rate of the rock.

Yin et al. (2001) obtained mean uplift rate 190 m/Ma of Hua Mountains (east part of Qinling Mountains in Central China) by the pair minerals of apatite and zircon (Yin et al., 2001).

Use of Fading-Reduced Track Lengths

One of the characteristics of track fading is the reduction of track length. The best representation of track length is by the length of confined track. Confined track length is the length of etched track which is entirely confined in the mineral (below the surface of the mineral) and etched via some channel of etchant, such as cleavage or another track which intersects the surface of the mineral. The former is called Track in Cleavage (TINCLE). The latter is called Track in Track (TINT).

Confined track length reduction also follows Arrhenius diagram [log(t~1/T)] if the percentage reduction is constant, where t and T are annealing time and temperature, respectively. For a given track length reduction and a period of time of annealing t, one can derive the annealing temperature T. This is one of the bases of geothermal chronology. In practice, the distribution of lengths of original fission tracks is very broad. To get a solution of geothermal history is very complicated, but it is possible (Guo et al., 1999; Chambaudet et al., 1993). Measurement of track length reduction has been used in oil exploration, in which the annealed track length has a monotonic variation with temperature (Kang and Wang, 1991; Gleadow et al., 1983; Gleadow and Duddy, 1981).

The best examples of applications of reduced track lengths by track fading are those contributions presented in the series of the International Conferences on Thermochronology.

CONCLUSIONS

(1) Track fading in inorganic solids at higher temperature is a basic phenomenon in track science and a source of knowledge in geosciences. The main mechanism of track fading in inorganic minerals or glasses is diffusion of interstitial atoms to the proper sites of the crystalline lattice. The fading rate is related to the temperature and diffusion coefficient of the interstitial atoms and further related to the masses of interstitial atoms produced in track formation process. The heavier is the interstitial atoms, the slower is the fading process. In the study of track fading and its applications, the difference of chemical compositions of minerals or glasses must be taken into consideration.

(2) Track fading in minerals and glasses has been successfully applied to geosciences, especially in archaeology, tectonics and geothermal chronology in China. These applications have provided new insights into the evolution of the earth and mankind.

(3) In order to get more precise and systematic knowledge on track fading and in its application domains, one should analyze the chemical compositions of each grain of minerals and natural glasses, at least of each batch of samples from a limited region on the earth with microprobes of elemental analysis.

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