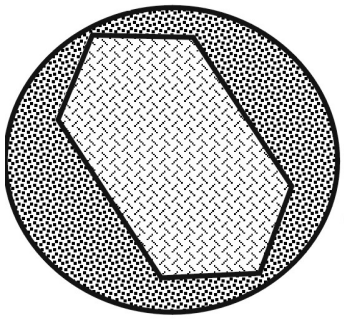

On Track

The Newsletter of the International Fission-Track Community

December 2000, Volume 10, Number 2, Issue 21

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On Track is a newsletter of the international fission-track community. It is printed in the months of June and December. The views expressed in On Track articles are those of the authors and do not reflect those of the fission-track community or the editor of On Track.

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Editor's Notes

I would like to thank **Richard Spikings** for his help during the transitional period of editorship. Richard provided me with just about everything, including templates, that made editing On Track simple and fun. All that was left to do was to collect the contributions and paste them at the appropriate places. I want to congratulate Richard with his new position at the University of Potsdam, and wish him the best of success. I also want to express my warmest thanks to all those who have contributed articles to this issue of On Track.

Diane Seward and her colleagues report the results of an intra-laboratory test at the ETH in Zürich, on the influence of the operator and etching conditions on mean confined track length. Their results show that a ~1 µm difference can result from a difference of only 6 seconds [!] in etching time. Their article raises many important questions: must we standardise etching conditions or can we define a set of equivalent etching conditions. Does this equivalence extend to D_{par}? None of us can afford not to read their article on page 19.

Many of us have been troubled by the closure of reactors in the past few years, and the spectre of further closures is looming large. We owe a great debt to **Edward Sobel** for presenting a compilation of data on a number of reactors, including technical and contact information. All you ever wanted to know about reactors, but never dared to ask, on page 16.

Sandro Guedes and his colleagues have developed new software for modelling apatite T[t]-paths. On Track invited them to show it in action. As if in passing, they introduce two concepts of cardinal importance: "batch"-modelling of different samples from a single area and "step"-modelling of a "single" thermal history. If you trust that your modelling program will find you the correct T[t]-path just by feeding it the age and track length data, think again ! Page 13.

Zircons annealed under well-defined T-t conditions in the geological environment are few and far between. The extrapolation of annealing models based on laboratory data is still very much an open question. On page 11, **Meinert Rahn** presents his latest data from the Alps, and discusses to what extent they allow him to distinguish between different models.

Are you happy with your zeta. Wouldn't you like to produce a real fission-track age at least once in your career, without having to lean on questionable standards and a procedure that is intrinsically untestable. It is a daunting task and you may have given up, but professor **Tatsuo Suzuki** has not. On Track invited him to present his insights on the standardisation of fission-track ages. Those that are prepared to take up his stimulating ideas will, in the end, confirm that "the determination of absolute fission-track ages is possible". Zeta-worshippers are not excused from reading Tatsuo Suzuki's article on page 9, because his method cuts both ways !

On Track invited professor **Lewis Chadderton** to share his insights on track formation and track structure with its readers. His article on page 5 is not for the squeamish but at the same time a rich source of fascinating and stimulating ideas. Are we unaware or unwilling to see that the entire edifice of T[t]-path modelling is cracking at the seams and in danger of collapsing, merely for lack of understanding of the basic properties of fission-tracks. Despite significant advances in the "calibration" of our tool, there remain no end of unanswered questions. How is track stability affected by chemical composition and what causes the unexplained [!] length reduction in the apatite age standards and in all apatites, resulting in the ludicrous "world-wide exhumation", to name but two problems relating to our best-understood mineral. All this time, on the other side of an invisible divide, are track physicists like Lewis Chadderton with knowledge of well-studied, well-understood phenomena that we haven't even dreamt of [read about PAPA on page 6]. We have come to define specific problems, they have identified specific phenomena, and yet the exchange of ideas is nil. Lewis Chadderton's article is a deliberate attempt, on the part of the author, to break down this barrier.

Lewis Chadderton is on the International Committee for the conferences "Nuclear Tracks in Solids" and proposes to exchange invited speakers at our conferences. The editor urges the organisers of the next FT-conference to support this initiative.

I want to thank Dr. Ralf Kuhn for his valuable help in establishing .pdf and .html versions of this issue of On Track.

Short Tracks

Amanjit Sandhu has moved to the University of Toronto, to work as research associate with Prof. John Westgate on fission-track dating of late Cenozoic tephra beds from the Yukon and Alaska. They have developed new and successful approaches to tackle fine-grained, distal tephra beds, allowing them to establish a tephrostratigraphical framework for the Yukon-Alaska region. Amanjit's new address is: Dr. Amanjit Sandhu, Physical Sciences Division, University of Toronto, Scarborough Campus,1265 Military Trail, Scarborough, Ont. M1C 1A4. Canada. E-mail: amanjitsandhu@usa.net.

Luis Barbero has set up a FT-lab at the University of Cadiz, Spain, after two visits to the London Fission Track Lab. Current projects are focused on the thermal evolution of a Mesozoic basin located in the external parts of the Betic Cordilleras, with support of Repsol Exploracion. He is also starting a collaboration with the University of Chile on the exhumation of part of the Andean Cordilleras and with the University of Zararagoza on the evolution of the Cameros basin in the Iberian Range, a Mesozoic basin that underwent extension during Late-Jurassic to Early Cretaceous and inversion during the Tertiary. Luis' address is: Dr. Luis Barbero, Grupo de Investigación de Huellas de Fisión, Dpto. de Geología, Facultad de Ciencias del Mar, Universidad de Cádiz, 11510 Puerto Real (Cádiz), Spain. Phone: INT-34-956-016279. Fax: INT-34-956-016040. E-mail: luis.barbero@uca.es.

Gérard Poupeau left Grenoble for Bordeaux, to take up the direction of the Centre de Recherche en Physique Appliquée à l'Archéologie of the Université Bordeaux III. This Centre has two branches. The first studies the characterization of archaeomaterials, in connection with provenance, ancient techniques and the conservation and restoration of archaeological objects. The second branch works on OSL, TL and ESR-dating and Gérard is establishing a FT-dating lab. His work will focus on the Plio-Quaternary, and is related to palaeoanthropological projects in the Eastern African Rift, but Gérard will also be involved, at least for some time to come, in more geological projects. Gérard's address is: Dr. Gérard Poupeau, Centre de Recherche en Physique Appliquée à l'Archéologie, Maison de l'Archéologie, Esplanade des Antilles, Campus Universitaire, Université Bordeaux III, 33607 Pessac, France. Phone: ++33 [0] 5 5712 4547. Fax: ++33 [0] 5 5712 4553. E-mail: gerard.Poupeau@montaigne.u-bordeaux.fr.

Peter van der Beek will run the Grenoble fission-track lab. Peter will set up research projects in both source area and detrital thermochronology, focusing on the French western Alps and the Nepal Himalaya. Claire Mock [Ph. D. Clermont-Ferrand, former post-doc at the London Fission Track Research Group] will stay on for an extra year as a post-doc in Grenoble. There are possibilities of obtaining post-doc grants from the French government for non-EU nationals. Finishing Ph.D. student who are interested in these possibilities should contact Dr. Peter van der Beek, Laboratoire de Géodynamique des Chaînes Alpines, Observatoire des Sciences de l'Univers de Grenoble, Université Joseph Fourier, Maison des Géosciences, BP 53, 38041 Grenoble, France. Phone: ++33 476 514 062. Fax: +33 476 514 058. E-mail: pvdbeek@ujf-grenoble.fr. Web: http://www.univ-savoie.fr/labos/lgca/.

Richard Spikings leaves the ETH-Zurich, Switzerland, at the end of March to take up a permanent assistantship at the rapidly growing Institute of Earth Sciences, University of Potsdam, Germany. His work in the research group of Prof. Patrick O'Brien [high pressure metamorphism and exhumation studies] involves the establishment and subsequent use of a mass spectrometer facility dedicated to $^{40}Ar/^{39}Ar$ thermochronology. Richard hopes and expects to be tackling some interesting geological problems using thermochronology in combination with the fission-track lab already established at Potsdam by Ed Sobel in the near future.

Kirsten Graefe has taken up a position at the newly established fission-track lab at the GFZ, Potsdam. Kirsten's new address is: Dr. Kirsten Graefe, Geoforschungszentrum Potsdam, Telegrafenberg, Gebäude C122, D-14473 Potsdam, Germany. Phone: 0331-288 1317. Fax: 0331-288 1370.

Marc Jolivet obtained his Ph.D. from the University Montpellier II, France, on Dec. 11th 2000, with a thesis on the kinematics of the deformation in North-Tibet. Marc has been running the FT-lab with Prof. Maurice Brunel in Montpellier for 2 years and, since January, has taken up a position with Prof. Paul Bishop in Glasgow, to start building up a new FT-lab.

Paul O'Sullivan has recently left the fission track group at the University of Melbourne, Australia, to take up a new position in the Department of Earth Sciences at Syracuse University, Syracuse, New York. At Syracuse he is working with Paul Fitzgerald and Suzanne Baldwin, who have both recently accepted new faculty positions, to help with the set-up of their new thermochronology labs, including both fission track and U-Th/He [please see the thermochronology web page at: http://128.230.24.246/ for more information]. At Syracuse, Paul will also be involved in ongoing projects with Kiwi in Antarctica and Arizona, as well as continuing to work in both Alaska and Australia. E-mail: POSulliv@syr.edu. Web: http://su-thermochronology.syr.edu /POS/POS.html.

Theses

KINEMATIC OF THE DEFORMATION IN NORTH TIBET. FISSION TRACK THERMOCHRONOLOGY, ANALOGUE MODELLING AND FIELD STUDY - MARC JOLIVET, UNIVERSITY MONTPELLIER II, FRANCE.

Studying the kinematic of the deformation on the northern edge of the Tibetan plateau is fundamental to understand the tectonic evolution of the whole Tibet. Several questions remain concerning the propagation of the deformation inside the Asian lithosphere, the exhumation rates of rocks, the rates of formation of the main relief and its age.

A fission tracks thermochronological study, associated with analogue modelling using granular material and combined with field work provide some new answers to these ques-

tions. We demonstrate that structures inherited from Palaeozoic and Mesozoic tectonic episodes are strongly controlling the localisation of the deformation. Fission tracks on zircon show that, since Jurassic times, the exhumation did not exceed 10km, explaining the small number of Cenozoic ages obtained by the other thermochronological methods. Fission tracks on apatite confirm the occurrence, in north Tibet, of important tectonic movements linked to the Mesozoic accretionnary episodes. Finally we show for the first time that the deformation associated to the India – Asia collision has been localized very early (around 40 Ma) along the Altyn Tagh and Kunlun faults. In early Oligocene it spreads over the whole north Tibet with a strong increase in Late Miocene. This work demonstrates the interest of fission tracks to study young tectonics, and allows us to present a new tectonic model of north Tibet.

[Marc Jolivet]

Positions

UNIVERSITY OF KANSAS: THERMOCHRONOLOGY AND TECTONICS. The Grinnell Fellowship is a one-year fellowship of up to $20,000 for a qualified Ph.D. student in the fields of thermochronology and tectonics at the Dept. of Geology, University of Kansas, Lawrence. Second and third years of support as an RA or TA will be offered if reasonable progress toward the degree is made. The fellowship recipient will be expected to conduct research in the new (U-Th)/He thermochronology laboratory. Potential research projects include the application of low-temperature thermochronology to regional tectonic problems in the western US, Tibet, and Iran and/or the further development of the (U-Th)/He thermochronometer. Other available analytical facilities at KU include fission-track, TIMS, ICP-MS, fluid inclusion, and cosmogenic nuclide extraction laboratories.

Details of research programs and facilities at KU are available on the World Wide Web at http://www.geo.ukans.edu/. For further information, contact Dr. Daniel Stockli (thermochronology/tectonics; 626-395-6177; stockli@gps.caltech.edu) or Dr. Douglas Walker (structural geology/tectonics; 785-864-4974; jdwalker@eagle.cc.ukans.edu), Dept. of Geology, 1474 Jayhawk Blvd., 120 Lindley Hall, University of Kansas, Lawrence, KS 66045. [Daniel F. Stockli]

LABORATOIRE DE GÉODYNAMIQUE DES CHAÎNES ALPINES, UNIVERSITÉ JOSEPH FOURIER, GRENOBLE, FRANCE. There are possibilities of obtaining post-doc grants from the French government for non-EU nationals. Finishing Ph.D. students who are interested should contact Dr. Peter van der Beek, Laboratoire de Géodynamique des Chaînes Alpines, Observatoire des Sciences de l'Univers de Grenoble, Université Joseph Fourier, Maison des Géosciences, BP 53, 38041 Grenoble Cedex, France. Phone: +33-476514062 Fax: +33-476514058 E-mail: pvdbeek@ujf-grenoble.fr.

Meetings

21st IAS MEETING OF SEDIMENTOLOGY, DAVOS, SWITZERLAND, 3-5 SEPTEMBER 2001. Fission-trackers who work with sediments may be interested in Symposia S6: Applications of geochronologic methods in sedimentary systems (Diane Seward and Bernhard Fügenschuh). Meeting Information at: http://www.ias-2001.ethz.ch/second/. Submit abstracts together with the registration and payment of fees before March 31, 2001. [John I. Garver]

CADIZ 2002. The Italian group has been organizing a series of meetings since 1997. At Chatillon [1999], it was decided that the next meeting should take place in Cadiz. A first circular, aimed at finding out how many people intend to take part and to establish the most convenient date and topic [fission tracks or more general low-T geochronology] will be distributed via Internet during the first semester of 2001. In the meantime, I would welcome any suggestions, at: luis.barbero@uca.es. The idea is to have 3-4 days of talks, depending on the number of participants, a field trip to the Ronda Massif, the largest alpine peridotite outcrop in the world [and close to Cadiz], and a visit to a Sherry winery. [Luis Barbero]

Abstracts

THE 20TH INTERNATIONAL CONFERENCE ON NUCLEAR TRACKS IN SOLIDS. The International Nuclear Track Society [INTS] organized the International Conference on Nuclear Tracks in Solids [ICNTS] in Portoroz, Slovenia, from August 28th to September 1st. The topics of the conference covered basic mechanisms of nuclear track formation in solids, nuclear track development and evaluation of etched nuclear tracks, as well as applications of nuclear tracks in diverse areas of the physical, technological, biomedical and geological sciences. The book of abstracts contains many interesting contributions, and can be downloaded in Adobe .pdf format from the web [http://www2.ijs.si/~icjt/djs/20ICNTS/].

Book

THE DATING GAME [ONE MAN'S SEARCH FOR THE AGE OF THE EARTH] by **Cherry Lewis** [Cambridge University Press, 253 p.]. A book about the life and work of Arthur Holmes, one of the pioneers of geochronology. The title is misleading, and will remind trackers, if no one else, of kneeling models in different states of denudation [a free copy of On Track to anyone who can say why!]. Beautifully written, at times poetic ['And so it was uranium, as old as the world herself, that must surely be the mother of time, giving birth to the daughters of decay'], it is most pleasant to read. The compulsive referee might find fault with certain statements [the demise of the dinosaurs was apparently due to the fashionable theory of meteorite impact], but everyone else is swept along by fact upon crystal clear fact about the history and prehistory of radioactive dating and about the life and times of Arthur Holmes. Perhaps, for the professional, 'The Dating Game' is somewhat light on the physics of radioactive dating, although the important discoveries and their significance are presented with great clarity. In filling a historical vacuum with a wealth of facts, Cherry Lewis has fulfilled an important and difficult task. To have done so in an entertaining book is a magnificent achievement.

Track Formation

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SOME THOUGHTS

Early TEM observations of fission fragment tracks on lithium fluoride surfaces, in bulk muscovite mica, and by direct crystal lattice resolution laid the path for the seminal work of Fleischer, Price and Walker - chemical track etching and its many applications. Unfortunately, the huge success of track etching, especially in geochronology and geothermometry, led to a bifurcation of research into chemical track 'development' on the one hand and, on the other, to fewer studies - mostly by physicists - of latent, undeveloped tracks. Chemical etching removes all of the latent stored information concerning the physics of basic track formation! However, optical microscopy is an inexpensive alternative to TEM - best used concurrently with the most direct of other analytical techniques, including TEM.

Chemically etched tracks are singular - one fission event produces one track, with definable width (a joint crystal/etchant property?) one length (range?), one overall geometry (fragment energy, general crystal 'softness', lattice anisotropy, surface energy minimisation etc). And for the geological clock, fortunately, latent tracks often fade and apparently disappear above a pre-etching annealing temperature.

This does not necessarily mean that storage of all of the fragment's kinetic energy as potential energy on and near to the ion's trajectory is completely reversed. Phase changes for example (e.g. in a crystalline → amorphous transition) sometimes only partially recover, and there can be conversion into crystal-specific point and extended defects - interstitials, vacancies, free radicals, dislocations, stacking faults, anti-phase domains, and so on. There can be substantial atomic rearrangements and a persistent, sometimes intermittent latent track. But then, maybe, this one does not readily etch! It should also be remembered that the electronic energy deposition depends not only on the energy and falling effective fission fragment charge Z_{eff}, but also on the primary vector momentum direction in the lattice, and spatial point of origin. Thus the lattice structure can mean that the linear electronic energy loss rate $(dE/dx)_e$, and therefore the range (~track length) and track width, can be extremely anisotropic due, for example, to channelling (stopping power much less than random) and quasi-channelling (much more than random). There is no such thing as a 'random direction' in a real crystal!

It is clear that there must be a fundamental association of anisotropy in the chemical track etching velocity v_t, and the physics of energy deposition vested in the range R(E) when the fission fragment (energy E, velocity v_p) is brought to rest. Chemical and physical attacks of a crystal are strongly related, differing only in their energy regimes[1]. Chemical dissolution can be measured in seconds, minutes, or hours, and manifestly follows the familiar laws of normal equilibrium thermodynamics. Fragment registration is on a time scale of ~10^{-11} to 10^{-13}s and is a non-equilibrium thermodynamic phenomenon. The link <u>is</u> thermodynamics.

SOME THEORY

Generally the classical non-relativistic Bethe/Bloch equation for the rate of energy loss to electrons - the stopping power[2] $S_e = -(dE/dx)$ - is initially adequate for range estimations if the model for the crystal (mineral) is assumed to be a random atomic array. Similarly one may use dedicated computer simulations such as TRIM or SHRIM for an overall view of fission fragment stopping. However, there are no analytical or numerical procedures, which properly translate primary energy conversion into real defects on tracks. TRIM predicts numbers and distributions (Kinchin-Pease theory) of interstitials and vacancies, but these are essentially meaningless in a random atom model. It is vital to remember that both track registration and annealing are dominated by mineral-specific defects. For elements (e.g. graphite and silicon) one defect may dominate. For compound minerals (e.g. micas and apatites) there can be contributions from what Jim Corbett generally called a unique 'suite of point defects', with differing activation energies for creation and trapping. There are many esoteric refinements to basic formulae, including Z_1^3 terms, the Barkas effect, the wake and vicinage effects etc. For present purposes one may safely ignore them! There are also theories developed for latent track widths (not necessarily an important parameter and difficult to measure accurately by TEM). Some of them, based on macroscopic sample thermal properties are helpful (see e.g. by Szenes), whilst others involve meaningless abstract mathematic extrapolations. One must be very careful! And, as in all modern science, there are far too many ('carried overboard') computer simulations where the approximations (e.g. time-steps too large) overwhelm physical reality.

Bethe/Bloch is essentially an integral over all the possible energy losses to free electrons in the 'random' target, described by screened Coulomb interactive collisions. But there has to be a sensible lower limit in the integral over all

---

[1] In irradiations of crystal surfaces with heavy keV ions the sputtering rate (atom ejection) in physical etching is determined by the nuclear (atomic) stopping power $S_n = (dE/ds)_n = S\ (hkl)_n$, where {hkl} are Miller indices for the exposed surface plane. Bulk chemical etch rates are generally expressed through the bulk etch rate $v_b = v(hkl)_b$.

[2] A perpetuated and regrettable misnomer in physics. The real stopping 'power' $(dE/dt)_e$ is measured in Joules per second.

impact parameters. Traditionally the first ionisation potential is used for an elemental crystal, or some average over electron shells I_{av} and there can be additive and properly weighted terms for contributions from the different elements in compound crystals. This is the so-called Bragg Rule of Additivity, first described in 1905 for clearly random gas mixtures.

It is possible to establish a real link here with different electronic band structures for different crystals (e.g. metals, semiconductors and ionic solids). Yet it's only a part of the story. And theorists have traditionally paid far more attention to the random stopping of a fragment - and much less to track formation in real 'ordered' crystals.

SOME MODELS

Fission, thermal, displacement, ion explosion spikes, and depleted zones! These and other models deserve deeper consideration elsewhere. But, frankly, we have been 'spiked' to death. It seems that, in both theory and experiment, we have visceral needs to prove one model over all others. In fact track formation is mostly an amalgam of all these features, and the act of fission fragment stopping is an extremely complicated many-body quantum-mechanical event. The electron, phonon, and defect systems of the target are all mutually interactive in a way that is unique for every crystal. It means that we must begin with simple models, which, though approximate, are target-specific and therefore relevant.

We can certainly talk about heat - trajectory central temperatures ~1800K, ~6000K and ~18,000K for fission fragments, heavy GeV ions, and 40MeV C_{60} cluster ions respectively. But temperature here has little meaning because over such short times (10^{-11}s), electrons 'freed' in the crystal obey Fermi-Dirac statistics before becoming Maxwellian-Boltzmann. It is difficult to accept simple general models for lateral spreading of energy based on immediate electron/lattice transfer, without specifying the specific phonon spectra and where equilibrium thermal coefficients are random 'averages' which do not reflect the always-ubiquitous anisotropy of real crystals.

We may also talk about Coulomb explosion. But nowadays this is understood to be a transitory non-dominant stage, because the so-called δ-electrons[3] are decelerated by Coulomb attraction from the core. They form a neutralising sheath around the moving fragment. It is a lesson of charge conservation drawn from the physics of plasmas.

Of course track formation models[4] can be built on the basis of systematic experimental observations. The key is to use as many analytical techniques as possible. If you use a single technique (e.g. small angle X-ray or neutron scattering), which requires playing around with a model until an angular fit is obtained, say, for olivine, then sparse are the grounds for supposing that the same model will also work, say, for mica. The same fission fragment, but a completely different target - and the crystal rules!

SOME CRYSTALS

Fission fragments appear randomly with the usual bimodal spectra for energy and mass. It is good to collimate them, even better experimentally to simulate them using low energy ion accelerators and known (goniometric) directions into the crystal. More recently a lot of vital information has come from accelerated particles and clusters at higher energies (especially from the Dunlop group using GANIL in Caen); that is different particles, same target. Consider the following crystalline targets:

1) Silicon, an artificial elemental diamond-cubic crystal, shows no fission fragment tracks in TEM, no GeV heavy ion tracks, but there are 40MeV C_{60} cluster ion tracks. This suggests a 'threshold' for amorphisation based on the deposition of energy density $(dE/dV)_e$ - but note that a 40MeV ion track is not simply a linear addition of 40 separate carbon ion tracks. There are additional vicinage (neighbourhood) ion-ion, and collective effects.

There is a huge body of information about the remarkable epitaxial recovery properties of silicon, mostly from lower energy (~100 keV) ion implantation physics. Evidently for fission fragments and GeV heavy ions some kind of PAPA (particle activated prompt anneal) phenomenon - takes place. An amorphising heat wave sweeps out at a velocity of ~10^{13}nm.s^{-1} - surprisingly very fast - but this promptly returns as a homoepitaxial recrystallisation cooling wave powered by point defects - essentially the swiftly mobile di-vacancy, and recovery is complete[5]. For C_{60} cluster ions, however, the recovery is incomplete and a permanent track of amorphous silicon is 'quenched-in'. Clearly the track width is determined by recovery, and not deposition, whilst its physical spatial contour is that of the thermodynamic 'triple point'.

The situation is similar for natural diamond and graphite (sp^3 bonding?). Note, however, that electronic sputtering from trajectories entering or emerging from surfaces yields an irreversible graphite-fullerene (C_{60}) phase transition there, and for graphite it appears that C_{60} projectiles might even produce C_{60} in the bulk.

2) Diatomic and turbostratic Molybdenite, MoS_2, shows strikingly beautiful fission fragment, GeV ion, and C_{60} bulk diffraction contrast tracks - often really regularly intermittent and continuous with a misleading quasi-sinusoidal anomalous intensity variation along the track length due purely to interference of the electron imaging Bloch waves in the crystal. They apparently do not anneal in the TEM. Surface 'tracks' can be chemically etched but it is a difficult procedure. The suggestion is that decomposition into stable molybdenum and volatile sulphur takes place but that there is some recovery - possibly even formation of (inorganic 'hyperfullerene') closed shell molybdenitenes $(MoS_2)_n$ in multiple concentric (Russian doll) shells. The corresponding 'point' defects are not known. Much more work is needed.

3) Diatomic Fluorite, CaF_2, both mineral and artificial, shows

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[3] Delta rays have their origin in fission fragment tracks in the dilute random gases of cloud chambers. It is obvious that this is far too crude an experimental model for crystals where there is order in the densely packed atomic array. It is easy, however, to make a simple working cloud chamber (for the kids (?)) and to see delta electron trajectories emerging from a fission fragment track: www.sas. org and www.tinkersguild.com.

[4] Two very early models due to Ozeroff and Brooks which have their origin in the Manhattan Project are now declassified and can be obtained from the United States AEC.

[5] For a full list of references see Chadderton and Fink, Radiation Effects and Defects in Solids, 152, 87 (2000), and home page http://wwwrsphysse.anu.edu.au/ampl/nanometrics/index.html

latent GeV ion and C_{60} cluster ion tracks (Dunlop et al.) which are quite remarkable - each track is an intermittent heterogeneously trajectory-nucleated row of faceted calcium colloids (capillarity of solids again!) in otherwise perfect crystal and very informative. The secret lies in a non-ionising excitation of the fluorine ion, formation of a self-trapped exciton in a radiationless transition, and the defect is the so-called V_k-centre or crowdion, which can only move along <100> directions on the anion simple cubic sublattice, and principally away from the particle trajectory.

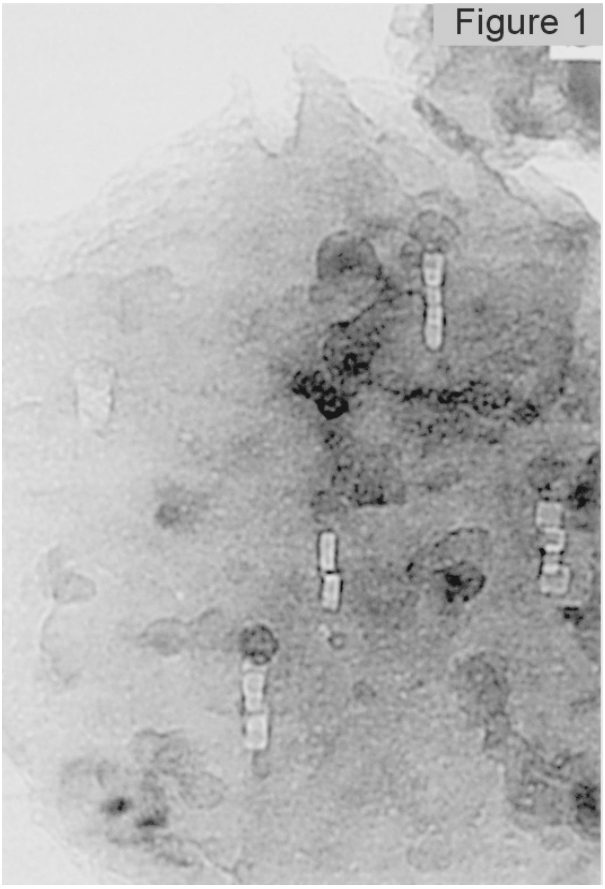

Figure 1. Heterogenous nucleation of faceted calcium colloids on intermittent tracks in CaF_2 irradiated with collimated 30.2 MeV C_{60} cluster ions. Colloids are larger at entry and exit surfaces (Jensen J., Dunlop A. and Della-Negra S. [1998] Nuclear Instruments and Methods, B146, 399).

The radiolytic effect of the imaging electrons in the TEM is a nuisance because of its own volition it leads to homogenous nucleation of a beautiful simple cubic superlattice of calcium colloids, seen in both diffraction and kinetic (phase) contrast, which can quickly mask and modify underlying (especially fission fragment) tracks. You have to be quick! Yet the lesson for tracks is once again learned from specific electron irradiations. It is a beautiful natural expression of physical order and energy minimisation due to movement of a simple intrinsic defect and, if only to understand the fundamental 'shadowing' mechanism proposed - an order out of disorder mechanism - it is truly worth a visit[6]. Ionisation damage never saturates in fluorite, which makes the general fluorite structure a potential candidate for the storage of radioactive waste!

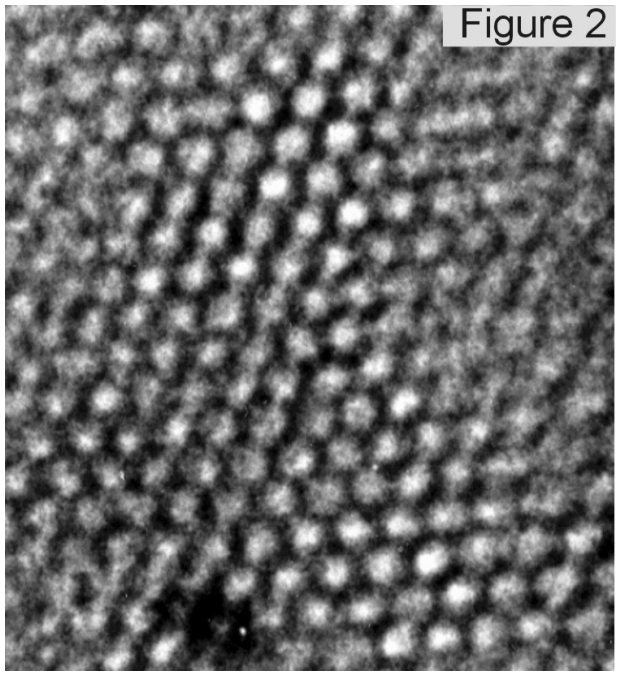

Figure 2. Homogeneous nucleation of faceted calcium colloids (~ 22 nm) - 'voids' on the simple cubic fluorine sublattice - in CaF_2 irradiated with 100 keV (TEM) electrons at room temperature.

In every case surface tracks can be etched, but etching of bulk tracks with hot acidic mixes, even though metallic calcium is an easy target, requires a deal of patience. Also latent fission fragment track formation in CaF_2 (intermittently delineated by quite tiny colloids) is a sample variable, and seems to be at or near the track formation threshold. This is not sharp because of the bimodal mass and energy distributions, so that the fission fragment track density is sometimes less than fluence. And there are clear chemically resistive ionic gaps between the metallic colloids (quantum dots?). It would seem that etching of fission fragment tracks in natural fluorite might be assisted by the presence of many defects and impurities, which may help chemical etchants to bridge the physical gap between colloids.

This suggests trying quite general radiative sensitisation for track-bearing minerals (e.g. apatite) by the introduction of a high intrinsic defect density with massive X-ray or cobalt-60 γ-irradiations, either prior to particle irradiation and/or prior to etching.

4) Triatomic Yttrium iron garnet, or YIG ($Y_3\,Fe_5\,O_{12}$), displays fine GeV ion and C_{60} ion tracks (see Dunlop and colleagues). There is unfortunately no report on fission fragment irradiations. The tracks are amorphous, and it is in this case that a simple thermal spike may be some guide to the energy dependence of track widths. The structural complexity of the crystal suggests that the crystalline → amorphous transition is irreversible. A totally random and sharply defined new phase is probably the simplest of all defects.

5) Muscovite mica is partly an enigma. Latent fission fragment tracks fade in the TEM. If there is complete recovery

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[6] Chadderton, Johnson and Wohlenberg, Comments Solid State Phys. 7 (1976) 105. Johnson and Chadderton, Radiation Effects 79 (1983) 183.

then this is an important surprise for such a complex crystal with almost certainly a broad suite of 'point' defects yet to be determined. The long-range strain field disappears. Is the response of mica due to its turbostratic structure? Do defects move easily in or between the lateral layers? Mica is a candidate for GeV ion and C_{60} ion irradiations and applications of other techniques!

SOME COMMENTS

Bulk track formation (crystal response), if it occurs and even if it does not occur, is more a function of specific crystal defects, rather than perfect lattice properties (e.g. phonon spectra, thermal diffusivity etc. - and likewise for annealing. It is predominantly on this basis that selection rules for the 14 Bravais crystal classes can be drawn up (in prep.) having reference to the periodic table, crystal structure and chemical bonding. Latent track structure in LiF (Trautmann and colleagues, GSI, Darmstadt), for example, is similar to that in CaF_2 because of self-trapped excitons on the anion sub-lattice, and the associated crowdion motion. Note the passivity of the cation sub-lattice in these cases. It means that the Bragg rule of stopping additivity cannot be carried over from the 'random' gaseous to the 'ordered' crystal world. It is wrong!

Endohedral faceting of etched tracks is simply an internal expression of the crystal structure through minimisation of surface energy in the thermodynamics of the capillarity of solids. It occurs also in nanotubes (e.g. graphite and boron nitride) and, exohedrally, in the sintering of small particles and the microstructure of sputtered surfaces. These are applications of the classic work in thermodynamics of J. Willard Gibbs.

Fission fragments probably create permanent 'surface tracks' in all targets, some of which can be chemically etched and developed in size. It is surprising that there have been so few applications of direct atomic observation e.g. AFM, STM etc., or of the C-RBS (channelling Rutherford back scattering) technique. Note, though, that interpretations of C-RBS results can be subjective and it is important to be careful. From elegant GeV heavy ion damage experiments in YIG, for example, there comes some suggestion of a 'second velocity effect' in stopping not included in Bethe/Bloch (there is always a broad maximum in the stopping at a certain velocity - the 'first velocity effect'). In fact it is difficult to see good physical grounds for this, and the detailed experimental results can as well be interpreted in terms of the first velocity effect appearing in surface tracks (to be published).

GeV heavy ions produce fullerenes (predominantly C_{60}) on projectile entry and exit from graphite surfaces. Fission fragments should do the same, but as yet there are no reports for such an experiment.

Juan Collar (CERN) has suggested that ancient fullerene might be due to carbon atoms "knocked-on" by weakly interacting massive particles (WIMPS) originating from the early life of the universe. If this speculation were to be verified we might then have cosmological dating to tag onto carbon-14 and fission track methods.

FT irradiation facilities at the Oregon State University reactor

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I have used the irradiation services at Oregon State University since the late 1980's and they do a wonderful job. Recently, I have received a number of inquiries about this facility due to reactor slowdowns and shutdowns around the world. If you are looking around for a new reactor, here is the scoop on OSU.

OSU charges $200 for up to a 7 hr irradiation (zircon) and $400 for >7 hour irradiation (apatite). Seven hours is equivalent to a thermal neutron fluence of $2x10^{15}$ n/cm^2. Shipping and handling rates are $180 per shipment plus shipping fees which are about $50 (by Fed EX in the US, but more internationally). Each run may include two Irradiation Poly tubes for the same price (you may irradiate one at a time). In comparison to other reactors, the tubes are huge: the internal diameter of the tube is 9 x 2.3 cm. Technically, this could accommodate about 90 zircon mounts (single Teflon mounts), glasses and standards. Because you may irradiate two tubes at the same time for the same price, you technically could irradiate a total of 180 (see fluence gradient below). For apatite the number is about half that depending on the thickness of the glass mounts. With my radiation license, turn around time (door to door) for zircon is 1 month, and for apatite is about 1.5 month.

There is about a 2% per cm gradient in the thermal flux. The thermal flux is two orders of magnitude higher than the epithermal and fast flux values. The details of the flux can be found at: http://www.ne.orst.edu/facilities/radiation_center/spec4.html. They quote Cd-ratio for Au of 14.

They require documentation of a current radiation license. Questions about your license can be directed to Kathy Brock, Senior Health Physicist, brockkm@rc.orst.edu. For each request, they require signed Irradiation Request forms (signed by the user and your RSO), which can be downloaded from http://www.ne.orst.edu/facilities/radiation_center/index.html (go to "services" and you need page 1 and page 2 - they are Adobe PDF). For full information contact: Steve Binney; Director, Radiation Center; Professor of Nuclear Engineering and Radiation Health Physics; 100 Radiation Center; Oregon State University; Corvallis, OR 97331-5903; Phone: (541)737-2344; Fax: (541)737-0480; Email: binneys@rc.orst.edu. Feel free to email me it you have any questions.

B_0 value of uranium doped glasses: a proposal for the standardisation of fission-track ages

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INTRODUCTION

The zeta age-calibration (Hurford and Green 1983) was recommended by the Working Group for the Standardisation of the Fission-Track Dating Method of the IUGS Subcomission on Geochronology (Hurford 1990). To date, it is widely applied for fission-track dating of zircon, apatite and sphene. In most cases of routine fission-track dating, calibration factors have not been measured directly from age standards included in every irradiation run [Z-method] because of space limitations in the irradiation capsules and the considerable amount of tedious track counting work involved. Thus, the calibration factors used by most researchers relate to specific standard U-doped glasses [ζ-method] and irradiation facilities. However, in cases where a well-thermalised irradiation facility is available, a more specific calibration factor can be defined and determined for the standard glasses, and used for routine fission-track dating.

On the other hand, the absolute approach is accepted for fission-track dating of apatite with the population method. This requires measurement of the thermal neutron fluence and the use of the decay constant (Van den haute et al., 1988, 1998). The need for absolute determination of the fission-track age also exists in other cases [glasses; other minerals] because of the lack of sufficient or appropriate age standards and the lack of a convenient means for independent confirmation of the results.

Based on these considerations, we have introduced the B_0-value for estimating the induced-fission reaction-rate of ^{235}U using uranium-doped standard glasses. The significance of the B_0-value for the standardisation of fission track ages will be discussed here.

WHICH IS REALLY NEEDED, THE NEUTRON FLUENCE OR THE REACTION RATE ?

Discussions of the determination of absolute fission-track ages (e.g. Hurford and Green, 1982; Van den haute et al., 1988) always refer to measurements of the thermal neutron fluence. It is well known that the neutron fluence is strongly dependent on the neutron energy spectrum in the irradiation field. In particular, the behaviour of epithermal neutrons is anisotropic in an irradiation facility, and is easily affected by sample geometry because of the extremely large resonance cross-sections of several nuclear reactions.

Therefore, inter-reactor calibration of the thermal neutron fluence with the help of pre-irradiated monitor glasses is sometimes very difficult and not so convenient for the precise fluence measurements required for fission track dating. For example, the pre-irradiated glasses SRM 961-964 (Carpenter and Reimer, 1974; Carpenter, 1984) provided by the NBS (NIST) confused users because of the discrepant fluences for the Au and Cu monitors, probably due to the use of closely packed pure metal foil monitors, and because of the depleted uranium and trace elements contained in the glasses. The problem in this case was to decide whether to use the Au- or Cu-foil fluences (Hurford and Green, 1982), although it appears that the Au-values should be nearer to the true fluence (Suzuki and Tomura, 1988; De Corte et al., 1991).

The thermal neutron fluence is not, in itself, a parameter that is required for calculating the absolute fission track age. It is only used for calculating the reaction rate of the $^{235}U(n,f)$-reaction. For this reason, it is better to use the induced-fission rate of ^{235}U, instead of neutron fluence, for characterising the neutron spectrum in the irradiation facility (Suzuki, 1992).

THE B_0-VALUE OF U-DOPED GLASSES

Before the zeta age-calibration was introduced, a B-factor was used for determining the neutron fluence with the aid of Uranium-doped glasses. B was defined by (Hurford and Gleadow, 1976):

$$\Phi = B\ \rho_d \qquad [1]$$

wherein: Φ = neutron fluence and ρ_d = track density resulting from induced fission ^{235}U. Here, a B_0-factor is used instead of the B-value because the B_0-value is independent from the neutron energy spectrum in the irradiation facility. B_0 is given by:

$$B_0 = [\sigma\varphi]_{total}\ /\rho_d \qquad [2]$$

wherein: σ = the fission cross-section of ^{235}U, φ = the neutron flux density, and $[\sigma\varphi]_{total}$ = the integral of $[\sigma\varphi]$ over all neutron energies; this is the induced-fission reaction-rate of ^{235}U.

Thus, from the equation of Hurford and Green (1983), we derive the following equation for ζ_0 [the calibration factor for the zeta-method without age standards]:

$$\zeta_0 = B_0\, I\, /\, \lambda_f \qquad [3]$$

wherein: I = the present-day isotopic abundance ratio ^{235}U / ^{238}U, and λ_f = the spontaneous-fission decay constant of ^{238}U.

B_0-values can be determined experimentally with different methods. First, so-called metal activation monitors like Au, Co, Lu, Zr and others can be used to determine the neutron energy spectrum. The ^{235}U fission-reaction rate can then be calculated from direct and precise measurements of the parameters of the neutron energy spectrum (Suzuki

and Tomura, 1990): the thermal neutron fluence, Cd-ratio, neutron temperature, the α-value of the epithermal neutron spectrum (e.g. De Corte et al., 1981) and the fast neutron flux. A B_0-value for Corning CN5 glass has been determined in this way. Using this value, a reasonable fission-track age was obtained for obsidian samples (Suzuki, 2000).

Second, the ^{235}U fission-reaction rate can be calculated from the uranium content and specific density of the standard glass and the effective range of fission tracks. In this case, of course, the track detection efficiency for the mica external detectors must be estimated in a separate experiment. I have tested this method on a natural glass (obsidian) for the blind test held before the Troy Conference in 1984 (Miller et al. 1986). At that time, no age standards or standard glasses containing natural uranium were available. The result was satisfactory although the neutron temperature was not taken into account at this stage and I used an average fission cross-section for the dosimetry but not for the age calculation. This experience confirmed that the absolute determination of fission track ages is possible. At that time, the detection efficiency of Fish Canyon Tuff zircon and apatite was determined by irradiating annealed zircon and apatite grains against a high-uranium glass. But this experiment must be repeated in the future for non-annealed samples.

Third, the induced-fission reaction rate can be calculated from gamma-spectrometry of the uranium-fission products. In this case, the accuracy of the result depends on that of the nuclear data for the fission yields of the different fission-products. This method was used for the calibration of a glass for neutron fluence measurements (Fleischer et al., 1965) and, more recently, De Corte et al. (1995) obtained consistent results with those from other metal foil monitors.

The ideal standard for measurements of the induced-fission reaction rate of ^{235}U must be an infinitely thin uranium film on plastic. Thin uranium-deposits on aluminium supports can be produced without difficulty, but it is problematic to produce an adequate number of identical samples. Thus, for the moment, we must determine the induced-fission reaction-rate using uranium-doped glasses, as a sufficient number of identical ones are available. Ideally, the B_0-values should be certified for fission track analysis, especially for new glasses.

Conclusions

The induced-fission reaction-rate is more useful and convenient than the neutron fluence for fission track analysis.

A B_0-value, as defined in eq. [2], should be determined and certified for uranium-doped glasses. B_0 has the advantage over B that it is an independent constant for most irradiation facilities.

It is important that inter-laboratory crosschecks of the B_0-values are performed for a number of glasses by different researchers from a number of laboratories, using different techniques.

Before we can determine the absolute fission track age of samples, problems related to the track detection efficiency remain to be considered. These will be discussed elsewhere.

Acknowledgement

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A long-term zircon annealing experiment

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Many of us, I am convinced, were impressed when Taka Tagami and his co-workers came up with the first 10.000 hours experiments (Tagami et al. 1998). With these experiments, the temporal range for laboratory annealing studies on zircon now covered five orders of magnitude (from four minutes to more than one year). Not enough, unfortunately, to clearly favour one of the two proposed annealing models, a parallel or a fanning relationship of the iso-annealing lines. Not enough, either, to bridge the gap between the experimental data range on one side and the geologically interesting time range on the other. 1 Ma equals 8.760.000.000 hours (even more if we include leap years...), thus the size of the gap to relatively short geologic time periods, which are resolvable by the FT technique, is in the order of 7-8 orders of magnitude. A large range to be worried about, large enough to doubt whether our ultra-short experiments are in fact relevant to such a time range.

To overcome this problem, FT studies were launched in contact aureoles (Tagami and Shimada 1996), or deep bore holes (Tagami et al. 1995, Green et al. 1996, Wagner et al. 1997), thus in systems with a long-term evolution and simple sampling geometry. So far, very little attention has been given to the possibilities in documenting zircon FT annealing in a low-grade metamorphic area with well-constrained metamorphic peak conditions and tightly bracketed time-temperature history.

In a previous "On Track" paper (Rahn 1997), I have presented a vertical FT data profile from the western Central Alps, and shown that the Alpine, i.e. Neogene, metamorphic peak temperatures may be nicely determined by a combination of fluid inclusion, illite crystallinity and vitrinite reflectance data. The derived minimum temperature for the uppermost part of the vertical profile was 270 °C. The vertical profile consisted of 6 samples, taken between 2420 and 740 m elevation. The samples included gneisses of the Aiguilles Rouges massif in the lower part, one Eocene flysch sandstone at 2055 m, and one granitic boulder at 2420 m from within the Eocene flysch. Along the profile, the zircon FT ages decrease from middle Triassic (top) to middle Cretaceous (bottom), following a nearly linear trend. The one exception is the flysch sandstone whose zircon age plots far off the trend. The zircons from this sandstone represent a multi-population mixture of detrital ages, which in part are younger than the initial Variscan cooling age of the basement zircons.

The fact that most zircon ages have very small standard errors, some of them even pass a χ^2 text, raised some doubts about their partially annealed character. Fortunately, the sampled lithologies helped to prove the young, i.e. Alpine formation of this data pattern. The uppermost sample yielded an age, which is consistent with the data trend further down. Before partial resetting, the ages of all granitic samples were Variscan cooling ages. The actual values, however, do not depend on the precise source area, but solely on the samples' position within the vertical section, which was created subsequent to flysch sedimentation.

Since 1997, we have added an additional sample from the valley bottom (560 m) and have added zircon track length measurements to the data set (Fig. 1). Mean track lengths range from 8.5 (top) to 7.5 μm (bottom), and confirm that the tracks are partially annealed. The lowermost sample seems to suggest a curved rather than linear trend in the age data set, which reminded me to the series of 1-hour annealing experiments, e.g. as presented by Kasuya and Naeser (1988), Tagami et al. (1990, 1998), and Yamada et al. (1995). What would happen, if we would take the predictions of the 1998 parallel and fanning model, and compare with the data from the vertical profile? Analogous

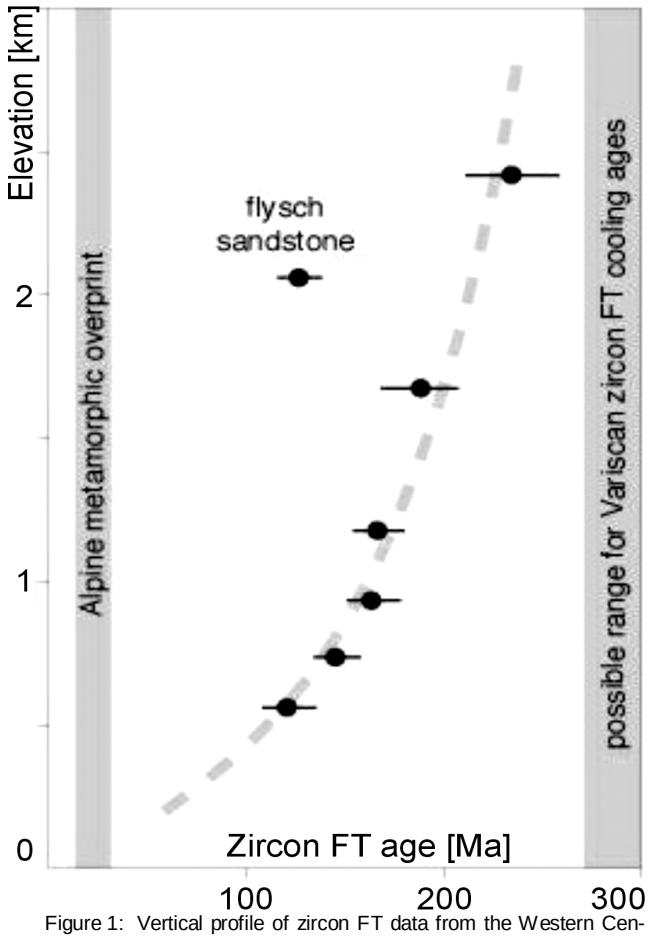

Figure 1: Vertical profile of zircon FT data from the Western Central Alps. The indicated age errors are 1σ. The grey dashed line suggests a curved age trend.

to the experimental curves, all samples from the vertical profile had undergone the same duration of heating. Furthermore, the sampling elevation may be taken as a proxy for a set of different maximum temperature values. Elevations simply had to be translated into a temperature profile.

In order to ascertain whether the data set from the vertical profile is representative of a long-term natural annealing experiment, the data had to be converted and the correct annealing predictions had to be selected. This included the following steps:

1. We had to evaluate the duration of the thermal event. In a recent paper, Kirschner et al. (1996) used Ar/Ar step-heating profiles from shear zones of the Morcles and Doldenhorn nappes, representing the sedimentary cover of the sampled crystalline basement, to model a well bracketed time temperature history for the nappes. These t-T histories are characterized by a 10 Ma metamorphic heating event. Therefore, we have selected the 10 Ma values from the parallel and fanning relationship to compare with the zircon FT data.

2. Predictions based on the Tagami et al. (1998) annealing model are given as track length data (L or L/L_O). For comparison, these must be converted to track densities (ρ/ρ_0). The solution to this problem is provided by Tagami et al. (1990), who observed a linear relationship between L/L_O and ρ/ρ_0.

3. The density ratio ρ/ρ_0 can be directly replaced by an age ratio t/t_0. However, this replacement implies knowledge of t_0, the initial age of all zircon samples. On the basis of biotite K/Ar cooling ages from the crystalline basements in the Central Alps (Hunziker et al. 1992), t_0 is estimated to be 300 Ma. Later tests showed that the influence of the initial age is of minor importance; even a change by up to 10% (±30 Ma) would only result in minor changes for the position of the annealing model curves in the relevant range.

4. The conversion of sample elevation into maximum temperatures experienced by the individual samples required estimating the thermal gradient during peak metamorphism. A thermal gradient of 20 °C/km was assumed, in agreement to the situation of a thickened crust due to intense nappes stacking prior to maximum burial. Since the indicated temperature constraints along the profile were derived from data within the flysch, the sampling elevation of 2500 m was defined to represent the 270 °C isotherm of the profile. Temperatures at the valley bottom (at 450 m) therefore would have been 310 °C during peak metamorphism.

The result of our comparison (figure 2) is better than expected. Both fanning and parallel model predict a slightly curved relationship between relative age and temperature. The predicted ages are the same for the upper section. Towards the bottom, however, predictions drift apart, and for an elevation of 500 m they differ by more than 30 Ma. With the exception of the flysch sandstone, the zircon ages along the profile nicely follow the predictions of the parallel model. However, the preference for this model must be interpreted with great caution. While the change of the initial age t_0, only slightly affects the geometry and position of the curves, there is a strong influence of the adopted thermal gradient on the obtained fit. If a thermal gradient of 28 °C/km is taken for the conversion of sample elevation into temperature, the fanning relationship would have provided a perfect fit.

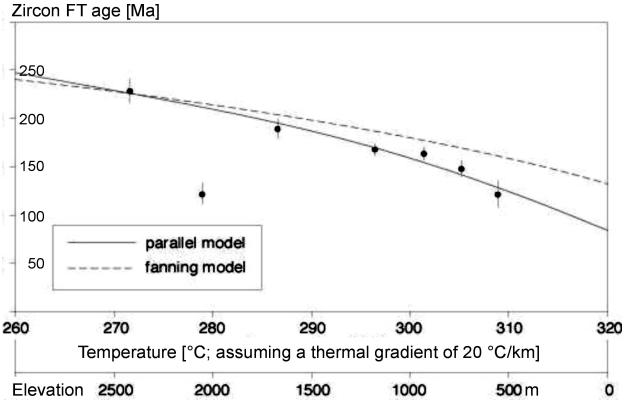

Figure 2: Comparison of model predictions (Tagami et al. 1998) and FT ages from the vertical profile in the western Central Alps. Age errors are 1σ.

On the basis of our knowledge of the geological boundary conditions in this area, the parallel annealing model of Tagami et al. (1998) seems to agree better with the data. Independently from our choice of annealing model, however, it is interesting to note that the data set is well within the predictions of the two models, and the slightly curved relationship between age and elevation along our vertical profile nicely corresponds to the experimental predictions. The results invest confidence in the extrapolation of the model predictions over 8 orders of magnitude, from laboratory to geological time scales. Furthermore, our data seem to exclude the possibility of a strongly curved extrapolation model, as it was recently proposed for apatites (Ketcham et al. 1999).

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Apatite fission-track thermal history modelling using PC compatible Brazilian software

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INTRODUCTION

The thermal histories of Brazilian regions Serra Negra, Salitre, Catalão II and Tapira were studied by applying the Fission-Track Method to apatite. We used the annealing model developed by Australian researchers (Green et al., 1986, Laslett et al., 1987, Duddy et al., 1988, Green et al., 1989) in combination with the modelling procedure (Inverse Method) proposed by Lutz and Omar (1991): thermal histories are randomly generated starting from a defined time and temperature interval (Monte Carlo Box). To each thermal history corresponds a simulated track length histogram that is statistically compared with the experimental histogram.

Considering that the Serra Negra, Salitre, Catalão II and Tapira regions present a uniform geological evolution and similar apparent fission track ages (~60 Ma), it is reasonable to suppose that they exhibit similar thermal histories. This was taken into account in our modelling method. We have grouped samples presenting similar geological characteristics and then looked for their common thermal history. To determine the thermal history of each sample, we used PC-compatible software, developed by the Chronology Group at UNICAMP, Brazil (Tello, 1994). This software is freely available on Internet at www.ifi.unicamp.br/cronologia.

RESULTS AND DISCUSSION

In this work we used the "Population Method". The apatite grains of each sample were divided in two parts: the first one to measure the fossil tracks and the other to measure the induced tracks. The latter were produced by irradiating the sample with thermal neutrons with a nominal fluence of ~ 1x 10^{15} neutrons/cm^2 in the IPEN/CNEN (São Paulo, Brazil) nuclear reactor. Before irradiation, the samples were heated at 450 ^{0}C during 10 h, to erase the fossil tracks.

The ages were obtained using an absolute method (Bigazzi et al., 2000), which requires an independent value of λ_f. We used the value obtained by Guedes et al. (2000). The error on the track densities was calculated from the largest of the standard deviations of the measured track density distribution and the corresponding Poisson distribution.

The weighted mean apparent age is: (61±4) Ma. The value of χ_v^2, where $\nu = 3$, is 1.408, which implies $P(\chi_v^2) \approx 0.35$. This value indicates that the ages are statistically compatible. The corrected ages were determined using a size-correction curve (Tello, 1998; Hadler et al., 2001). The weighted mean value of the corrected age is: (79 ± 6) Ma. The value of χ_v^2, where $\nu = 3$, is 1.532, which implies $P(\chi_v^2) \approx 0.15$.

The histograms of lengths of confined fossil tracks, containing the information on the thermal history of the samples, are shown in Figure 1.

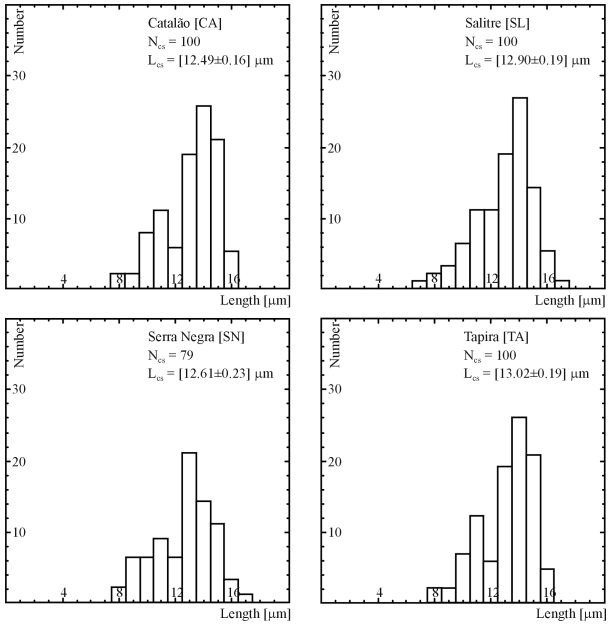

Figure 1: confined track length distributions for the Catalão II, Salitre, Serra Negra and Tapira samples.

To obtain the common thermal history of the group of samples, we carried out 5 different treatments. In the first, only one Monte Carlo box was used. In the second treatment, two boxes and so on up to five boxes in the fifth. To generate a thermal history, a point in each one of these boxes is randomly chosen (Figure 2) and the points inside adjoining boxes are joined by straight lines. The point inside the box representing the most recent time interval is linked to the fixed point (t = 0, T = 25^o C) representing the present time. This sequence of straight lines constitutes a possible thermal history, generating a value for the apparent age and track length distribution, which are compared statistically with the experimental results. This thermal history is accepted if both the apparent age agrees with the experimental value (within two standard deviations) and the generated length distribution is compatible with the experimental distribution, according to the χ^2 test. In this way, repeating this procedure approximately 500 times, a group of thermal histories that fits the experimental data can be obtained.

The first treatment, where only a Monte Carlo box is used, is shown in Figure 2a, b, c, d, corresponding to the Catalão (CA), Salitre (SL), Serra Negra (SN) and Tapira (TA) samples respectively. The time interval of the first box is defined as: corrected age ± 2σ, where σ is the weighted

standard deviation. The temperature interval was defined between 20–120 ^{0}C, which corresponds to the interval wherein the tracks are partially annealed over geological times.

The thermal histories accepted in the first treatment are linear cooling type ones, as can be observed in Figures 2 a, b, c. It can also be seen that this type of thermal history is not acceptable for the Tapira sample (Figure 2 d). The hypothesis that all the samples have a common thermal thus rules out linear cooling. Therefore, we pass on to the second treatment.

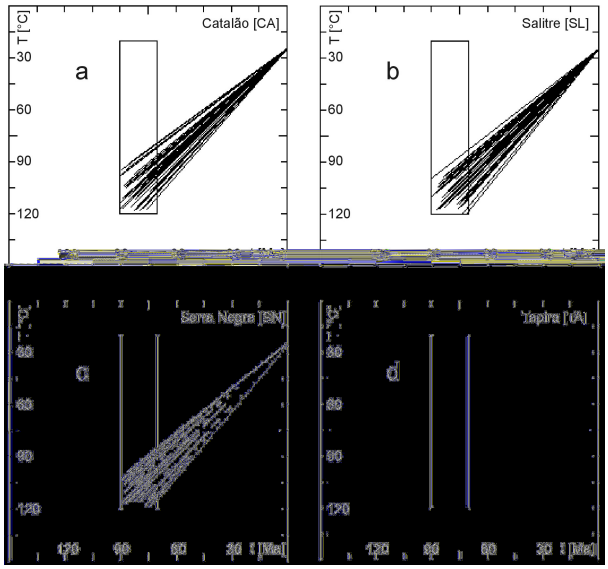

Figure 2: Temperature-time paths obtained with one Monte Carlo box.

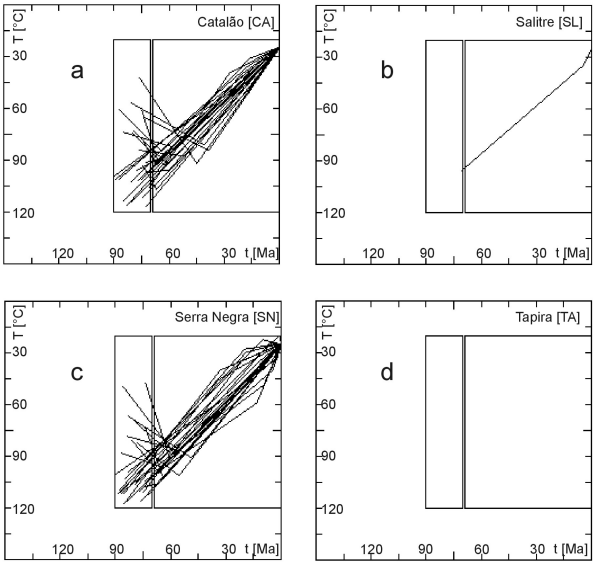

Figure 3. Temperature-time paths obtained with two Monte Carlo boxes.

In the second treatment, two Monte Carlo boxes are used (Figure 3a, b, c, d). The first box is the same as in the first treatment. The time interval of the second box is extends from the lower value of first box to 0 Ma. Thus, a greater variety of thermal histories can be tested. In this case, the accepted thermal histories continue basically to represent linear cooling. A second type of thermal history is given by a heating followed by a linear cooling. However, as these histories appear in a very small number, they should be statistically neglected. On the other hand, the Tapira sample (figure 3d) again did not accept either of the two types of thermal history. Again, this led us to carry out the third treatment.

In the third treatment, three boxes were used, as can be seen in Figure 4a, b, c, d. The first box was the same as in the first and second treatment. The second and third boxes were defined dividing in two the time interval of the second box of the second treatment. In this case, acceptable thermal histories were obtained for all four samples. For Serra Negra (Figure 4c), Catalão (Figure 4a) and Salitre (Figure 4b) samples there are different possible histories: a) linear cooling between ~80 Ma and 0 Ma, b) fast cooling to near-surface temperatures (~25^{0}C) at ~50 Ma, followed by heating during the interval 50-30 Ma, cooling again during the last 30 Ma, c) a thermal history similar to that described in b) except that the first cooling reached ~40 ^{0}C instead of surface temperature at ~50 Ma. Significantly, the data for the Tapira sample only agreed with the last thermal history. We conclude that the common thermal history of the samples, considered as a group, is c), because it is the only one that agrees with the data for all the samples.

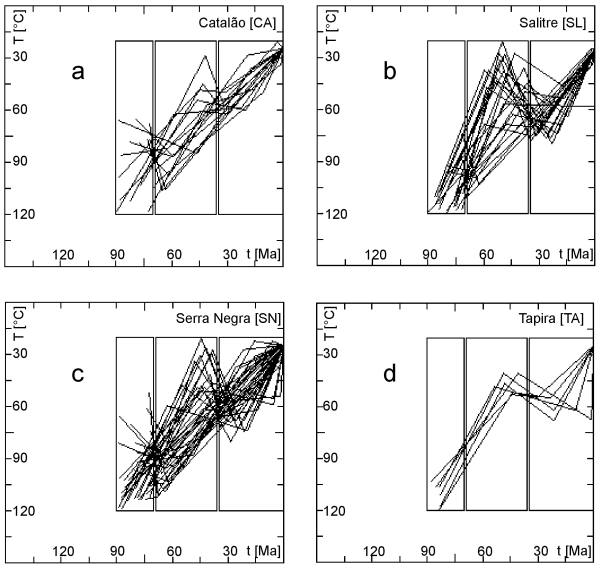

Figure 4. Temperature-time paths obtained with three Monte Carlo boxes.

In the fourth and fifth treatment the second box of the second treatment was divided in 3 and 4 for a total of 4 and 5 boxes, respectively. The thermal histories resulting from these two treatments (Figure5 a, b, c, d and Figure 6 a, b, c, d) are similar. We also see that those obtained with the third treatment are included in the following treatments. In other words, from the third treatment on, all the samples present basically the same thermal history. It is worth noting that more complicated thermal histories that were also generated were not compatible with the experimental results.

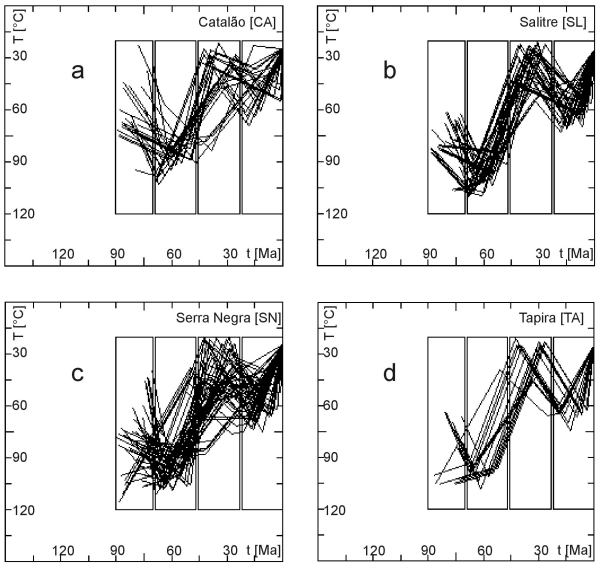

Figure 5. Temperature-time paths obtained with four Monte Carlo boxes.

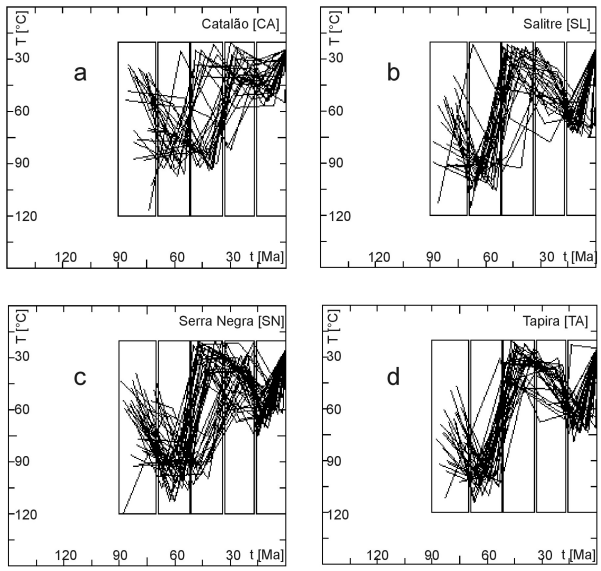

Figure 6. Temperature-time paths obtained with five Monte Carlo boxes.

CONCLUSIONS

Our approach has shown that that the common thermal history Serra Negra, Salitre, Catalão and Tapira samples involves fast cooling to ~40^{0}C at ~50 Ma, heating to 60°C during the interval 50-30 Ma, and renewed cooling during the last 30 Ma. Independent geological evidence must of course be taken into consideration to decide whether this result is acceptable. For instance, more complex thermal histories might be expected in regions of intense tectonic activity. In this case, it is indicated to search for thermal histories of greater complexity using three or four Monte Carlo boxes.

The important point concerning the approach presented in this paper is to take into account the common geological characteristics of the studied areas to find a common thermal history. Conclusive results can thus be obtained from a reduced number of samples.

The examples presented here also demonstrate that the results of thermal history modelling do not only depend on the actual input [apparent age and length distribution] but that they are very sensitive to the user-entered constraints [Monte Carlo boxes]. A stepwise approach like that presented here allows us to distinguish the different types of good-fit thermal histories that result from changes in the model constraints.

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Reactors in flux: A tabulation of irradiation parameters for several reactors

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In the last two years, many trackers may have shared my experience of getting an email or fax saying that the Risø DR3 reactor was closed, at first temporarily, then permanently. Although I only had the chance to use Risø for a few years, I was quite sad when I heard that the DR3 reactor was closed. They (particularly Ulf Jacobsen) provided a really high quality service for the FT-community. After the first shock came the horrid questions. Where should I send my next irradiation? How do I pack my samples for reactor X? What paperwork do I need? Will there be an effect on my zeta?

My first response to a problem (after a few sharp comments) is often to email a few people and ask for advice. Having pestered a lot of people in the last year, I thought that I would try to repay my debt by deflecting some of the questions, which might be repeated in the future. Therefore, I pestered even more people, with the goal of summarising the characteristics and logistics for a group of reactors. I hope that this will help trackers to compare between and choose a reactor the next time that they have to switch facilities.

Information on irradiation facilities is presented in two parts. Table 1 summarizes irradiation parameters and logistical data, which I have been able to track down. I have included information on Risø for comparison. Table 2 contains contact and reference information.

Details of sample packing, payment and irradiation permits always have to be dealt with on an individual (or at least national) basis. Therefore, I have only tried to provide a rough idea about these questions (Table 1) but have included contact information (Table 2) so that one can readily find out exactly what is required.

The question of how an irradiation influences zeta has been addressed by Hurford (1998). Comparing a robust database of zeta values determined by a single analyst from 4 well-thermalised irradiation facilities, the values were seen to vary by ±2%. Unfortunately, of these 4 reactors, only Lucas Heights is still available. However, providing that this condition is met, one should be able to change reactors without being greatly concerned about the effect on one's zeta value. Note that because the SRM glasses have an unusual isotopic ratio, they are more sensitive to the degree of thermalisation than the Corning glasses.

What is a well-thermalised reactor? In order to avoid epithermal ^{235}U or fast ^{238}U and ^{232}Th fission, which will bias an FT age, samples must be exposed primarily to a flux of thermal neutrons. The actual thermalisation required depends on the Th/U-ratio in the sample. According to Wagner and Van der Haute (1992), the thermal/epithermal flux ratio should be >50 and preferably >100. For absolute dating, it should be >200. The thermal/fast flux ratio should be >7.5 and preferably >80. A thermal/epithermal value of 100 corresponds to a cadmium ratio of 6.4 for Au and of 50 for Co.

In my naive youth, I used to say that it was best if the FT community used only a few reactors, so that we could readily compare our irradiations. However, it has become clear that we should also explore new possibilities for irradiations. Our group is currently applying for permission to irradiate at the Hahn Meitner Institute in Berlin; hopefully the next issue of On Track will contain a report on our results.

Acknowledgments

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Wagner G.A., and Van der Haute P. Fission-Track Dating, Solid Earth Sciences Library, 285 pp., Kluwer Academic Publishers, Dordrecht, 1992.

REACTOR INFORMATION CHARACTERISTICS	RISØ DR 3 graphite reflector	LUCAS HEIGHTS HIFAR X7 position	OREGON TRIGA Mark-II thermal column [inner face]	THETIS positions 6,7,8,15,16
Thermal fluence:	3.7×10^{13}	$3 - 5.7 \times 10^{12}$	1.0×10^{11}	$1.0 - 3.0 \times 10^{11}$
Epithermal fluence:	1.0×10^{10}		5.0×10^{08} [c]	$0.6 - 4.3 \times 10^{09}$
Fast fluence:	2.6×10^{10}		5.0×10^{08}	$0.8 - 5.0 \times 10^{09}$
Thermal /fast:	1423		145 [b]	60 - 120
Thermal/epithermal:	3700		200	70 - 160
Cd ratio for Au:		~125, ~98	14	
Cd ratio for Co:				
Radial gradient:			3%/cm	6% / cm
Axial gradient:		~ 5 %/cm		1% / cm
Foreigners ?	Closed	Yes	Yes	Yes
Price [nationals]		A$350 /can [?]	$ 200 (zr)	175 Euro /7h
Price [foreigners]		A$350 /can plus shipping	$ 400 (ap) plus shipping	175 Euro /7h incl. ship. [g]
Packing:		Ti cans [a] [supplied]	polyethylene	
Can size [mm] : [diam. x length]		20 x 50	23 x 90 price for 2 cans	19 x 70

REACTOR INFORMATION CHARACTERISTICS	VIENNA TRIGA Mark-II	PAVIA TRIGA Mark-II Lazy Susan Rot. spec. rack	PAVIA TRIGA Mark-II Thermal Column	KYOTO KUR
Thermal fluence:	1.0×10^{13}	1.0×10^{12}	3.8×10^{09}	4.0×10^{11}
Epithermal fluence:	[d]			6.0×10^{08}
Fast fluence:		$9.0\ 10^{11}$		8.0×10^{07}
Thermal /fast:		1.1		5000
Thermal/epithermal:				700
Cd ratio for Au:		6.5	31	~200 [f]
Cd ratio for Co:		48		
Radial gradient:				
Axial gradient:				
Foreigners ?	Yes	Yes	Yes [e]	No
Price [nationals]	Free	On demand		
Price [foreigners]	Variable, ± $80 /can	On demand		No commercial use
Packing:	plast. up to 80 h oth.: Al+quartz	plastic, Al can, glass, etc.	plastic, Al can, glass, etc.	plastic capsule
Can size [mm] : [diam. x length]	35 x 100	22.5 x 50	22.5 x 50	

TABLE 1: comparison of reactor parameters. Notes: [a] Mass of sodium containing glass must not exceed 15 g per can; total mass of can + contents must not exceed 55 g. Some users report problems with broken samples; [b] Extrapolated from 6" from face using 10%/cm gradient; [c] Measured 6" from face; [d] Epithermal neutron flux is high; induced Th-fission can be a problem; [e] thermal column is presently unavailable for FT-irradiations; [f] Cd-ratio is pers. com. [1988] Prof. M. Koyama to T. Tagami; [g] except by specialised transport.

Lucas Heights, HIFAR

ADDRESS: Australian Radioisotopes, Radiopharmaceuticals Division, ANSTO, New Illawarra Road, Lucas Heights, NSW, Australia.

WEBSITE: www.ainse.edu.au/

CONTACT: David J. Hurwood
Fax: ++61 (0)2 9717 9287
E-mail: dhx@ansto.gov.au

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Oregon State University TRIGA Mark-II

ADDRESS: Radiation Center, Oregon State University, 100 Radiation Center, Corvallis, OR 97331-5903, USA.

WEBSITE:
www.ne.orst.edu/facilities/radiation_center/index.html

CONTACT:
Steve Binney (Director): binneys@rc.orst.edu
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Vienna, TRIGA Mark-II

ADDRESS: Atominstitut der Österreichischen Universitäten, Stadionallee 2, A-1020 Wien, Austria.

WEBSITE: www.ati.ac.at/~kerntech/TRIGA_eng.htm

CONTACT: Doz. Dr. Böck:
Phone: ++43 1 58801-14168
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E-mail: boeck@ati.ac.at

Note that the Seibersorf reactor (Austria) is now closed.

Gent University, THETIS reactor

ADDRESS: Institute for Nuclear Sciences, Gent University, Proeftuinstraat 86, B-9000 Gent, Belgium.

WEBSITE:
http://allserv.rug.ac.be/~jddonder/AnalChem/incmain.htm#HOME

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See also On Track, issue 20 [June 2000], and the present issue.

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Balestrieri M.-L., Bigazzi G. and Oddone M. [1996]. The thermal column: a new irradiation position for fission-track dating in the University of Pavia Triga Mark II nuclear reactor. Journal of Radional and Nuclear Chemistry Letters, Volume 213, 99-108.

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ADDRESS: Division of Nuclear Safety Research, Isotope Production and Application, Research Reactor Institute, Kyoto University, Noda 1010-1, Kumatori-cho, Sennan-gun, Osaka, 590-0494, Japan.

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Etch times and operator variation for spontaneous track length measurements in apatites: an intra-laboratory check

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Some 20 years ago measuring confined spontaneous track lengths in apatite became an integral part of our work. Since that time it has become clear that this data set forms an essential component of apatite fission-track (AFT) analysis that has allowed us to attempt to derive plausible T-t paths from AFT data using whatever algorithm the operator chooses. We are all aware of the publications regarding the measurement of confined track lengths (e.g., Laslett et al. (1982) and review chapters in Wagner and Van den haute (1992)). However, before individual models (from different operators and different labs) can be directly compared, it is important to establish which of the various reported track-etching conditions yield equivalent track length information. We present a list (Table 1) of measurements of confined lengths in apatites from both the Fish Canyon Tuff and other apatites recorded by various authors using different etching conditions. We have chosen this data set somewhat at random but feel it is representative of the inconsistency and variation in etching conditions that exists.

WITHIN LABORATORY CALIBRATION

We were concerned within the laboratory at the ETH about consistency between operators using different etching conditions (all with $HNO_{3(aq)}$). What combinations of etching duration, temperature and concentration generate the same mean track lengths? This problem has been addressed in the past at the intra-laboratory scale and there may be some yawns from the "older" trackers as we report this. However, we feel that a further repeat is justified by the large range of reported etching conditions in the literature (Table 1), as well as the growing number of newly established fission-track labs. We would like to stress that the data set reported here is purely a laboratory test that we ran for our own internal check. However, we subsequently feel that this information will be of interest to the community. Not all operators were able to find the time to complete the full exercise, and hence we have not analysed the data statistically. The two main aims of this study were:

a) To analyse our within-laboratory operator variation by measuring etched confined spontaneous lengths in apatite extracted from the Fish Canyon Tuff. The etching conditions of each sample were kept secret from the operator.

b) A large range in etching conditions has been reported over the past 40 years (Table 1). These have tended to converge to two commonly used $HNO_{3(aq)}$ concentrations (5N and 1.6N (7%)). Therefore, the second aim of this study was to assess which etch times, at constant temperature (21.0±0.5°C), yielded similar mean spontaneous track lengths for these two etchants.

METHODS

We prepared mounts of Fish Canyon Tuff apatite in petropoxy resin on glass in the usual manner. Internal surfaces of the apatites were exposed and polished. In order to reveal the fission tracks the two standard etchants, 7% $HNO_{3(aq)}$ and 5N $HNO_{3(aq}$, were carefully prepared. The temperature of the etchants was controlled at 21.0±0.5 °C by immersing them in a thermostatically controlled water bath. Each mount was etched for a specific time followed by quenching in cold water for at least 30 minutes. For the

Table 1. Some examples of published etching data for length measurements [[a]: In: Gleadow et al. (1986)].

Analyst	Number of Tracks	Mean Length (µm)	Std. Deviation (µm)	Etching Conditions Time (s)	Temp (°C)	Etchant [$HNO_{3(aq)}$]	Microscope sett. Magn.	oil/dry
FISH CANYON TUFF								
N. Naeser, unpub. data	81	15.49±0.12	1.04	60	24	7%	1875	oil
A. Gleadow et al., 1986	100	15.60	0.91	20	20±1	5N	?	dry
P. Green, 1986 [a]	100	15.00	1.14	20	20±1	5N	?	dry
I. Evans 1986 [a]	100	15.30	1.00	20	20±1	5N	?	dry
OTHER APATITES								
Fleischer & Price, 1964				10 to 30	23	?		
Fleischer et al., 1964				25	23	?		
Green, 1985				20	room temp.	5N		
Bojar et al., 1998				35 to 40	20	7%		
Foster et al., 1994				20	room temp.	5N		
Crowley et al., 1991				40	20±1	7%		
Carlson et al., 1999				20	21	5.5N		

'fast etch' using 5N $HNO_{3(aq)}$, etch times were 17, 20 and 23 seconds. A large variation exists in the literature for the reported etch time (35 – 60 seconds) using 7% $HNO_{3(aq)}$ (Table 1). Thus for the 'slow etch' with 7% $HNO_{3(aq)}$, samples were etched for 35, 45 and 55 seconds.

Lengths of horizontal confined tracks were measured in apatite grains lying in the plane of the crystallographic c-axis using a drawing tube and digitising tablet. Tracks were measured using a dry objective with a total magnification of x1250 (operators B, C and D) and x1600 (operator A).

Results and Discussion

a) Between operator variation

As would be expected, the mean track length for each operator increased for both etchants as the duration of etching was increased (Figure 1). Furthermore, the etch rate (µm/s), obtained by interpolating between the average length measured for any given etching time, appears to be constant for each etchant for all etch times, displaying no obvious break in slope on Figure 1.

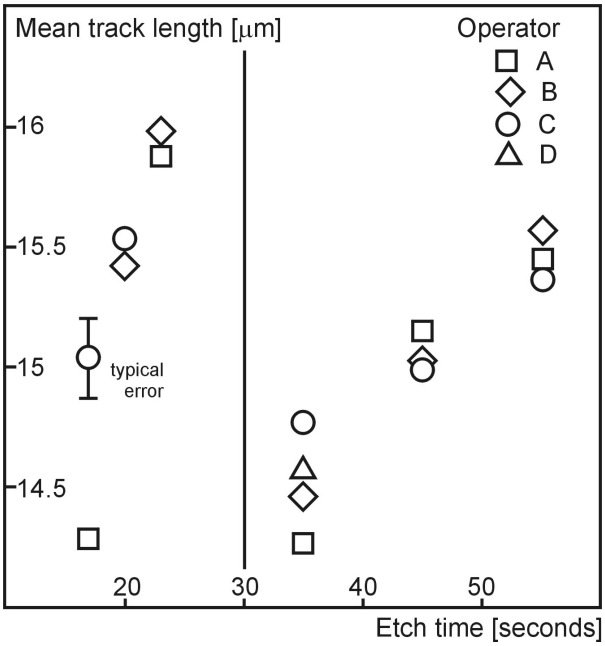

Figure 1. Mean spontaneous confined track length in Fish Canyon Tuff apatites, all etched at 21.0±0.5 °C for different times and measured by different operators

Fast Etch (5N $HNO_{3(aq)}$): Etching for 17 seconds revealed a significant spread of ~0.8 µm in mean confined track length between operators. Operator 'A' measured an average shorter mean length than operator C. 'A' was also able to locate 100 confined horizontal tracks on one mount whereas 'C' had to cover four mounts to find less than 100. There was clearly a difference in the definition of 'horizontal' at this level of etching. We were able to determine that operator 'A' was measuring tracks which were too far from the horizontal for short etch times (and not fully etched tracks), which resulted in an inaccurate, shorter mean length. However, for etch times of both 20 and 23 seconds the mean track lengths of each operator were indistinguishable; the mean length at 23 seconds was ~0.5 µm longer than at 20 seconds.

Slow Etch (7% $HNO_{3(aq)}$): Etching for 35 seconds revealed a significant spread of mean lengths up to ~0.5 µm. A majority of lengths appeared underetched. However, etching for 45 and 55 seconds resulted in smaller spreads (~0.2 µm) between operators.

b) Equivalence of etch times between etchants

The standard reported etch time used within the last 10 years for the 5N $HNO_{3(aq)}$ etchant is 20 seconds. However, reported etch times with 7% $HNO_{3(aq)}$ show a greater variation - from 35 to 60 seconds. Both etchants are reported at varying temperatures, some of which are quoted as 'room temperature'. Therefore, we chose to take etching with 5N $HNO_{3(aq)}$ for 20 seconds as our standard set of conditions for comparison with other concentrations. For this, our group reported mean confined track lengths varying between 15.26±0.13 and 15.54±0.17 µm for 5N $HNO_{3(aq)}$ at 21°C. Equivalent track lengths (15.38±0.14 to 15.58±0.10 µm) revealed with the 7% $HNO_{3(aq)}$ at 21°C were measured by the same operators after etching for 55 seconds.

Conclusions.

a) All operators were measuring statistically the same mean lengths for fully etched tracks at 21±0.5 °C for 5N $HNO_{3(aq)}$ at 20 seconds and 7% $HNO_{3(aq)}$ at 55 seconds.

b) The difference in time between each etching step in this study is 3 seconds (fast etch, 5N $HNO_{3(aq)}$) and 10 seconds (slow etch, 7% $HNO_{3(aq)}$). The mean confined spontaneous track lengths of each step in this study differ by ≤ 0.5 µm. Therefore it is plausible to suggest that the etching conditions reported in Table 1 are not equivalent and may result in significant track length variations. This study does not address how different etching conditions influence the measured mean lengths of significantly annealed tracks. However, if a similar relationship exists to the one presented in this study, then different etching conditions may result in the generation of different temperature-time models for the same rock. This alone could potentially result in a wide-ranging set of very different geological interpretations for the same region.

Next step and further thoughts….

In this experiment we ignored the influence of varying etching temperatures. 'Room temperature' is frequently cited in the literature but how does the temperature of your lab vary between the winter and summer? At the ETH in Zürich, room temperatures have varied between >25 and 16°C throughout the year. In the next issue of On Track we hope to present the results of some experiments, which will compare etched track length with etching temperature for a fixed etch time using the same two etchants reported in this study. A further interesting thought is the fact that the rate of etching (µm/s), obtained by interpolating between the average of each cluster at any given time, appears to be constant for each etchant for all etch times (Figure 1). We would expect the rate of etching to reduce as the latent track extremities are reached, exposing the etchant to more stable pristine lattice and subsequently forming tracks with 'rounder'

terminations.

Finally…. we are all aware of the qualitative relationship between etch time and mineral age in zircon. Does a similar relationship exist for apatites and is it significant within our required resolution? For example, etching of apatites from the Himalayas, which yield apatite fission-track ages of ~0.5 Ma, took at least 1 min 20 seconds in 7% $HNO_{3(aq)}$ at 21°C (Seward, unpublished data).

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The Thetis reactor of the Gent University (Belgium): Facilities for irradiation of samples for FT analysis

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The Thetis reactor of the Institute for Nuclear Sciences at the Ghent University is equipped with 16 pneumatically served irradiation facilities, five of which are interesting for FT-work:

Channel 8: thermal neutron flux ≅ 1×10^{11} $n.cm^{-2}s^{-1}$; thermal-to-epithermal neutron flux ratio ≅ 160; thermal-to-fast neutron flux ratio ≅ 120;

Channels 7 and 16: thermal neutron flux ≅ 1.7×10^{11} $n.cm^{-2}s^{-1}$; thermal-to-epithermal neutron flux ratio ≅ 120; thermal-to-fast neutron flux ratio ≅ 100;

Channels 6 and 15: thermal neutron flux ≅ 3×10^{11} $n.cm^{-2}s^{-1}$; thermal-to-epithermal neutron flux ratio ≅ 70; thermal-to-fast neutron flux ratio ≅ 60.

The reactor operates six days a month (on Tuesdays and Thursdays), each time during 7 hours [except during university holiday periods, e.g. mid-July till mid-August and between Christmas and New Year]. Thus, in one irradiation-day the thermal neutron fluences that can be obtained range from ≅ 2.5×10^{15} $n.cm^{-2}$ (channel 8), over ≅ 4.3×10^{15} $n.cm^{-2}$ (channels 7 and 16) to ≅ 7.5×10^{15} $n.cm^{-2}$ (channels 6 and 15). Evidently, irradiating the samples for more than one day will increase the fluences. The irradiation vials have a cylindrical internal space of 1.9 cm diameter × 7 cm height. There are small spatial thermal neutron flux inhomogeneities in the vials, the effects of which in our own work are corrected for by simple co-irradiation of relative flux monitors. Upon special request, the flux inhomogeneity in channel 8 can be reduced to a negligible level.

The above-mentioned facilities can be used by external FT-teams at a charge of 175 EUR per irradiation-day. Shipment by regular mail of the irradiated samples is included, at no extra cost, on condition that the legal regulations with respect to the activity of radioactive samples are applicable. For most of the samples that we irradiated thus far, shipment in this way was possible within a few weeks after irradiation. If earlier shipment is required, or if in general these regulations are not met, we have to call upon an external carrier specialized in isotope transports, which entails extra costs that we have to charge.

Laboratories interested in using these facilities are invited to contact: Frans De Corte, Institute for Nuclear Sciences, Gent University, Proeftuinstraat 86, B-9000 Gent, Belgium; phone: INT 32 9 2646627; fax: INT 32 9 2646699; e-mail: frans.decorte@rug.ac.be.

Fission-Track Papers

The following is a list of recent and soon-to-be published fission track papers that were submitted by the authors for inclusion in this issue of On Track. With 278 entries, the list is extensive but still far from complete. It may however serve as a starting point for compiling a 'complete' list of fission-track papers. We would all agree that such a list has practical use as a reference to what is happening in fission-tracks or in your study area. This cannot be achieved without everyone's active co-operation. So, if you have or know of a paper that you would like to see listed in this section, please send the complete reference or a photocopy of the first page to the editor. We are also interested in non-fission-track papers that may be of interest to the fission-track community.

1998

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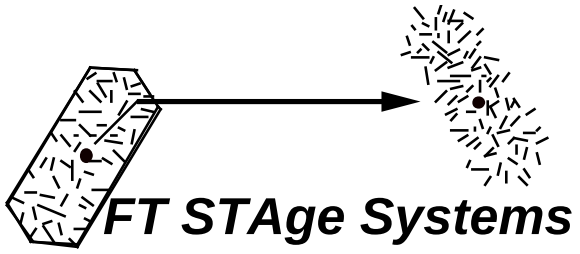

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Stage is driven primarily with the digitizing tablet cursor rather than a joystick. For example, to center a grain or track, just superimpose the cursor on it, push a button, and the stage automatically centers it. This avoids tedious manual centering via the joystick. Most software commands are driven from the cursor buttons, which are easily distinguished by feel, so there is no need to look away from the eyepieces to the computer screen or keyboard.

Fission Track Laboratories Using the System
(year installed; *adapted to a non-Kinetek stage)

- Stanford University, Stanford, California (1991)
- University of California, Santa Barbara, California (1992)
- ARCO Exploration and Production Technology, Plano, Texas (1992). Moved to University of Minnesota, Minneapolis, Minnesota, in 1999.
- Universität Bremen, Bremen, Germany (1993)
- E.T.H., Zürich, Switzerland (1993*)
- Kent State University, Kent, Ohio (1993)
- University of Wyoming, Laramie, Wyoming (1993)
- University of Arizona, Tucson, Arizona (1993)
- Max-Planck-Institut, Heidelberg, Germany (1993*)
- Union College, Schenectady, New York (1994)
- Monash University, Melbourne, Australia (1994*). Moved to University of Melbourne in 1999.
- La Trobe University, Melbourne, Australia (two systems, 1994*). Moved to University of Melbourne in 1999.
- University of Pennsylvania, Philadelphia, Pennsylvania (1995)
- Universität Tübingen, Tübingen, Germany (1995)
- Universidad Central de Venezuela, Caracas, Venezuela (1995)
- Brigham Young University, Provo, Utah (1995)
- Central Research Institute of the Electric Power Industry, Chiba, Japan (1995)
- Universität Salzburg, Salzburg, Austria (1996)
- University of Southern California, Los Angeles, California (1996)
- E.T.H., Zürich, Switzerland (second system, 1996*)
- Geologisk Centralinstitut, Copenhagen, Denmark (1996*)
- University of Waikato, Hamilton, New Zealand (1996*)
- Università di Bologna, Bologna, Italy (1997)
- Centro di Studio di Geologia dell'Appenno e delle Catene Perimediterranee, Florence, Italy (1997)
- University of Wyoming, Laramie, Wyoming (second system, 1997)
- Universität Potsdam, Potsdam, Germany (1997)
- Seoul National University, Seoul, Korea (1998)
- E.T.H., Zürich, Switzerland (third system, 1998)
- Universität Basel, Basel, Switzerland (1998)
- University of Florida, Gainesville, Florida (1998)
- Université Paris-XI, Paris, France (1998)
- Universität Graz, Graz, Austria (1998)
- Göteborgs Universitet, Göteborg, Sweden (1999)
- Universidad de Cádiz, Cádiz, Spain (1999)
- Universite Montpellier II, Montpellier, France (1999)
- Kurukshetra University, Kurukshetra, India (1999)
- Universität Tübingen, Tübingen, Germany, (second system, 1999)
- California State University, Fullerton, California (2000)
- Geoforschungszentrum, Potsdam, Germany (2000)
- Polish Academy of Sciences, Krakow, Poland (2000)

Further Information:

An early version of the system is described in a paper in Nuclear Tracks and Radiation Measurements, vol. 21, p. 575-580, Oct. 1993 (1992 Philadelphia Fission Track Workshop volume). For detailed information please contact: Dr. Trevor Dumitru, 4100 Campana Drive, Palo Alto, California 94306, U.S.A., telephone (auto-switching voice and fax line): 1-650-725-6155.

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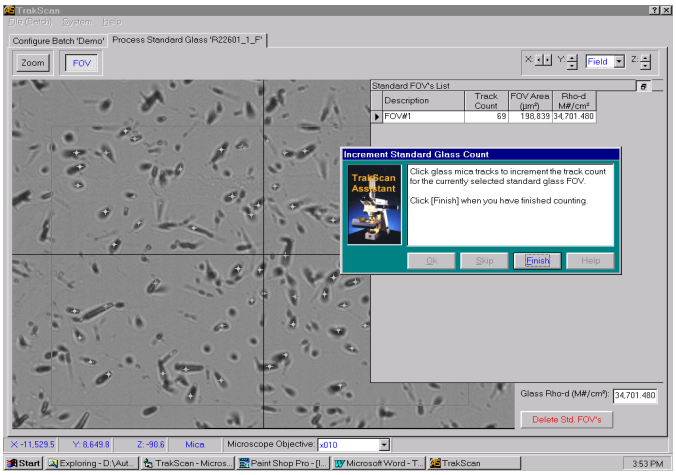

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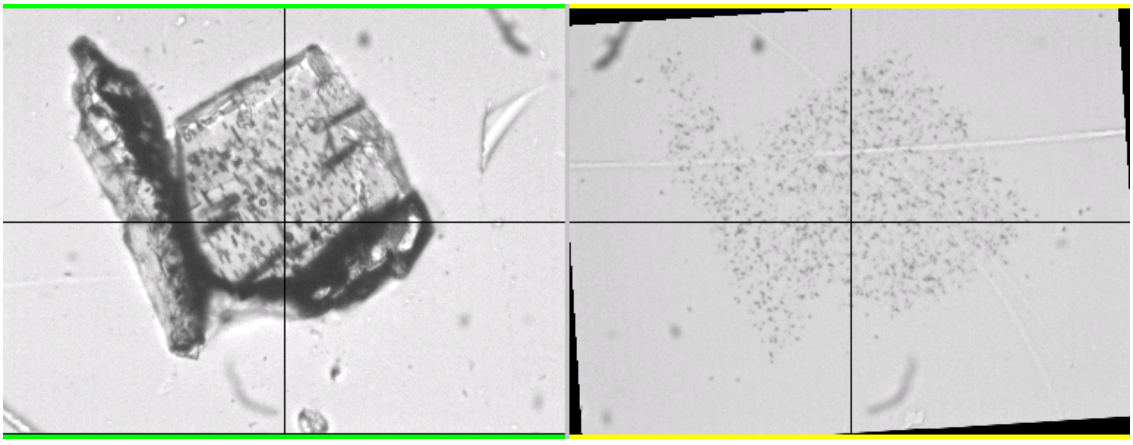

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International Fission-Track Directory

We regret that, for reasons of space, we cannot include the usual International Fission-Track Directory in this issue of On Track. Please consult previous issues or the Short Tracks section on page 3 for recently changed addresses. We are preparing a revised and extended list for the following issue, including members of the INTS. A considerable number of trackers now also have homepages, which we would like to include in the next list. If you want to have your homepage included in the list, if your e-mail has changed, if you have changed your address, or know someone else who has, please let the editor know [r.jonckheere@mpi-hd.mpg.de].

Call for Contributions

The next issue of On Track is scheduled for late July 2001 and we are looking for contributions. On Track welcomes contributions of virtually any kind, including scientific articles, news, gossip, job openings, descriptions of new lab techniques, reviews of useful products, ravings about what the other labs are doing wrong, meeting announcements, cartoons and descriptions of what you are doing in your research.

If you would like to contribute, please send the final document no later than **June 15, 2001**. If you intend to submit a substantial article, please let the editor know as soon as possible.

On Track includes a list of recent and forthcoming fission-track papers. If you know of a paper that was published recently or is in press and should appear in the list, please let me know so that it can be added to the list. Also, if you happen to change location due to a change in jobs or finishing off the thesis and graduating, please inform the editor.

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Afterthoughts

There is something fascinating about science. One gets such wholesale returns of conjecture out of such a trifling investment of fact. [Mark Twain]

There is one thing even more vital to science than intelligent methods; and that is the sincere desire to find out the truth, whatever it may be. [Charles Sanders Pierce]

I you can't prove what you want to prove, demonstrate something else. […]. In the daze that follows the collision of statistics with the human mind, hardly anybody will notice the difference. [Darrel Huff]

What see'st thou else in the dark backward and abysm of time. [Shakespeare - The Tempest]

And so it was Uranium, as old as the World herself, that must surely be the Mother of Time, giving birth to the Daughters of Decay. [Cherry Lewis]

If I was able to see further, it was because I stood on the shoulders of giants. [Isaac Newton]

If I was able to see further, it was because I was surrounded by dwarfs. [Murray Gell-Mann]

Do you not know I am a woman; when I think, I must speak. [Shakespeare - As You Like It]

Much as we would like to, we cannot afford to send a paper copy of On Track to every member of the fission-track community. Please pass this copy on to your colleagues. Additional copies can be photocopied or printed from the Adobe .pdf file.