of the lavas is in the order of 1-2 mm/a with a southwestward average direction of displacement. Based on these data, we suggest that a wide sector of Somma-Vesuvio is spreading on its plastic sedimentary substratum, which have been identified by drilling. Volcanic spreading appears to have controlled the magmatic evolution and the energy decrease of major historic explosive eruptions since 79 AD. If our interpretation is correct, major plinian eruptions should not occur in the near future. On the other hand, rifting around the caldera suggests that volcanic activity could soon be renewed.

V22A-0572 1330h POSTER

Gravitational and magma forced spreading of Mount Etna volcano revealed by InSAR data

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Mount Etna volcano underwent a cycle of activity over the past ten years from a large flank eruption ending in March 1993, to quiescence, followed by resumed summit activity in August 1995 and recent large flank eruptions in 2001 and 2002-2003. Observations from differential interferometric synthetic aperture radar reveal patterns of surface deformation that result from the changing magma and structural dynamics of the volcano. Here we compute a time series of ground deformation from more than 100 radar interferograms to reveal Mount Etna's time varying surface deformation from 1992 to 2001. We find that during this time interval it experienced magmatic inflation and radial spreading to the West, South, and East. Steady motion between the West-South flanks and between the East-North flanks during this time interval suggests they are related to gravitational spreading of the volcanic edifice. In particular, we find spreading across conjugate, arcuate crossing faults that fit laboratory models of volcano spreading. In contrast, time series analysis shows that southeastern basal anticline growth is not constant, but initiated with the end of magma recharge in 1995, thus showing a direct link between deep-seated magma intrusions and edifice spreading. We will present both results of the time series analysis as well as examples from numerous interferograms. Together these observations support a more complex mode of radial gravitational collapse underlain by deeper magma driven basal spreading.

V22A-0573 1330h POSTER

Large scale ground deformation of Etna observed by GPS between 1994 and 1999

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Using the GAMIT software, we processed 33 GPS campaigns carried out at Etna from 1994 to 1999. The temporal evolution at twenty-two points observed three times or more is analyzed. Our solution confirms, improves and extends the one previously published by Bonforte and Puglisi (2003), estimated for the period 1994-1996 processing their data with the Trimble GPSurvey 2.3 software. The times series at almost all points show no temporal change of the deformation pattern during the five years period. This suggests that at large scale the volcano evolved in a steady manner during this interval, although this was not the case for the eruptive activity registered at the summit, which varied from calm to episodically explosive during the same period. The deformation field is interpreted as the sum of a global inflation of the volcano and an eastward motion of its eastern flank. This measured eastward motion reaches 40 mm/yr along the Ionian coast, on the eastern and south-eastern flanks of the volcano, and is still 9 mm/yr on the southernmost border, in Catania. Previously published InSAR data covering the same time interval quantitatively agree with our GPS results. Moreover they allow to accurately assess the location of the active structures that decouple the mobile flank from the stable part of the volcano. To the South those are mainly the Nicolosi - Tremestieri fault and the Gravina fault and to the North the Pernicana fault. The GPS results show that the relative motion has the same direction of those three structures, highlighting that they are affected by pure shear strain, without almost any component of compression or extension. Our GPS solutions are not accurate enough to estimate vertical velocities, which in any case do not show evident trends, as horizontal components do, and are very little in magnitude.

V22A-0574 1330h POSTER

Rapid opening of the Asal rift in Afar observed with radar interferometry

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Located at the western end of the Aden ridge, the Asal rift is the first emerged section of the ridge propagating into Afar and the locus of intense volcanic and seismic activity. We use radar interferometry data acquired by the Canadian satellite Radarsat between 1997 and 2003 from both ascending and descending passes to measure the surface deformation in a 100 km wide region centered on the rift. The turbulent atmosphere in this sub-tropical region produces a phase delay error in the data exceeding the tectonic signal we seek. To estimate the deformation rates from the series of interferograms, we solve a least-square problem and derive the vertical and rift-perpendicular, horizontal components of the surface velocity from the series of ascending and descending line of sight observations by the radar. The resulting 2-component surface velocity map of the rift area shows the following features: A 40 km wide zone centered on the rift is inflating at a rate of 7 mm/yr. The 8 km-wide central rift subsides at a rate of 2mm/yr with respect to the shoulders of the rifts. The horizontal velocity indicates extension across the central rift at a rate of up to 20 mm/yr, gradually decreasing in the far field, the maxima of the horizontal velocity being located on both side of the rift, 12 km from its axis. This local opening rate exceeds the 13 mm/yr far-field plate motion between the Arabia and Nubia plates, suggesting that magmatic activity is currently controlling the opening of the Asal rift. Preliminary models shows that a 4 km deep dyke system expanding both laterally and upward accounts for the observed velocity field across the Asal rift.

V22A-0575 1330h POSTER

General Expressions of Internal Displacement and Stress Fields due to a Moment Tensor in an Elastic-Viscoelastic Layered Half-Space

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We succeeded in deriving general expressions of internal deformation fields due to a moment tensor in a gravitational two-layered elastic-viscoelastic half-space. In general, any indigenous source can be expressed in a form of moment tensor, and a moment tensor can be uniquely decomposed into three different types of sources corresponding to isotropic explosion, crack opening, and shear faulting. Among these three different types of sources, the expressions for shear faulting have been already obtained, but not for isotropic explosion and crack opening. To derive the expressions, we begin with the classical expressions of static displacement fields due to a moment tensor in an infinite elastic medium in Cartesian coordinates. Applying Hankel transformation to the expressions in Cartesian coordinates, we obtained the expressions in cylindrical coordinates. These expressions correspond to the special solution originated from a force term of the equilibrium equation of an infinite elastic medium. In order to obtain the general solution, the homogeneous solution for a two layered half-space must be added to the special solution. With a generalized propagator matrix method, we obtain the general expressions of internal deformation fields due to a moment tensor in a two-layered elastic half-space. The general expressions of internal deformation fields due to a moment tensor in an elastic-viscoelastic layered half-space can be obtained applying the correspondence principle in linear viscoelasticity to the elastic solution. In this presentation, as examples of numerical computation, we show the internal velocity fields caused by steady plate divergence at mid-ocean ridge. We also show the change in internal stress fields associated with magmatic intrusion.

V22A-0576 1330h POSTER

Dike Models of Tiltmeter Data From the 1984 Rifting Event at Krafla, Iceland: Testing for a Vertical Component to the Propagation Direction

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The September 4th 1984 Krafla fissure eruption occurred in northern Iceland at the end of the 1975-1984 rifting episode. The surface deformation resulting from the propagation of the feeder dike was monitored by three continuously recording tiltmeters located around the southern end of the 8.5 km long fissure, within the Krafla caldera. The tiltmeter time series (east and north components) were compared to models of dike propagation and magma chamber deflation by computing model-predicted tilt from both a growing dislocation and a deflating Mogi source in an elastic half-space. End-member models (vertical vs. lateral propagation) favored vertical dike propagation, indicating that there was an important vertical component to the propagation direction. However, dike propagation models that combined lateral and vertical dike propagation indicated that, below 1 km, the continuous tiltmeter network was inadequate for determining the depth at which the dike initiated vertical propagation. We also found that the fit to the continuous tiltmeter time series was improved by adjusting some of the dike and magma chamber model parameters. These parameters had been estimated based on EDM, leveling, and optical tilt data that spanned different time periods. We ran inversions of EDM, leveling, and optical leveling tilt data with the continuous tilt data to provide a realistic model for the dike and magma chamber parameters. Results from this study can improve our understanding of the magma transport mechanisms at Krafla and similar volcanic systems such as mid-ocean ridges.

V22B MCC: Level 1 Tuesday 1330h

Many Facets of Garnet: Recorders of Crust and Mantle Dynamics III Posters *(joint with T)*

Presiding: **D L Whitney,** University of Minnesota**; M Pertermann,** Swiss Federal Institute of Technology Zurich

V

V22B-0577 1330h POSTER

Garnet Solid Solutions: Microscopic-Macroscopic Strain and Implications for Thermodynamic Mixing and Trace Element Substitution Behavior

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The aluminosilicate garnets ($X_3Al_2Si_3O_{12}$ with X = Fe^{2+}, Mn^{2+}, Mg, Ca) are an important rock-forming solid-solution system. We are investigating their microscopic-mesoscopic crystal chemical properties using various spectroscopic, diffraction and computational techniques. The results are used to interpret and understand the bulk physical and macroscopic thermodynamic properties. The volumes of mixing of the six binaries in this system have been determined. Positive deviations from ideal thermodynamic mixing are observed for five binaries. They are largely a result of lattice strain arising from the exchange of X-site cations of different sizes. The magnitude of nonideality is a function of the volume difference between the two end members and can be described using a quadratic function that has a physical basis in strain theory. These experimental results are in excellent agreement with static lattice energy simulations that have been carried out. The simulations show a clear quadratic dependence for the magnitude of the excess volumes of mixing versus volume difference of the end members. Excess enthalpies of mixing behave similarly. The simulations demonstrate the importance of local structural distortions and site relaxation in affecting the thermodynamic mixing properties and strain in solid solutions. IR and Raman spectroscopic measurements give a measure of local structural heterogeneity over different experimental length scales. The phonon systematics, such as nonlinear variations in the mode wavenumbers and line broadening in binary solid solutions, can be correlated with thermodynamic mixing behavior. Wavenumber shifts correlate with excess volumes and line broadening with the enthalpies of mixing. ^{29}Si NMR measurements show the presence of short-range ordering of Mg and Ca (clustering) in pyrope-grossular garnets. The degree of order is related to the temperature of equilibration and has a measurable, but secondary effect on macroscopic strain. It can be expected that trace element substitution behavior in garnet is a function of microscopic strain. Our investigations show that the state of alternating bonds' best describes the bond behavior for the X-site cations. Thus, the presence of two quasi sublattices' will govern trace-element substitution at the X-site.

V22B-0578 1330h POSTER

Major and Trace Element Concentrations in Garnet Performed by Electron Microprobe and MicroPIXE

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The chemical composition of rock-forming minerals reflects their crystallisation history and provides information on the temperature and pressure conditions during their formation. Among metamorphic minerals, garnet is one of the most commonly studied in metamorphic petrology because a chemical zoning is often observed in porphyroblasts that potentially records the changes in the reaction history of the rock. In the past, only major element composition could be determined by non-destructive analytical procedure. However, at high temperature major element growth zoning may be significantly modified by intra-crystalline diffusion. Consequently, the study of trace elements distribution, which may be less susceptible to diffusional modification, becomes of fundamental importance. In this regard, an inverse correlation between yttrium concentration in garnet and metamorphic grade has been recently proposed for pelitic rocks (Pyle & Spear, 2000). This coupling is of great advantage as it may be used to calibrate new geothermometers based on exchange equilibria involving trace elements in garnet In the present paper, a micro-beam Proton Induced X-Ray Emission (micro-PIXE) analytical technique and a WDS electron microprobe (EPMA), were been applied to a specific geological problem particularly affected by the limitations of other techniques. The collected samples come from meta-pelitic samples belonging to the tectonic unit of Monte Rosa Nappe (Western Alps). Selected garnet crystals were analysed for major (Si, Al, Mg, Ca, Mn, Fe) and trace elements. The former were analysed by EPMA and the latter by micro-PIXE. The considered garnet crystals show well-defined compositional zoning, characterised by a smooth and concentric variation of the selected elements from core to rim. As regards the trace elements distribution, the two-dimensional X-ray maps display a strong Y enrichment in the core, followed by a flat pattern at the inner and outer rim. Y concentration spreads over and interval of two orders of magnitude, from about 50 ppm at the rim, to almost 2500 ppm at the core. Comparing the sharp Y pattern distribution with the smoothed profiles shown by major elements, no correlation can be supposed; only a weak similarity between Mn and Y pattern can be observable. In addition, the sharp and steep Y profiles suggest that the diffusion of Y through the garnet may be very slow compared to the major elements, which were strongly modified by diffusion at high temperature. The slow diffusivity of trace elements in garnet allows the recognition of most petrologic events that were either unrecorded by major elements, or were recorded but subsequently obliterated by high-temperature diffusive re-equilibration. Pyle J.M. & Spear S.S. (2000) - Contrib. Mineral. Petrol., 138, 51-58.

V22B-0579 1330h POSTER

Obtaining Age Information on Metamphic Process Using Mn and HREE Diffusion in Garnets

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Garnet is the main mineral containing Mn and HREE in metamorphic rocks. Usually Mn and HREE exhibits some zoning in garnets. Both Mn and HREE contents increase with temperature drop. Garnets from the polymetamorphic Belomorian complex (Tupaya Guba region) were studied using ion microprobe. These garnets from the gneisses are related to high pressure granulite stage 2 followed without interruption by high pressure amphibolite stage 3 (Drugova, 1999). The garnets are untypical zoned in HREE as low-grade garnets. HREE drop rimward significantly. The minimum temperatures of metamorphism were determined as 730-760° for garnet core and 680-700° for garnet rim by garnet-biotite thermometer. The pressure was constant - about 6.5-8 kbar. HREE exhibit a Rayleigh fractionation profile, Mn concentration has been homogenised to flat profile (1,18 wt. per cent at the core and increase in the outer rim upto 1,73 wt. per cent). It can be explained only by quick time (approximately 10-15 Ma) estimated for the metamorphic event. HREE diffusion rates more than two orders of magnitude slower than Mn diffusion rate (Van Orman et al., 2002), and more time of metamorphic event is required to homogenise the HREE profiles. The alike results of modelling of trace element and Mn data were presented for garnets from the Zanskar area of the Indian Himalaya - 3-10 Ma estimate for the metamorphic event (Ayres & Vance, 1994). References Drugova, G.M., Principal stages in metamorphic evolution of Chupinskaya series in Belomorsky folded belt. Proc. Rus. Min. Soc., No 3, 49-57 (1999). Van Orman, J. A., Grove, T. L., Shimizu, N. et al., Rare earth element diffusion in a natural pyrope single crystal at 2.8 Gpa. Contribs Mineral. Petrol., Vol. 142, 416-424. (2002). Ayres, M. and Vance, D., Constraints on the thermal evolution of the Indian Himalaya from manganese and erbium distributions in metapelitic garnets. Mineral. Mag., Vol. 58A, 34-35. (1994).

V22B-0580 1330h POSTER

Mode of Occurrence, Chemistry, Equilibrium Domain, and Texture of Non-equilibrium Growth of Garnet and PT Evolution of Regional Metamorphism

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The bell-shaped Mn distribution of garnet was noticed in the Sanbagawa belt in 1965. The sequence of mineral zones from low to high temperature of this belt, ascending as the chlorite, garnet and biotite zones, has been questioned as it owes to high Mn and high Ca contents of the pelitic rocks. However a trial pseudosection (Matsumoto and Banno to submit) shows that it is due to nothing but higher pressure of metamorphism. Garnet presumably formed maintaining surface equilibrium with chlorite, epidote and calcite. We confirmed Goto et al. (2002)'s notion that the pelitic schists of the Sanbagawa schists in central Shikoku contain calcite by further examining the cores of 3 drill holes of 2000m long. It follows that garnet forms at lower temperature and pressure than hitherto considered as grossular is formed more easily by calcite-bearing assemblage than that free from it. Garnet from Sanbagawa pelitic schists shows, 1) different mineral zones have slightly different P-T paths, 2) Ca maximum in concentrically zoned garnet shows that the maximum pressure is reached in a middle grade of prograde metamorphism, 3) garnets that grew in a volume of 1cm3 or so have the same zoning pattern suggesting that the domain of equilibrium is fairly large. Thus garnet is an excellent tool to decipher the P-T path of the Sanbagawa regional Metamorphism. A few new types of garnet zoning formed by non-equilibrium crystallization have been found. The first type is the vicinal sector zoning that develops normal to crystal surface. The second type is concentric zoning with Mn-poor core from which XMn increases gradually to the smooth maximum in the midst of garnet (figure for Mn). After the maximum is reached XMn decreases to the rim where XMn is similar to the value of normal garnet porphyroblast. We define the normal zoning for the crystal grows without, in extreme case, body diffusion under fractionation (e.g, plagioclase in igneous fractionation and garnet in prograde metamorphism) and reverse zoning vice versa. The reverse zoning mentioned above forms when the system is rapidly brought to multi-components reaction volume (Banno, to submit). Reverse zoning can be numerically simulated by using the non-equilibrium model with various initial conditions (Kitamura, to submit) to find optimum conditions to particular garnet. Garnets formed by these processes occur characteristically nearby the epidote amphibolite masses, retrograded eclogites. This suggests that those masses had higher temperature than that of the Sanbagawa schist to which they emplaced.

V22B-0581 1330h POSTER

Significance of Ilmenite for REE and P Distribution in Garnet From Metapelitic Schists

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The distribution of trace elements in metamorphic minerals such as garnet and monazite is of interest in studies of the timing and conditions of petrologic and tectonic events. We have analyzed major element concentrations and trace element zoning in garnet and ilmenite in metapelitic rocks from the garnet, lower staurolite, and upper staurolite zones of the Barrovian sequence in Dutchess County, New York. This study was in part motivated by the observation that ilmenite in these rocks contains trace elements of interest, such as Ce, P, and possibly Y. In the garnet zone sample, minute grains of phosphate minerals (apatite, monazite) are ubiquitous as inclusions in garnet and as matrix phases, and occur in both the trace element-rich, Ca-poor garnet core and the trace element-poorer rest of the garnet. Garnet cores are relatively enriched in Y, Yb, and Sc; the Sc-enriched core region is larger than the Y-rich region, which is in turn larger than the Yb-rich core region. Ilmenite inclusions occur only outside these trace element-enriched regions. Staurolite zone samples show a similar distribution of phosphate minerals, but Y zoning in garnet is reversed, with Y-poor cores and Y-richer rims. Unlike in the garnet zone, the garnet core is enriched in Ca, and ilmenite occurs as inclusions in the Ca- and Yb-rich core. Both inclusion and matrix ilmenite from garnet and staurolite zone samples can be seen in X-ray maps to contain elevated Ce, P, and Yb relative to the host garnet outer core/rim. In all samples, some inclusion ilmenite is significantly higher in Mn than matrix ilmenite, and negatively correlated with Fe. Mn partitioning between ilmenite and garnet is well behaved in the staurolite zone, but more erratic in the garnet zone. With our preliminary data, we have documented the potential importance of ilmenite as a carrier of trace elements such as Ce and P in metapelitic rocks, indicating that ilmenite must be taken into account when considering metamorphic reactions that account for REE and other trace element zoning in garnet, and in particular equilibria involving garnet and phosphate minerals.

V22B-0582 1330h POSTER

Fracture Toughness of Silicate Garnets: Applications and Preliminary Data

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A novel technique for assessing and possibly quantifying the magnitude of high-temperature decompression and the unroofing pressure-temperature trajectory of formerly deep rocks involves interpreting microcrack patterns in garnet. Of particular interest are microcracks that radiate from mineral inclusions, as their formation is likely initiated by decompression. By documenting the conditions at which the difference between lithostatic pressure and the internal pressure on mineral inclusions (e.g., quartz, plagioclase) will fracture a host garnet in a radial pattern about the inclusion, it may be possible to calculate tectonic variables related to exhumation of mid- to lower-crustal rocks. Application of such techniques has been hindered by a lack of information about the fracture toughness of silicate garnets. Previous modeling of garnet fracture mechanics used data from YAG (e.g., Whitney et al., 2000). We have obtained contact deformation and fracture data on silicate garnet (almandine-pyrope solid solution) using microindentation and depth-sensing indentation (nanoindentation) techniques. As a preface to the garnet study, a systematic study of the minerals in the Mohs hardness scale was conducted in which hardness, modulus and fracture toughness data were obtained. The results indicated that neither of the above material properties vary monotonically with Mohs number. This is unsurprising in that scratch testing, the basis of the Mohs classification, is affected to different extents by hardness, modulus and fracture toughness values for each mineral. For example, while almandine-pyrope garnet has hardness and modulus similar to topaz (H = 21 GPa; E = 265 GPa), the garnet's fracture toughness is near that of calcite (T = 0.187 MPa*mE0.5). Here we report contact deformation and fracture data for a variety of end-member garnets.

V22B-0583 1330h POSTER

MODELLING THE FORMATION OF ELLIPTICAL GARNETS DURING HIGH STRAIN IN A PARTIALLY MELTED METAPELITE

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Some metapelitic xenoliths in the NVP (Neogene Volcanic Province) of SE Spain, display the development of high strain zones during partial melting. These rocks are composed of biotite (XMg= 0.29-0.35, TiO2= 4-7 wt %), sillimanite, plagioclase (An%= 45-55), garnet, hercynite (XMg = 0.15-0.20), cordierite (XMg = 0.45), graphite and melt. Melt of granitic composition occurs as inclusions in minerals and as intergranular pockets. In the high strain zones, the foliation is outlined by layers of oriented fibrolite, biotite, graphite and melt, which wrap around crystals of garnet ranging in shape from elliptical to sigmoidal. Elliptical garnets may have aspect ratio up to 4:1. Both from microstructural and chemical ground, the garnets are characterized by well distinguishable core and mantle. The core typically contains primary inclusions of biotite and melt, trapped during garnet growth. The concentric pattern of inclusions of garnet core is often truncated at strain caps. This part of the garnet is chemically homogeneous, with a composition of Alm76-Pyp08-Sps14-Grs03. The cores are surrounded by a thin (100 mm) mantle, which is irregular in shape and appears to overgrow the foliated matrix around garnet. Along the strain caps these mantles are rich of oriented fibrolite inclusions, whereas they are intergrown with biotite at strain shadows. In places, the overgrowths form skeletal elongated arms which extend parallel to the foliation. Compared with the cores of garnets, the overgrowths have composition poorer in Mn, but maintain the same XMg= 0.85. These elliptical garnets might be interpreted as a result of: a) crystal plastic deformation b) dissolution (and redeposition) c) constrained growth Investigation by means of orientation contrast imaging and electron backscattered diffraction, leads us to rule out crystal plasticity as a possible mechanism. Based on the observed intracrystalline microstructures and chemical zoning of garnet we can model the formation of elliptical garnets in multistage sequence. After growth of idiomorphic garnet cores, rich of melt inclusions and high in Mn, a process of pressure-solution - redeposition occurred during foliation development, with dissolution at strain caps and growth of garnet poorer in Mn in the strain shadows. In a later episode, after the strain event ceased, a mantle poorer in Mn continued to grow all around garnet. The elliptical shape and the skeletal arms were constrained by the adjacent foliation, and garnet included trails of oriented matrix phases, mainly biotite and fibrolite. Grt-Bt thermometry of the elliptical garnets provides high temperatures, in the range 800-950°C, and in agreement with the Grt-Crd thermometer. There are no systematic differences in T among the different microstructural domains (core, strain shadow, strain cap, skeletal arm) of elliptical garnets. This suggests that high temperature conditions were present throughout the whole garnet development, which is in accordance with the presence of melt both within and outside garnet.

V22B-0584 1330h POSTER

Origin of Poikilitic Garnet in a Leucogranite Dike

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Garnet is a common accessory phase in aluminous granites. Its origin has been variously attributed to: incorporation of xenocrysts; solid-state replacement; reaction between solid or early-formed phases and granitoid melt; crystallization directly from granitoid melt. Here, we describe garnets from a leucogranite dyke from the Isle of Man. The garnets are typically 0.5 mm sized, Mn-rich, poikilitic, faceted crystals occurring as skeletal clusters up to 3 mm across. Magmatic origin has been previously suggested for these garnets, but there are problems with this interpretation. The garnets are strongly poikilitic, except at contacts with muscovite where wide (300-500 microns) inclusion free faceted rims develop. Inclusions are almost entirely quartz grains, which tend to be a little smaller than matrix quartzes (86 vs. 110 microns), but have a similar frequency per unit area (c. 550 crystals per sq mm). Both matrix and inclusion quartz crystals display a weak shape alignment and a random crystal preferred orientation, determined using electron backscatter diffraction (EBSD). It is not clear if the shape alignment is an igneous or subsolidus fabric, but either way the implication is that garnet nucleation and growth must have been either very late in the magmatic history or subsolidus (i.e. after nucleation of quartz completed). Microprobe study indicates that the garnets are strongly, concentrically zoned, typical of Rayleigh fractionation during growth from a melt. EBSD indicates that garnets in a cluster have similar crystallographic orientation indicating either multiple nucleation of similarly oriented garnets or subsequent rotation of garnets into a similar orientation. The general absence of non-quartz inclusions together with the development of inclusion free rims at muscovite contacts, suggests a coupled solution-precipitation mechanism. Formation of Mn-rich garnet from a final stage granitoid melt/fluid could involve nucleation of garnet at a favourable site coupled with diffusion through the fluid phase of garnet components to that site, dissolution (Pl+Kfs+Ms) and precipitation (Grt). The skeletal garnet geometry may reflect growth along end-stage melt/fluid pathways.

V22B-0585 1330h POSTER

Submicron Mineral Inclusions in Garnet: a Key to Unravelling Otherwise Unrecognized Metamorphic Events

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Mineral inclusions are important in metamorphic petrology because they can often be used to establish prograde portions of the pressure-temperature (P-T) path, earlier P-T histories and tectonic events of metamorphic terranes that might be difficult to derive from host minerals alone. These mineral inclusions generally are micrometers in size and can be studied through careful microscopic observation and electron microprobe analysis. However, if the inclusions are of submicron (i.e., nanometer) size, they cannot be identified by conventional methods and are often overlooked. Such tiny inclusions can now be identified by analytical electron microscopy and have the potential to reveal otherwise unrecognized metamorphic events as demonstrated by us in the examples including (a) submicron polyphase inclusions in garnet of metapelite from the Tananao Metamorphic Complex, Taiwan; (b) nanometer-size alpha-PbO2-type TiO2 in garnet of ultrahigh-pressure gneiss from Erzgebirge, Germany; and (c) diamond-containing multiphase inclusions in garnet of ultrahigh-pressure gneiss from Erzgebirge, Germany and in ultrahigh-pressure garnet-clinproxene-quartz rock from Kokchetav, Kazakhstan.

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Polymetamorphic Garnets in the Menderes Massif (Western Turkey): Insights into the Metamorphic History of a Complexly-Deformed Region

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The Menderes Massif in the Aegean region is a prime example of an area that experienced a complex, multi-stage metamorphic history. Post-collisional extension exhumed the Menderes Massif, which covers an area of >40,000 km^2. The Massif experienced polyphase deformation, but distinguishing Pan-African events from Alpine metamorphism, and discriminating Eocene-Oligocene compression from the post-collisional extension are controversial. To identify if Menderes Massif garnets record this polymetamorphic history, we used an electron microprobe to X-ray element map and identify zoning types. One southern Menderes Massif sample has garnet + biotite + muscovite + chlorite + plagioclase + ilmenite + zircon + allanite + monazite + quartz. X-ray element maps of the garnets show a discontinuous Mn increase not found near minerals characteristic of retrogression, defining a $\sim$30-μm plateau. The Mn increase appears at the same location as a sharp Ca decrease and Mg increase. The profile leaves open the possibility the garnets grew during two stages and/or experienced a change in bulk composition during rim growth. One garnet from the Kuzey Detachment, which bounds the northern edge of the Central Menderes metamorphic core complex, shows no zoning in Mn, Fe, Mg, or Ca, and has a 483±5 Ma monazite inclusion. This result indicates the sample experienced significant diffusional relaxation since its time of formation. Garnet-based P-T conditions are frequently used to evaluate and develop models for the tectonic evolution of the Menderes Massif. If the garnets are detrital, polymetamorphic, or developed during a previous metamorphic event, using their compositions in combination with matrix minerals generates misleading conditions and erroneously constrained tectonic models.

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Comparison on geochemistry of minerals in garnet peridotites from Paleozoic and Neogene xenoliths and from Triassic UHP terrane to constrain the lithospheric evolution of east China

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Major and trace element data of minerals in garnet peridotite xenoliths from early Paleozoic (457-500 Ma) and Neogene (16-18 Ma) volcanics within the North China Craton are compared with those from tectonically exhumed Triassic Sulu ultra-high pressure (UHP) terrane along its southern margin. Estimated P-T conditions of the Paleozoic and Neogene garnet peridotite xenoliths reflect different geotherms corresponding to surface heat flow of $\sim$40 mW/m^2 (Paleozoic) and $\sim$80

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mW/m^2 (Neogene). Paleozoic peridotite xenoliths are compositionally similar to cratonic mantle; they have high Mg number in olivine (mean 92.7), Cr number in garnet (mean 27.6), and Ni and La/Yb (19-25) in clinopyroxene (Cpx). They have low Al_2O_3, TiO_2, HREE and Y in Cpx, low Y/Ga in garnet (0.33-1.34), and show LREE-enriched pattern of Cpx. Neogene peridotite xenoliths represent a more fertile mantle with low Mg number in olivine (mean 89.5), Cr number in garnet (mean 3.5), and La/Yb (2.5-3.3) in Cpx. They have high Al_2O_3, TiO_2, HREE and Y in Cpx, and high Y/Ga in garnet (8.45-20.7), and show flat REE pattern of Cpx. The differences suggest that the buoyant refractory lithospheric keel present beneath the eastern part of the North China Craton in Paleozoic time was largely replaced by younger and hotter fertile lithospheric mantle during late Paleozoic-Paleogene time. The Triassic Sulu UHP peridotites have lower Mg# in olivine (91.5±1.0) and garnet (73.2-82.0), Cr# in garnet (1.9-18.3), and Al_2O_3 of orthopyroxene (0.15-0.34) than the Paleozoic xenoliths. Cpx in the peridotites contains very low HREE (0.02-0.29 ppm) and incompatible trace elements (except Sr), displays sinusoidal to LREE-enriched patterns with La/Yb of 80.3-143 and exhibits distinctly negative Nb, Zr and Ti anomalies. Garnets have low REE and strongly negative Ce anomalies (δ Ce=0.24-0.56), and Y, Cr_2O_3, Nd/Y and Sc/Y are typical of highly to moderately refractory mantle. The UHP peridotites are interpreted having evolved from Paleozoic-like protoliths through interaction with crust-derived carbonatitic and silicate melt/fluids, before UHP metamorphism. Exhumation of the Sulu UHP rocks may have occurred in an extensional regime allowing the asthenospheric upwelling. Peridotites sampled by Neogene basalts represent the newly accreted lithosphere derived from cooling of the upwelling asthenospheric mantle in Jurassic-Cretaceous and Paleogene time.

V22B-0588 1330h POSTER

Majoritic Garnet-bearing Eclogite-Ultramafic Rocks With Rhythmic Layering Structure In The Sulu UHP Terrane, China

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The Yangkou ultramafic blocks of tens m size, are enclosed within gneiss at the middle part of the Sulu UHP terrane. The blocks consist of peridotite (Grt+Ol+Di+En+Ilm), clinopyroxenite (Grt+Di+Ilm) and eclogite (Grt+Omp+Rt) with "rhythmic layering" structure in hand specimen and thin section scales. Individual layer ranges from ∼1 mm to >10 cm thick. Garnet is minor in peridotite, but abundant in clinopyroxenite and eclogite, whereas Cr-bearing pargasite is common in peridotite. Peridotite is nearly equigranular with grain size of 0.3 to 0.5 mm and has a weak to strong foliation. Prismatic enstatite (En_{92-93}) is partially or totally replaced by talc, and euhedral orientated amphibole (0.2-0.6 x 0.3-1.75 mm) contains inclusions of olivine and garnet. Pyropic garnet ($Prp_{62-67}Alm_{23}Grs_{10-15}Sps_{1-2}$) is homogenous in composition in individual sample, but varies in Cr_2O_3 content (<0.5 to 2.25 wt%) from sample to sample. Diopside with low FeO and Al_2O_3 (both <2 wt%) content has positive correlation with garnet in Cr_2O_3 content (0.3 to 1.2 wt%). Most layers of garnet clinopyroxenite and eclogite show porphyroblastic texture. Garnet ($Prp_{51-63}Alm_{25-33}Grs_{10-19}Sps_1$) of clinopyroxenite contains much higher pyrope component than eclogitic garnets ($Prp_{34-41}Alm_{34-45}Grs_{23-36}Sps_1$). Porphyroblastic garnets of 1-5 mm in size from both rocks contain abundant exsolved rutile needles and minor apatite ± clinopyroxene rods. A few cores of exsolved rutile needles-bearing eclogitic garnets have high Si of 3.07 ± 0.01 and low Al of 1.91±0.02 per formula unit indicating that the garnets contain at least about 8-10 mole% majorite component defined by significant coupled substitution of $2Al^{3+}$ in the octahedral site by $(Mg,Fe)^{2+}Si^{4+}$. The P-T estimates of peridotite using the Grt-Opx barometer and Grt-Cpx thermometer yield about 3.7-4.3 ± 0.2 GPa at 700-730± 50°C. The matrix of pyroxenite and eclogite had lower equilibrium temperature of about 600degC ± 50°C. The rhythmic layering probably represents a relict cumulate structure, rather than metamorphic differentiation. Preservation of rhythmic layering and majoritic garnet may be attributed to (1) a stable condition for magma differentiation to form layered mafic-ultramafic protoliths, and (2) the original structure has not been significantly modified during UHP metamorphism in a dry environment and rapid subduction and exhumation of the UHP slab. This suggestion is consistent with preservation of gabbroic structures and minerals and occurrence of intergranular coesite in a nearby coesite-bearing eclogite body.

V22B-0589 1330h POSTER

An Oceanic Protolith for the UHP Eclogites and Garnetites from Western Sulu, Northeast of China

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The occurrence of coesite in the Dabei-Sulu eclogites led to the establishment of the ultra-high pressure origin for the Dabei-Sulu metamorphic terranes. So far, all of the analyzed Dabei-Sulu eclogites are characterized by enrichment in highly incompatible elements and positive ϵNd and $\delta^{18}O$ values. Therefore, a continental protolith was inferred. Although not impossible, subduction of a large volume of continental protolith to ultra-high pressure regime is uncommon for its low density. To overcome this dilemma, it was proposed that the Dabei-Sulu continental protolith was dragged by an oceanic lithosphere in the subduction front. Upon reaching the ultra-high pressure regime, the break-off of the oceanic lithosphere led to the re-bounce of the metamorphic continental lithosphere back to the Earth's surface. However, the absence of outcropped oceanic protolith weakens this model to some extents. For the first time, we discover eclogitic samples with oceanic signatures from western Sulu terrane. Rutile and kyanite eclogites along with garnetites were sampled from Maobei western Sulu near the site of Chinese Continental Scientific Drilling project. Most of these eclogites show general depletions in LREE with positive eNd values, reflecting characteristics of oceanic lithosphere. In the $^{87}Sr/^{86}Sr$ - ϵNd space, some Maobei eclogites deviate from the mantle array toward higher $^{87}Sr/^{86}Sr$ values, consistent with seawater alteration. These Maobei eclogites have REE abundances lower than the Pacific MORB but comparable to the Oman ophiolites, which are representatives of cumulates from N-MORB-like melts. The similarities in the major element distributions between Maobei kyanite eclogites and Oman olivine gabbro further support the oceanic affinity of Maobei kyanite eclogites. The rutile eclogites, however, are lower in MgO but higher in TiO_2 and total iron contents with slight enrichments in La and Ce compared to the Oman ophiolites. We interpret these geochemical signatures as consequences of fluid metasomatism, which may be a major process for rutile formation. Another type of fluid metasomatism caused the development of amphibole veins resulting in the concaved down REE pattern in one of the studied eclogites. Finally, a kyanite eclogite is distinct from other Maobei eclogites for its LREE enriched REE pattern and a lower ϵNd of -5 indicating involvement of some proportions of continental materials. In summary, the studied Maobei eclogites are representatives of cumulate assemblages from MORB-like melts with some samples show fingerprints of fluid metasomatism and addition of continental materials. It is, therefore, inferred that there existed an oceanic lithosphere between the Yangtze and Sino-Korean cratons providing supports for the slab break-off and re-bounce model for the formation of Dabei-Sulu UHP terranes.

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H and C Impurities in Synthetic Majoritic Garnets: Implications for Speciation and Solubility

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Impurities were revealed in four high-pressure, high-temperature synthetic polycrystalline garnets along the pyrope [$Mg_3Al_2Si_3O_{12}$] - majorite [$Mg_3(MgSi)Si_3O_{12}$] join by infrared absorbance, Raman scattering spectroscopy, and detailed electron microprobe analyses (EMPA). Close examination of slight differences in the backscatter-electron images of one sample of Mj_{40} and subsequent X-ray imaging and spot analyses documented the presence of Mj_{95} interstitial impurities and a silica rich phase near the 5% level. These phases would not have been observed in a typical traverse. Spectroscopic measurements show that all samples contain the narrow bands of OH^-, broad bands of fluid water, hydrocarbons, and disordered graphite. Hydroxyl is expected in either structural sites or as defects, whereas the other impurities are most likely on grain boundaries or as microscopic inclusions. Whereas infrared spectroscopy is needed to ascertain OH^- and H_2O contents, and is more sensitive to hydrocarbons that Raman scattering, the later is required to detect graphite. The source of C is likely acetone traces from sample preparation that were entrapped in the sealed capsules. The source of H could be moisture in the air or acetone. Band profiles and heating experiments show that water is the main carrier of H in our samples. Similar broad bands in published IR spectra of many high-pressure samples have been misattributed to OH^-, thereby overestimating both concentrations and solubilities of OH^-. Low concentrations are predetermined by the starting materials (oxides in the stoichiometry of the desired mineral phase plus water), and by charge balance. Our results contraindicate extensive hydration of the lower mantle. In addition, hydrocarbons or water on grain boundaries of synthetic samples provide lubrication, which can affect measuremens of pressure derivatives. Detailed EPMA and spectroscopic characterization of high-pressure synthesis products are essential.

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Navajo Garnetites and Rock-Water Interactions in the Mantle

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Garnetite xenoliths from ultramafic diatremes in northeastern Arizona provide insights into mantle-water interactions. The garnetites are more than 95% garnet with subequal proportions of Grs, Alm, and Prp. Accessory minerals include rutile, ilmenite, chlorite, clinopyroxene, and zircon. Textures and mineral compositions are consistent with garnetite formation by hydrous metasomatism at about 500°C near contacts between mafic rocks and peridotite. Trace element abundances and isotope ratios measured by LA-ICP-MS and -MC-MS document xenolith histories. Typical garnets are slightly enriched in MREE relative to HREE, and small positive Eu anomalies are present in garnet of one xenolith. Zircon shapes in one garnetite are diverse. Most U-Pb analyses of these zircons plot on or near concordia in the range 60 to 85 Ma, but analyses of several grains lie off concordia, and chords between these discordant results and the main cluster have Proterozoic upper intercepts. Hf 176/177 ranges from about 0.2818 to 0.2828, yielding depleted mantle model ages from 1.9 to 0.5 Ga that cluster at about 1.8 and 1.1 Ga. More radiogenic Hf is roughly correlated with decreasing U-Pb age in the interval 85 to 60 Ma, and zircons are zoned to more radiogenic Hf, core to rim. The high Hf 176/177 in the young zircons and zircon rims is consistent with the modelled evolution of Hf in the garnet (mean Lu/Hf about 30). These data establish that the garnetite inherited Hf and zircons from a protolith at least 1.8 Ga in age, and suggest that the garnetite itself formed around 85 Ma ago, and some zircon within it crystallized episodically during the interval 85 to 60 Ma. The zircon data eliminate the possibility that the garnetites are fragments of the Farallon plate. The time interval for garnetite crystallization overlaps the 80 to 30 Ma range recorded by zircons in typical Navajo eclogites, consistent with the hypothesis that both eclogites and garnetites record the interaction of water with Proterozoic mantle. These rocks may document movement of water into the overlying continental mantle from the Farallon plate during low-angle subduction and later mobilization of that water.