THE CHANGING FACE OF FISSION TRACK DATING: RECENT ADVANCES.

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Abstract.

Fission Track Dating has undergone something of a renaissance in recent years. What began as a rather unreliable method of geochronology has now become a rigorous and dependable means of measuring not only geological time but also paleotemperatures. Developments such as the "zeta" calibration technique, rigorous statistical data analysis, investigation of confined track lengths and detailed studies of annealing behaviour have all contributed to advances in the technique.

INTRODUCTION.

The field of fission track dating originated over 20 years ago, as a straightforward method of geochronology. Over the years however, the technique has developed as the unique temperature sensitivity of fission tracks has become recognised. Now the technique offers the potential of combining geochronological information with the ability to define the variation of temperature through geological time. It is finding wide application in oil and mineral exploration, as well as in defining the geological time scale, studying the uplift of mountain ranges, and defining the timing and scale of large scale fault movements.

In this paper, we concentrate on some of the recent developments in the field, including advances in our understanding of the response of fission tracks to elevated temperatures (annealing) and conclude with a brief survey of some current fields of application.

NUMERICAL CALIBRATION OF FISSION TRACK DATING.

Development of Fission Track Dating (FTD) was, for a long time, hindered by problems associated with neutron dosimetry and choice of an appropriate value for λ_f, the spontaneous fission decay constant of ^{238}U. The confusion that arose because of these problems has been eliminated by the explicit use of age standards to calibrate FTD against other dating techniques. In the zeta calibration method, age standard minerals are used to derive a single calibration parameter, "zeta", which combines the constants contained in the age equation into a single, empirically determined constant, from which unknown ages can be evaluated. An extensive assessment of the zeta calibration approach has demonstrated its viability and its advantages when compared with explicit use of neutron dosimetry and values of λ_f.

REPRODUCIBILITY AND APPLICATION TO THE GEOLOGICAL TIME-SCALE.

The suitability of fission track dating for placing constraints on the Geologic Time Scale has been the subject of considerable debate in recent years. This debate has centred around the role of both systematic and random errors in determination of fission track ages. Systematic errors can be eliminated by careful and consistent use of the zeta calibration technique described above. The scale of random errors is controlled largely by the numbers of tracks counted in determining the age (because of the Poissonian nature of radioactive decay). The results of repeated analyses of the same sample by experienced observers show consistency, within the allowed limit of Poissonian variation.

The uncertainty in a single fission track age usually represents a balance between the amount of effort necessary to count sufficient tracks, and the benefit of that effort. Generally, a 2σ error of around 10% is typical. As such these sort of measurements are of little use in stratigraphy, where 2σ errors of about 2 or 3% would be desirable. However, repeated determinations can bring the error level down towards the desired level of precision. For instance, the weighted mean of six age determinations on Fish Canyon Tuff Zircon (a commonly used fission track age standard) has a 2σ error of 3.7%, eight determinations of Tardree Rhyolite - 3.6%; thirteen determinations of Mount Dromedary - 3.%. This level of precision could be useful in stratigraphy, and greater numbers of repeated determinations could bring the precision down further. However, this would entail a large amount of work, and the effort required would need to be balanced against the benefit gained from the final result.

PRACTICAL CONSIDERATIONS IN APPLICATION OF FISSION TRACK DATING.

Fission track dating is by no means a simple matter that can be picked up quickly. On the contrary, precise reproducible track counting can only be achieved through experience and constant practice. Six months of intensive and dedicated practice would seem to be the absolute minimum time necessary. In most cases, a year might be more appropriate.

Furthermore, this practice must be designed around a desire for consistency in repeated determinations of some parameter. This parameter could be either the ratio of fission track densities obtained from different dosimeter glasses in the same irradiation, or zeta values obtained from both repeated determinations of the same sample and from several different samples. It is essential that consistent results be obtained from both types of experiments before any reliable unknown ages can be determined.

Discussion during the 4th International Fission Track Dating Workshop at

Troy, New York, U.S.A. (1984) showed, disappointingly , that many fission track workers still have no experience of age standards. Sadly, this was reflected in the results of the interlaboratory comparison exercise held in conjunction with the Workshop in which roughly a third of all ages returned were outside $\pm 2\sigma$ of the known ages of the samples used (even with 2σ errors of between 10 and 20%).

FISSION TRACK LENGTHS IN APATITE AS INDICATORS OF THERMAL HISTORY.

Fission-track ages in apatite are generally accepted as giving a measure of the time over which a sample has been exposed to temperatures below approximately 100°C. Investigation of the lengths of confined fission tracks in a wide variety of different apatites has shown that the distribution of confined track lengths can provide unique information on the nature of thermal history in the temperature range below about 150°C over times of the order of 10^7 to 10^9 years.

The distribution of confined lengths of freshly produced induced tracks is characterised by a narrow, symmetric distribution with a mean length of around 16.3 μm and a standard deviation of the distibution of approximately 0.9 μm. In volcanic and related rocks which have cooled very rapidly, and never been reheated above about 50°C, the distribution is also narrow and symmetric, but with a shorter mean of 14.5 to 15 μm, and a standard deviation of the distribution of approximately 1.0 μm. In basement terrains which are thought never to have been significantly disturbed thermally, the distribution becomes negatively skewed, with a mean around 12 or 13 μm and a standard deviation between 1.2 and 2 μm. This distribution is thought to characterise continuous cooling from temperatures in excess of 125°C, to ambient surface temperatures.

More complex thermal histories produce correspondingly complex distributions of confined tracks. The length of each track shrinks to a final length characteristic of the maximum temperature it has experienced. This, combined with the continuous production of tracks with time, gives a final distribution which directly reflects the nature of the variation of temperature with time.

Most distinctive of the myriad possible forms of the final distribution are the bimodal distributions, which give clear evidence of a two-stage history, including high and low temperature phases.

LABORATORY STUDIES OF FISSION TRACK ANNEALING IN APATITE.

Previous fission-track annealing studies have described the reduction in track density in terms of a series of fanning lines on an Arrhenius plot, each denoting conditions of temperature and time producing an equal degree of annealing. This has been interpreted in terms of a range of activation energies corresponding to different degrees of annealing, with activation energies varying by a factor of 2 or 3 between complete track retention and total erasure.

New high precision measurements of confined track lengths in annealed Durango apatite however have led to the development of a new mathematical formalism to describe annealing, of the form:

$$C_1 \log(1-l/l_o) = \log(t) - C_2 - C_3/T$$

where t=time and T=temperature (^oK). This equation involves only a single activation energy (approx. 1.6 eV), or a very narrow range (~30%), implying a near parallelism of lines for various degrees of track length reduction in an Arrhenius plot.

Borehole studies have shown that different apatite grains respond to the same annealing conditions in differing degrees. Electron microprobe studies of these apatites indicate that the annealing properties of individual grains are strongly controlled by their F/Cl ratio. The interpretation of laboratory annealing studies, and to a lesser extent borehole studies, in terms of fanning Arrheniusplots may be understood as the result of the superposition of a series of near parallel Arrhenius plots corresponding to the range of compositions present, each characterised by different activation energies.

The new formalism can easily be extended to annealing treatments in which temperature varies with time. Predictions of mean track length, using this approach, in apatite samples annealed in the laboratory under variable temperature conditions show generally excellent agreement with observed values, supporting the validity of the treatment.

The shortening of individual tracks under linear heating and cooling show very different characteristic patterns. This behaviour leads to predictions of track length distributions under geological annealing in qualitative agreement with observation. However, it is not possible, at present, to extend the treatment to quantitative modelling of natural track length distributions, because of a variation of annealing behaviour between different apatites. Rigorous quantitative prediction of fission track parameters under geological annealing must await further data on the variation of annealing properties with apatite composition.

APPLICATIONS.

Recognition of the sensitivity of apatite to thermal episodes involving temperatures of only around 100°C has opened many new realms of application for FTD. Investigation of apatite fission track ages around rifted continental margins, such as south eastern Australia, reveal a decrease in age towards the coast due to the thermo-tectonic events associated with rifting. Study of track lengths in such regions can allow maximum paleotemperatures to be estimated which can be used to constrain viable models for the development of rifted margins.

The coincidence between the temperature range in which apatite shows observable annealing effects, and that in which liquid hydrocarbons are generated has led to an explosion in applications of Apatite Fission Track Analysis (AFTA) in the field of oil exploration. AFTA has been applied in a number of sedimentary basins, in Australia and around the world, in order both to study the annealing of tracks under well understood geological conditions, and also to apply the principles developed from these reference studies to other less understood situations. Areas under study include the Otway, Gippsland, Bowen, Amadeus and Cooper- Eromanga Basins of Australia, the Appalachian Basin of the U.S.A. and the North Sea.

A study of zircons from fault rocks associated withthe Alpine Fault, South Island, New Zealand has shown that the present fault zone has established along a much earlier line of weakness. The fission track results show evidence of at least three stages in the development of the present fault zone. The first stage was complete by around 80 Myr ago. At about 9 Myr, compression across the fault heralded a new regime in which uplift led to the formation of the Southern Alps, with a rapid increase in the rate of uplift at about 5Myr.

These are just a few of the many situations in which fission track dating is now being applied, and which illustrate the unique information that the method can provide. The coming years should see a rapid expansion in the study of thermo-tectonic processes using Fission Track Dating.