ROCK PHYSICS, EARTH MATERIALS

Introduction

Geological and geophysical observations of the response of the Earth to naturally applied stresses, which vary widely in intensity and timescale, provide much of the motivation for the Rock Physics Group’s work. In the laboratory, ultrasonic wave propagation and lower frequency forced-oscillation methods are used to probe the elastic/anelastic behaviour which determines seismic wave speeds and attenuation. On longer time scales and at higher stresses, the mechanical behaviour of synthetic faults and fault gouge is studied with particular interest in the complex interaction between chemical reaction, crustal deformation and fluid flow. The fact that all but the simplest elastic behaviour of geological materials is controlled by microscopic defects such as dislocations and processes operative at grain boundaries, places a premium on the complementary microstructural studies involving light and electron microscopy.

Members of Rock Physics collaborate widely within RSES and beyond. Within the Earth Materials area of RSES, the preparation and characterisation of synthetic rock specimens and their precursors involves intensive collaboration between the Rock Physics and Experimental Petrology Groups. The interest in the structures and microstructures in naturally deformed rocks and related fluid-chemical studies is similarly widely shared – especially with members of the Structure/Tectonics group and the Thermochronology laboratories and the Department of Earth and Marine Sciences, Faculty of Science. Natural links with the Seismology Group, Earth Physics are based on a common interest in the interpretation of seismological models for the Earth’s interior.

The group’s current research has two main themes: seismic properties and interpretation and the coupling between fluid flow, deformation processes and reaction – led by Professors Ian Jackson and Stephen Cox, respectively. Vital contributions to the group’s research effort are provided by postdoctoral/research fellows Drs Ulrich Faul, Stephen Micklethwaite and Eric Tenthorey, and Ph. D. students Shaun Barker and Silvio Giger. The capacity to operate novel equipment, and the further development and timely exploitation of associated experimental techniques, depend heavily upon the skill and commitment of research support staff Messrs Harri Kokkonen and Craig Saint and Ms. Lara Weston along with the staff of the School’s Engineering and Electronics Workshops. Mrs Kay Provins provides critical administrative support for the Group, including responsibility for website development and maintenance. The Group pursues this ambitious research agenda using core funding from RSES boosted by several grants from the Australian Research Council.
Within the wider ANU community, the influence of the Rock Physics Group is felt in a variety of forums. For example, the ANU's flagship TEM which serves the needs of the campus materials science community is housed within the School and operated by John Fitz Gerald and Mr. David Llewellyn on behalf of the ANU Electron Microscope Unit.

The group also is committed to undergraduate and graduate teaching, and for many years has participated in the CSIRO Student Research Scheme with students from Canberra secondary colleges.

Seismic properties and interpretation

Coupling between fluid flow, deformation processes and reaction

Seismic properties and interpretation: the structure of the Earth’s mantle interpreted through laboratory measurements of seismic wave speeds and attenuation – introduction

Seismic wave speeds typically increase with increasing depth in the Earth’s mantle – the generally smooth variation evident in global average models being punctuated by discontinuous increases of 5-10% at depths near 410 and 660 km. Superimposed upon this radial variation is substantial lateral variability especially in the uppermost 300 km of the mantle and near the core-mantle boundary.

Are the discontinuities near 410 and 660 km depth simply the result of known pressure-induced changes in crystal structure or is the mantle sharply stratified in chemical composition? What causes the marked lateral variability of the shear wave speed and attenuation in the upper mantle? Variations in temperature? Compositional heterogeneity? Partial melting?

These questions are central to an understanding of the internal dynamical processes represented at the Earth’s surface by continental drift and plate tectonics. Answers require measurements on appropriate materials performed under controlled laboratory conditions of pressure and temperature.

The variation of elastic wave speeds with pressure and temperature, like thermal expansion, arises from asymmetry of the interatomic potential energy. Such ‘anharmonic’ variations of elastic wave speeds can be conveniently measured in the laboratory on mineral or rock specimens of ~0.1 mm – cm size at sufficiently high frequencies (MHz-GHz) by ultrasonic interferometry and opto-acoustic techniques (Fig. 1a). During the past decade, both single-crystal and coherent polycrystalline specimens of most of the major mantle minerals (including high-
pressure phases) have been characterised with these high-frequency methods. Much has been learned about the pressure, and more recently temperature, dependence of their elastic wave speeds. However, substantial uncertainties remain – especially as regards the combined influence of pressure and temperature.

At the much lower frequencies of teleseismic wave propagation (< 1 Hz) the shear modulus and hence both shear and compressional wave speeds may be profoundly altered at high temperature, and in the presence of fluids, by viscoelastic relaxation. The stress-induced migration of crystal defects (vacancies, dislocations and grain boundaries) and/or redistribution of interstitial melt results in additional strain and hence lower wave speeds accompanied by attenuation.

These effects have only recently become amenable to laboratory study through the testing of cm-sized cylindrical specimens at mHz-Hz frequencies with sub-resonant torsional forced-oscillation methods (Fig. 1b). Creep methods (Fig. 1c) probing microstrain deformations in torsion distinguish recoverable (anelastic) from permanent (viscous) strains, whereas axially compressive creep tests constrain the steady-state rheology at moderate strains (~20%).

The development and application of ultrasonic, forced-oscillation/microcreep and compressive creep methods - 2004 highlights:

High-temperature ultrasonic interferometry: applications to pyrope garnet and ScAlO₃ perovskite

High-temperature viscoelastic relaxation in olivine-dominated upper-mantle materials and its seismological implications

The moderate-strain rheology of melt-free olivine
High-temperature ultrasonic interferometry: applications to pyrope garnet and ScAlO$_3$ perovskite

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Elastic wave speeds are precisely measured by ultrasonic interferometry at high temperature and moderate pressure (300 MPa) in gas-medium high-pressure apparatus (Fig. 1).

For small specimens and temperatures $< 1000$ K an alumina buffer-rod tapered to roughly match the specimen diameter and an NaCl pressure-transmitting ‘cup’ is used. For higher temperatures (to 1600 K), a simple cylindrical buffer-rod and soft Fe cup are employed as in our recently published study of Fo90 olivine (Jackson, Webb, Weston & Boness, Phys. Earth Planet. Interiors 148, 85-96, 2005).

Elastic wave speeds have recently been measured at high temperature in both solid- and gas-medium apparatus for small polycrystalline specimens of pyrope garnet hot-pressed and characterised at Stony Brook as part of an ARC-NSF funded collaborative research program.

The temperature dependence of the wave speeds is particularly well-constrained by the data from the gas apparatus (Fig. 2a) whereas analysis of the combined dataset (Fig. 2b) yields the pressure derivatives of the elastic bulk and shear moduli and potentially useful constraints on the mixed second derivative $d^2M/dPdT$ (Gwanmesia, Jackson & Liebermann, AGU Fall Mtg, San Francisco, 12/04).
Elastic wavespeeds were successfully measured during 2004 on polycrystalline ScAlO$_3$ – a close structural analogue for the silicate perovskite MgSiO$_3$ – previously measured in the ANU laboratory by Jennifer Kung over a more restricted temperature range. The two datasets are broadly consistent and the analysis and interpretation of the combined dataset is underway.

The moderate-strain rheology of melt-free olivine

Faul, Kokkonen, Saint & Jackson

Our recent measurements of shear modulus and attenuation in pure, fine-grained solution-gelation-derived olivine at seismic frequencies (Jackson et al., JGR, 2002) have highlighted the need to better constrain the finite strain behaviour of these materials. Accordingly we have begun a program to determine the rheology of these materials through triaxial compressive tests in a Paterson-type gas medium apparatus. A particular aim is to determine the activation energy for diffusion creep over a similar temperature range as for the torsional forced oscillation data.

Individual experiments clearly show the transition from diffusion to dislocation creep at stresses of 100 to 150 MPa. When the diffusion creep data are normalized to a common grain size with a grain size exponent of 3, strain rates at a given stress for these genuinely melt-free samples are up to 2 orders of magnitude lower than those observed by Hirth and Kohlstedt (JGR, 1995) for nominally melt-free samples with grain sizes less than 10 micron prepared from natural olivine. However, our strain rates are similar to those reported by Beeman and Kohlstedt (JGR, 1993) for melt-free samples with grain sizes similar to ours. These initial results suggest that the presence of melt has a larger
effect on the strength of upper mantle rocks than has previously been reported (Faul and Jackson, AGU Fall Annual Meeting, 2004).

High-temperature viscoelastic relaxation in olivine-dominated upper-mantle materials and its seismological implications

Faul, Fitz Gerald, Jackson, Kokkonen & Saint

In recent years we have applied torsional forced oscillation/microcreep methods in seismic-frequency studies of the high-temperature viscoelastic behaviour of fine-grained materials based on the dominant upper-mantle mineral olivine. Initially we fabricated and tested a suite of dense, high-purity olivine polycrystals – establishing the 'base-line' behaviour in the absence of melt. The variations of both shear modulus G and strain-energy dissipation 1/Q with oscillation period, temperature and mean grain size were quantified. The behaviour is of the type commonly referred to as 'high-temperature background' in which 1/Q varies smoothly and monotonically with period and temperature without any resolvable dissipation peak. Qualitatively different behaviour has been observed for a second suite of olivine specimens containing basaltic melt fractions ranging between 0.01 and 4%. For these specimens, a broad dissipation peak superimposed upon a melt-enhanced background results in the more complicated frequency and temperature dependence displayed in Fig. 1b. The
high-temperature dissipation background and associated modulus dispersion are attributed to grain-boundary sliding with diffusional accommodation, whereas the peak seen only in the melt-bearing materials is thought to be caused by elastically accommodated sliding facilitated by the rounding of olivine grain edges at triple-junction melt tubules (Jackson, Faul, Fitz Gerald & Tan; Faul, Fitz Gerald & Jackson, J. Geophys. Res., 2004).

During 2004 we sought to extend to the basaltic melt-bearing olivine polycrystals a parameterisation of the viscoelastic behaviour based on a Burgers-type creep function. The attraction of this approach, already successfully applied to melt-free olivine, is the internally consistent description of the variations with frequency, temperature, grain size and melt fraction of both the shear modulus $G$ and the strain-energy dissipation $1/Q$. Torsional forced-oscillation data for individual melt-bearing specimens have been successfully described (Fig. 1) but we are still working towards a satisfactory model for the behaviour of the entire suite of melt-bearing specimens (Jackson, Frontiers in High-Pressure Research: Geophysical Applications, in press).

Such models, securely based on an appropriate creep function, provide a robust framework for application of the insights gained in the laboratory to teleseismic wave propagation in the upper mantle. Our model for the behaviour of melt-free olivine, first applied to the structure of the oceanic upper mantle, has this past year also been used to model shear-wave speed versus depth profiles for contrasting tectonic provinces within the continental upper mantle. It is found, for example, that the widely differing structures of the Archaean and Proterozoic terranes of Western and Northern Australia, and the Palaeozoic South-east can be plausibly explained by variations of the depth at which the conductive geotherm meets a common mantle adiabat (Fig. 2). The inference in both oceanic and continental regions is that most of the lateral variability of wave speeds (and attenuation) is of thermal origin (Faul and Jackson, Earth Planet. Sci. Lett., in press).
Coupling Between Fluid Flow, Deformation Processes and Reaction

Experimental, field-based, microstructural and numerical modelling approaches are being used to explore several aspects of coupling between deformation processes, fluid transport, reactions and the strength of earth materials in crustal environments.

Experimental studies have focussed on measuring changes in permeability of simulated fault gouges and cracked granitic materials in hydrothermally-active, isostatic stress regimes, as well as during deformation. In high temperature hydrothermal regimes, the permeability evolution of quartz gouges is found to be strongly dependent on the flow regime and grainsize of the materials. Flow of quartz-undersaturated fluid though the gouge is associated with much more rapid permeability reduction than is the case for a no flow regime. In cracked granite, permeability evolution in the presence of high temperature pore water is sensitive to competition between rates of growth of crack dilatancy and rates of by pore clogging due to growth of micas during hydrothermal breakdown of feldspar. The results have implications for understanding flow in fault zones, ore-producing hydrothermal systems, and in utilisation of geothermal energy resources.

Both field-based and numerical modelling studies are being used to further test our new model that mesothermal lode gold systems can develop in faults and related fracture arrays that are repeatedly reactivated during aftershocks.
following major slip events on nearby crustal-scale faults. New field and modelling case studies, in several well-explored areas in the Eastern Goldfields province of WA, have provided further support for the concept that co-seismic static stress changes associated with mainshocks and large aftershocks on high displacement faults provide a first order control on the distribution of gold deposits in fault systems.

Field-based studies are also using LA-ICPMS trace element studies of vein systems to explore evolution of fluid chemistry and growth of fracture-controlled fluid pathways during upper crustal. Cyclic changes in REE concentrations in vein calcite correlate with individual crack-seal events, and are interpreted as being related to episodic migration of fresh batches of pressurised fluid through the fault/fracture system in response to fault failure events. The work highlights the potential role of migrating pore pressure waves in driving repeated fault slip events and the growth of fracture controlled percolation networks.

**Permeability evolution in fault gouges under hydrothermal conditions**

Silvio Giger, Stephen Cox and Eric Tenthorey

The evolution of permeability ($k$) and porosity ($\Phi$) during rock deformation is of fundamental importance in understanding fluid transport through rocks. In particular, the time evolution of permeability and fluid pressures in active fault zones leads to shear strength being time-dependent, rather than constant, during the seismic cycle. This can play a critical role in controlling rupture nucleation and recurrence.

At depths of 10 –20 km in the normally low permeability continental crust, seismogenic faulting generates permeability, disrupts fluid pressure states, and drives transient redistribution of crustal fluids during and immediately after rupture. In hydrothermally active environments, compaction of fault wear products (gouge), and healing and sealing of fractures, then gradually reduce fault permeability in the interseismic interval. The time-dependence of permeability and thus fluid pressure evolution in fault systems accordingly plays a critical role in governing fault behaviour. In this study, we are exploring the time-dependence of permeability in artificial quartz fault gouges in high temperature, high pressure, hydrothermally active environments. The results will allow us to develop quantitative models of the effects of fluids in driving earthquake nucleation and recurrence.

We have examined the evolution of permeability during simulated interseismic fault healing using hot isostatic pressing (HIP) experiments at temperatures up to 1200K, confining pressures to 250 MPa, and pore water pressures of 150 MPa. To test grain size effects on the compaction process we used fine
(≤37µm), coarse (20-250µm) and intermediate (5-250µm) grainsize quartz powders. We performed two different types of experiments: (1) HIPing the sample for a given time and measuring permeability only at the end of the HIP (i.e. no fluid flow during compaction), and (2) HIPing with permeability measurements at many stages during compaction (i.e. episodic flow).

The initial k of all samples is of the order of 4x10^{17} m^2. The no flow experiments for all grainsize groups exhibited a k-decrease of less than 50% over 2 days (Fig.). Similar results were obtained during HIPping of the coarse gouge during episodic flow. However, during the episodic flow experiments on the fine and intermediate grainsize gouges, and initial period of slow permeability decrease in the first hour or so was followed by k-decrease of up to two magnitudes within less than 20 minutes. This sudden drop in k is followed by a further reduction at much slower rate, ultimately reaching a value around 10^{-19} m^2 after about 10 hours.

Fig. Top No flow vs. episodic flow experiments. Note the dramatic k-decrease of two orders of magnitude as an effect of flow. Bottom Fast k-decrease is also predominant even after previous HIPping for several hours. No k-decrease is detectable for coarser grained samples.
Finally, to test the history-dependence of the fast $k$-drop, we performed experiments in which a no flow period was followed by episodic flow. HIPing without flow prior to episodic flow had no significant influence on the rate of $k$-decrease once flow started.

Our experiments demonstrate that $k$ evolution in grain aggregates can be influenced markedly by fluid flow regimes. Especially at fine grainsizes, flow of silica undersaturated fluid through the gouge drives dissolution-controlled compaction at rates much faster than in the presence of stationary fluid. Accordingly, the time required for faults to shut-off fluid flow following rupture events will be strongly dependent on levels of saturation in the fluid, and also on flow rates. This has implications for rates of post-seismic fluid pressure recovery and rupture recurrence in active fault systems.

**Reaction-induced permeability change in thermally cracked and deformed aplite: Importance of reactive surface area and mineralogy.**

Eric Tenthorey and John Fitz Gerald

Figure 1. TEM micrograph showing muscovite laths precipitating on primary quartz and albite grains. In the centre of the photo, muscovite actually bridges
the gap between thermally cracked grains, elucidating the mechanism by which permeability reduction occurs.

This experimental program investigates hydrothermal reactions in a granitic system and attempts to quantify how such reactions affect hydrologic properties, namely specimen permeability. Understanding the long-term permeability evolution of rocks is crucial in current times, where environment and the idea of sustainable development are of paramount importance. Geothermal energy, disposal of radionuclides and sequestration of greenhouse gases are all closely reliant on the long-term physics of fluid flow in the Earth. Of specific interest here is the evolution of permeability under variable differential stress conditions, from the compactional and dilatancy regimes to that of shear failure. Under these different stress conditions, reactive surface area will vary, possibly affecting the rate and absolute magnitude of permeability change.

The experiments were conducted using a Paterson gas apparatus capable of independently controlling confining pressure (Pc), pore pressure (Pp) and axial load. Most experiments were conducted at Pc=100 MPa and Pp=50 MPa with temperatures of 200-600°C. Following the initial thermal cracking and permeability increase due to the application of temperature, specimens exhibited a gradual permeability reduction during hydrothermal reaction. We find that permeability decays by an exponential function of the form:

\[ k \propto \mu(1-e^{-rt})^2 \]

suggesting a precipitation type mechanism for the observed permeability change. Microstructural analysis of the post-experiment specimens reveals precipitation of muscovite on primary minerals (see figure).

Permeability was also found to decrease with time when deformed and held either in the compactional, dilatant or shear failure regimes. Overall, the reaction rate constant (r) was enhanced during dilatancy and after rupture, an observation suggesting a negative feedback effect, in which enhanced mineral precipitation moderates permeability generation during episodes of deformation.

As stated above, understanding and quantifying hydrologic behaviour in high temperature granitic systems is of paramount importance to a number of earth science disciplines. In particular, the results presented have important implications for precipitation-induced sealing in granitic fault zones, where hydrologic changes might alter various physical properties of the fault.
Figure 2. Reaction rate constant (r) plotted against differential stress. The rate constant describes the transient change in permeability as a new chemical equilibrium is attained. The rate is greatest during the dilatant and shear failure regimes, when the mineral surface area is greatest.

**Fault-slip, fluid flow and Stress Transfer Modelling for mineral exploration in ancient fault-related gold systems**

Steve Micklethwaite and Stephen Cox

Determining where large earthquakes and aftershocks repeatedly developed within ancient mineralised fault systems is proving to be a powerful tool for mineral exploration. The permeability evolution, fluid pathways, and distribution of mineral deposits in fault-controlled hydrothermal systems is dependent on coseismic permeability enhancement and interseismic fault sealing. Accordingly, exploring what factors influence where the highest permeabilities develop within active fault systems is providing insights about the controls on distribution of mineral deposits in gold-producing regions such as Archaean greenstone-gold provinces.

Stress Transfer Modelling (STM) is an exciting new technology that emerged from earthquake hazard prediction, and is now proving to be a successful tool in mineral exploration. In response to an earthquake on a major fault, the rock volume around the rupture undergoes changes in stress. Those regions where stress states are brought nearer to failure are closely associated with aftershocks
or triggered creep on smaller faults. Aftershock networks seem to be particularly important in controlling post-seismic redistribution of hydrothermal fluids in crustal-scale fault systems. The distribution of regions with enhanced aftershock potential can be predicted using STM. In our research, we have applied STM and shown, for the first time, that certain Yilgarn mesothermal goldfields occur where aftershocks and/or creep are predicted to have been triggered by rupture events on nearby crustal-scale faults in the past. STM is able to match distributions of brownfield gold deposits, identify new potential target areas and identify the regional structures responsible for mineralisation. We are able to explain why mineral deposits tend to be hosted by low-displacement faults adjacent to large-displacement regional faults, and why mineral deposits occur in clusters. The ST models also explain why some goldfields occur adjacent to contractional and dilational jogs in the regional fault system and why they are in a range of rock types.

Fig. STM results from the well-constrained St Ives goldfield. (a) Simplified fault map of the modelled area. The Boulder-Lefroy fault is the major first-order
driving structure. The Delta and Playa faults are poorly mineralised second-order faults in the goldfield, which are likely to have been triggered following ruptures on the Boulder-Lefroy fault. Mineralisation in the Revenge to Victory area is mainly on reverse faults, but in the Intrepide area it is mainly on strike-slip faults. (b)-(c) Zones of positive stress change for optimally oriented reverse and strike-slip faults respectively. Triangles are deposit locations, which are closely matched by the zones of predicted triggered slip. (d) Model result if the triggering of the Delta and Playa faults is not accounted for, highlighting the improved predictability of STM, if second-order fault slip is modelled.

In 2004 we further tested the application of STM in a number of well-explored brownfield and under-explored brownfield case studies. A major advance was made in the well-explored brownfield areas, where a good knowledge of fault architecture exists. We found that one or two large aftershocks, on second-order faults, can substantially modify the main shock-induced static stress changes. When we account for this behaviour, there is a precise correlation between the distribution of mineralisation on minor faults in the goldfield and modelled coseismic stress transfer. Application of STM in the two poorly explored brownfield case studies proved useful for identifying which regional structures were important for controlling the distribution of mineralisation, and defining large, goldfield-scale exploration targets.

Links between folding, faulting and fracture-controlled fluid flow – an example from the Lower Devonian Murrumbidgee Group, New South Wales

Shaun Barker and Stephen Cox

Coupling between deformation processes, fluid flow and fluid pressure states plays a key role in driving the growth of fluid pathways in hydrothermal systems, and also influences the evolution of the strength and mechanical behaviour of the crust. Exhumed vein systems contain a record of where fluid flow was localised, how flow has influenced the mechanical behaviour of the crust, and the nature of chemical fluid-rock interactions along pathways. We are combining field-based structural studies, microstructural and microchemical analysis, stable isotope studies, and fluid inclusion analysis to (1) explore the dynamics of the structural and geochemical evolution of a fracture-controlled hydrothermal system, and (2) examine the role of fluid pressures in driving deformation processes and growth of a fracture-controlled percolation network during folding and faulting in an upper crustal regime. Field studies are focusing on a one kilometre thick, upright folded, Lower Devonian carbonate sequence (Murrumbidgee Group) in the Taemas area of the Lachlan Fold Belt (south-eastern Australia).
Fluid flow during deformation of the Murrumbidgee Group was localised along fold-related and fault-related, high permeability fracture networks, and was associated with widespread development of calcite-quartz veins. Our previous stable isotope studies indicate that systematic vertical changes in O-isotope compositions of veins in the carbonate sequence are related to upwards migration of externally-derived, low $\delta^{18}O$ fluids across the base of the sequence, combined with kinetically-controlled oxygen isotope exchange during reaction with the host rocks along the structurally-controlled fluid pathways.

Major vein types at Taemas include (1) extension veins associated with stretching of fold limbs (dominantly in massive limestone), (2) fault-fill veins and associated extension vein arrays in low displacement, bedding-discordant reverse faults, and (3) bedding-parallel veins associated with flexural slip during fold growth (present in both shale and limestone units). Folding, faulting and veining are closely related. Many low displacement faults are accommodation structures formed during fold growth. Internal textures in many veins indicate growth involved cyclic failure and fracture sealing events (crack-seal), with some centimetre-scale veins recording up to hundreds of crack-seal growth increments.

Analyses of whole calcite veins reveal that the stable isotope composition is generally related to the trace element composition. Calcite veins with fluid-buffered oxygen isotope compositions generally have lower REE concentrations than samples with rock-buffered oxygen isotope compositions. Microscale analyses of bedding-parallel and fibrous calcite, by laser ablation ICPMS, demonstrate variations in trace element and REE concentrations of 100’s to 1000’s of ppm over distances of < 500 $\mu$m. Peak REE concentrations are spatially associated with crack-seal bands (Fig. 1). Regions of high REE concentration probably form due to preferential incorporation of REE into calcite by fractional crystallisation from small fluid batches early during each fracture sealing event, whereas calcite deposited late in the sealing cycle is relatively REE depleted.

These results provide some of the first geochemical evidence to support earlier theoretical arguments that crack-seal events and fault slip events, can be driven by episodic migration of fluid pressure pulses through fault/fracture networks. The geochemical results indicate that each pulse of fluid migration supplied a new batch of fluid which was enriched in REE relative to REE-depleted fluid left over from the previous pulse of fluid migration.
Figure 1:
(a) Photomicrograph showing the microstructure of the bedding-parallel vein analysed in this study. Note inclusion bands, and multiple crack-seal bands at approximately 25 degrees to inclusion bands. The start and finish of the laser ablation traverses on this specimen are marked (both inclusion band parallel and perpendicular traverses). Photomicrograph is approximately 20 mm wide. Note that the photomicrograph and distance versus concentration graphs (Figures 2b to 2d) are approximately the same scale.\n
(b) Distance versus silica concentration %wt. Peaks represent the locations of crack-seal bands.

(c) Distance versus Sr concentration (ppm). Note that sudden change in Sr concentration across 2 crack-seal bands at about 2 mm and 4 mm.\n
(d) Distance versus La (black line) and Ce (grey line) concentrations (ppm). Rare-earth element peak concentrations are typically slightly offset from inclusion bands.