

V32B-0975 1330h POSTER

A Technique for Determining Methane Hydrate Stability Limits Based on Raman Analysis of Synthetic Fluid Inclusions

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Methane hydrate is a naturally-occurring ice-like compound that is stable at low temperatures and high pressures. During the past decade interest in the occurrence and properties of natural gas (methane) hydrates has increased significantly owing to its potential as an energy source, its potential effects on current and past climates, as an agent of submarine erosion and as a hazard to ocean-going ships.

To better understand the properties of methane hydrates, a technique was developed which allows the P-T limits of the hydrate phase to be determined accurately and unambiguously. Synthetic fluid inclusions containing known concentrations of methane and water were prepared by loading measured amounts of water and aluminum carbide into platinum capsules, along with a fractured quartz core. The aluminum carbide reacts with water to form methane plus aluminum oxide. The capsules were placed into cold-seal bombs to heal fractures in the quartz to produce synthetic fluid inclusions. The resulting inclusions were examined on a microscope heating/cooling stage, and the temperature at which the methane hydrate phase dissociates was determined optically. Then, the same fluid inclusion was analyzed by Raman spectroscopy at this same temperature to determine the position of the C-H symmetric stretching band. The position of this band varies systematically with pressure. Using the pressure peak position calibration determined using a high pressure cell on the Raman microprobe, the methane pressure corresponding to the measured peak position was calculated. Using this technique, methane hydrate stability in pure water and aqueous salt solutions has been determined to pressures of approximately 400 bars.

The P-T limits of methane hydrate stability in pure water determined in this study are in good agreement with published values. However, results obtained for hydrate stability in the presence of 5, 10 and 20 weight percent NaCl aqueous solutions show poorer agreement with published data. Specifically, pressures obtained using the synthetic fluid inclusion Raman technique are generally higher than those obtained with other techniques. These differences may reflect failure to obtain equilibrium in some earlier studies, owing to the sluggish nature of the hydrate dissociation reaction.

V32B-0976 1330h POSTER

Barite Dissolution Rates Derived From Vertical Scanning Interferometry: A Comparison Between VSI and AFM

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Barite (BaSO₄) occurs naturally in many environments including crustal rocks, hydrothermal deposits, and marine sediments, and is sparingly soluble in aqueous fluids. Barite scaling in oil reservoirs and drill pipes is a common problem associated with extraction of heavy hydrocarbons. Waters used for volume replacement during the extraction process, can interact with barium in the reservoir and precipitate barite that obstructs flow and reduces oil recovery. Chelating agents such as EDTA are commonly used to keep barium ion in solution by complexing with it, effectively controlling the amount of barium able to react with the sulfate anion in solution. With a sound understanding of the dissolution/precipitation kinetics, the amount of chelating agent used by the oil industry can be minimized. This will help keep costs down during pumping, and reduce the amount of environmental contaminants needed for the process.

Most available data on barite dissolution rate have been collected using Atomic Force Microscopy (AFM). AFM provides excellent resolution of the mineral surface during dissolution; however, this excellent resolution comes at the cost of a narrow field of view. This project will provide a comparison between vertical scanning interferometry (VSI) and AFM. VSI is a relatively new technique in the field of Geochemistry. VSI can be used to measure retreat normal to the mineral surface. Because VSI offers a larger field of view, the amount of material removed can be integrated over a larger surface area, thereby averaging out inhomogeneities that might exist on the scale of AFM observations. VSI will provide information that will augment the current AFM data to allow a more complete understanding of barite dissolution.

This project involves measuring surface retreat on a freshly cleaved barite surface during treatment

with aqueous solutions with variable concentrations of EDTA over temperature ranges of 25-80°C. This study will generate dissolution rates from the barite surface to compare with those found through the use of AFM. This study will also look for trends in etch pit morphology on a larger scale and compare it to trends found using AFM.

V32B-0977 1330h POSTER

Rates of Mineral Dissolution Under Hydrothermal Alteration

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The significant gap between field and experimental rate estimations, attributed to the use of single minerals during experimental evaluation, makes controversial the evaluation of alteration budget in natural conditions. We propose an original approach to evaluate, simultaneously, the dissolution rate of K-feldspar, biotite and plagioclase during experimental alteration of granite rock by fluids having an initial composition close to the saturation with neogenic phases. The technique based on the isotopic doping technique is suitable for granite where minerals have different strontium isotopic signature and Rb/K ratio. Experiments were carried out at different temperature (i.e. 80°, 120°, 180°C) spiking the initial fluid composition in the less abundant isotope K and Sr isotopes (i.e. 39, 84 respectively) and following the evolution of the chemical and isotopic composition for 1 year. We demonstrate that the complex water-rock processes can be experimentally represented by an isotopic mixing proportion between the dissolving minerals and spiked solution from the first days of reaction. We have found that the (87Sr/86Sr) and (Rb/39K) dissolved rock end members do not change significantly in the range of temperature investigated in this study allowing to calculate the proportion of dissolved mineral, assuming the mass conservation law and the mixing isotopic equations for the system. Rates of mineral dissolution were, thus, estimated assuming the isotopic equilibrium of (41K/39K) ratio between fluids and neogenic phases precipitated during the interaction and the constancy of the surface area. Irrespective of the temperature we have found that the dissolution rate of plagioclase is only one order of magnitude higher than biotite and orthoclase. Since the constancy of the mineral dissolution rates with temperature, we propose that the strontium isotopic composition of natural hydrothermal fluids depends mainly on mineral proportion abundance and age of the granite rock.

V32C MC: Hall D Wednesday 1330h

Ultra High Pressure Petrology

Presiding: E Walsh, University of California

V32C-0978 1330h POSTER

P-T Estimates For Phengite-Kyanite Uhp Eclogites From A Highway Roadcut Near The Qinglong Mountains, Eastern China

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Recent highway construction across the Qinglong Mountains in Donghai, eastern China has exposed a 660 m section of gneiss, eclogite, and minor quartzite. The outcrop consists of steeply SE-dipping layers cut by several high-angle (normal?) faults. Eclogite layers are concordant with gneissic rocks and minor quartzites; a few discordant eclogite contacts appear to be intrusive. Most eclogites are characterized by abundant hydrous phases including talc, phengite, and epidote; many also contain kyanite. Inclusions of quartz aggregates after

coesite were identified in garnet and kyanite of both eclogites and quartzites, consistent with the reported occurrences of inclusions of coesite and coesite pseudomorphs in epidote and kyanite from both eclogite and quartzite, of this region (Zhang et al. 1995). Peak conditions of 3.0-3.5 GPa and 600-750°C were estimated using the thermobarometer of Ravna and Terry (2001) and the data set of Holland and Powell (1998). The Qinglong Mountains contain a variety of UHP eclogites, and are the classic locality for negative $\delta^{18}\text{O}$ values (-14 to 16‰/‰) for UHP minerals in eclogites, quartzites and surrounding gneisses (Yui et al. 1994; Rumble and Yui 1998) indicating that fluid may have been absent during peak-stage metamorphism.

V32C-0979 1330h POSTER

Northern Qaidam Caledonian UHP Terrane A New Discovery

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Several new Alpine-type HP/UHP terranes occur in the Altun-Qaidam-Mountains and Beishan of NW China; we have identified UHP garnet lherzolite and eclogite in the North Qaidam Mountains. This finding is supported by Raman spectrum identification of coesite inclusions in zircon separates from paragneissic rocks in the eastern part of the North Qaidam belt (Dulan region). Eclogite and garnet peridotite bodies of various sizes occur as blocks and layers in the Upper Proterozoic sequence of gneiss, amphibolite, marble, and schist. Comparable rocks have been identified from east to west in the Dulan, Xitianshan, and Da Qaidam areas, constituting an EW-trending belt over 350 km long, and from a few to Several new Alpine-type HP/UHP terranes occur in the Altun-Qaidam-Mountains and Beishan of NW China; we have identified UHP garnet lherzolite and eclogite in the North Qaidam Mountains. This finding is supported by Raman spectrum identification of coesite inclusions in zircon separates from paragneissic rocks in the eastern part of the North Qaidam belt (Dulan region). Eclogite and garnet peridotite bodies of various sizes occur as blocks and layers in the Upper Proterozoic sequence of gneiss, amphibolite, marble, and schist. Comparable rocks have been identified from east to west in the Dulan, Xitianshan, and Da Qaidam areas, constituting an EW-trending belt over 350 km long, and from a few to 10+ km in width. Most eclogite blocks are small (< 10 x 20 m), but few are up to 0.5 km². Eclogites in the Dulan area consist mainly of Grt + Omp + Phe (Si = 3.45) + Rt, with calculated P-T conditions of T = 624 - 735°C and P = 3.0 ± 0.2 GPa. Associated garnet peridotite P-T estimates are 837°C and 2.5 GPa. The enclosing gneissic rocks consist of Qz + Fsp + Bi + Hb ± Grt; the occurrence of coesite inclusions in zircon indicate in-situ UHP metamorphism. U-Pb dating of zircons from the Da Qaidam eclogite yields 495 Ma, consistent with new SHRIMP U-Pb dating of 443-495 Ma and Sm-Nd dating of 496 Ma for eclogite, suggesting that the UHP metamorphism of the North Qaidam terrane occurred in Early Paleozoic time. The eclogite-bearing subduction complex appears to be similar to the Triassic Dabie-Sulu UHP terrane in terms of occurrence, rock types, and P-T conditions, except for the Caledonian time of continental subduction and collision. The North Qaidam Mountains evidently constitute another coherent UHP metamorphic terrane, marking the NE tectonic boundary of the Tibetan Plateau the Caledonian suture zone between continental blocks in NW China.

V32C-0980 1330h POSTER

Relationship between UHP eclogite and two different types of granite in the North Qaidam, NW China: Evidence from zircon SHRIMP ages of granites

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The southern margin of the Qilianshan is a long, narrow mountain range extending from the Altyn Mtn southeastward to the Alciotoshan for about 800 km and

consists chiefly of Proterozoic and Paleozoic rocks. Our recent studies show that this foldbelt consists of a Caledonian north Qaidam UHP belt near the Qaidam Basin and I-type and S-type granites to the north near the Qilianshan. Two types of granite bodies at the Aolaoshan and Qaidamshan were selected for zircon SHRIMP dating. The results indicate that the Aolaoshan granites range from 496 ± 7.6 to 445 ± 15.3 Ma whereas the Qaidamshan granites range from 435 ± 6 to 456 ± 11 Ma. The Aolaoshan granites have geochemical characteristics similar to I-type granite probably formed in an island arc setting whereas the Qaidamshan granites are S type granites coeval with timing of collision. The UHP eclogites at Yuca have $^{238}\text{U}/^{206}\text{Pb}$ age of 494.6 ± 6.5 Ma, representing the peak stage of UHP metamorphism, and the $^{39}\text{Ar}/^{40}\text{Ar}$ plateau and isochron ages of phengite respectively at 466.7 ± 1.2 Ma and 465.9 ± 5.4 Ma represent the cooling ages of retrograde metamorphism during exhumation. In addition, the SHRIMP ages of UHP eclogites from Xitieshan and Dulan are the Caledonian. These spatial and temporal relationships suggest that UHP eclogites and two different types of Caledonian granites occur in north Qaidam with the eclogite belt to the south and the granite bodies to the north. The country rocks of UHP eclogites are Proterozoic age whereas granitic bodies have both Proterozoic and Paleozoic groups. Thus, an early Caledonian northward subduction of an oceanic lithosphere resulted in the formation of high-P eclogite to the south and I type Aolaoshan granite to the north. Subsequent continent-continent collision induced widespread partial melting of continental crust to form S type Qaidamshan granites. Hence both eclogite and two different types of granites in this foldbelt are the products of two different stages of plate subduction.

V32C-0981 1330h POSTER

K-bearing hydro-phases in Sulu UHP garnet peridotites from eastern China

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K-bearing hydro-phases, amphibole and phlogopite, were identified in UHP garnet peridotites from the Sulu terrane, eastern China. Phlogopite with high Mg/Mg+Fe (0.95-0.96) occurs as matrix and inclusion phases mainly in lherzolite. Amphibole exhibits two model occurrences: matrix phase occurs as euhedral crystal in wehrlite and lherzolite and exsolution (\pm garnet, \pm ilmenite) lamellae in clinopyroxene inclusions that enclosed in garnet megacryst from porphyroblastic garnet clinopyroxenite. These matrix hydro-phases exhibit sharp contact with other phases and are in equilibrium with Grt, Opx, Cpx and Ol of UHP garnet peridotites. Most amphiboles are pargasite, and have highly magnesian compositions that plot in or close to the compositional field of upper mantle-derived amphiboles in terms of CaO-Al₂O₃ and MgO-FeO. The K₂O content of amphibole ranges from 0.8 to 1.2 wt%, and may store as a richterite [KNaCaMg₅Si₈O₂₂(OH)₂] component. Phlogopite-bearing lherzolites have P-T estimates at $880-910 \pm 50^\circ\text{C}$ and $4.0-5.3 \pm 0.2$ GPa. Whereas amphibole-bearing lherzolites were recrystallized at $790-940 \pm 50^\circ\text{C}$ and 4.5 ± 0.2 GPa using thermobarometers; these pressures are lower than those estimates (> 6 GPa) inferred from exsolution microstructures of Cpx + Ilm + Grt. These petrological data together with experimental studies in the system K₂O-Na₂O-MgO-Al₂O₃-SiO₂-H₂O indicate that K-bearing hydro-phases are stable at mantle depths > 120-200 km and are carriers of H₂O and K₂O to deep mantle through cold subduction zones.

V32C-0982 1330h POSTER

Metamorphic and Magmatic Evidences to Neogenic Slab Breakoff Beneath S-Karakorum and S-Tibet

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On the S-Karakorum margin, Neogene granulites define an east-west trending thermal anomaly. These rocks have been heated from 600 to 750°C during a slight pressure drop, from 0.7 to 0.5 GPa. Their retrogressive path cross-cuts the relaxed geotherm of tectonically thickened crust. Such a P-T evolution can be obtained only if an advective source of heat is involved. Involvement of an advective heat source is also implied by the occurrence within the granulite area of Neogene granitoids and lamprophyres. These rocks are strongly enriched in LILE relative to primitive mantle and show negative HFSE anomalies. We interpret these geochemical characteristics as resulting from melting of the metasomatized Asian lithospheric mantle. ϵ_{Nd} (-12 to -7) and $^{87}\text{Sr}/^{86}\text{Sr}$ (0.705 - 0.725) of the S-Karakorum Neogene magmatic rocks further suggest they could have originated from mixing between Asian metasomatized mantle and Asian Precambrian crust. By contrast, the origin of the youngest magmatic rocks (< 10 Myr), here exemplified by the Hemasil Syenite and associated lamprophyres, requires involvement of depleted mantle. The ϵ_{Hf} signature of these rocks ($\epsilon_{Hf} = +10.4$ to $+11.5$) further indicate that the asthenospheric mantle source of the Hemasil syenite was contaminated by pelagic sediments, likely during the earlier subduction of the Tethyan ocean.

Other Neogene magmatic rocks with the same geochemical characteristics and evolution as those of the S-Karakorum have been previously described in S-Tibet. On the basis of their location and the evolution of their source, we propose that the Neogene magmatic and metamorphic evolution of the S-Asian margin was controlled by slab breakoff of the subducting Indian continental margin starting at about 25 Myr.

V32C-0983 1330h POSTER

New Occurrence of Garnet Amphibolite and its Tectonic Implications in the Western Dabie Block, Eastern China

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We report a new occurrence of deformed garnet amphibolite as discontinuous pods enclosed within impure marble in the western rim of the Dabie tectonic block. The rock association ($115^\circ 4' \text{E}$, $31^\circ 2' \text{N}$) is located close to the Macheng fault, the western limit of the Dabie block, and situated along the previously postulated boundary of the amphibolite unit (AU) and the Northern Orthogneiss unit (NOU). The field occurrence resembles those of well-documented coesite-bearing eclogites enclosed in marbles and schists in the south-eastern Dabie. The studied marble contains mainly calcite with accessory phases of phlogopitic mica, quartz, plagioclase (andesine), and tremolitic amphibole. The mineral assemblage indicates metamorphic equilibrium under lower-to-middle amphibolite-facies conditions. In one garnet amphibolite, porphyroblastic almandine-rich (50-57 mol%) garnet commonly surrounded by a corona of symplectitic sodic plagioclase and hornblende indicates retrograde metamorphic reactions between the garnet porphyroblast and matrix precursor sodic clinopyroxene. In another sample, fine-grained intergrowths of diopsidic clinopyroxene (Na₂O = 0.6-0.8 wt%) and sodic plagioclase (oligoclase) represent breakdown products from precursor omphacitic clinopyroxene. Domains of magnesio-hornblende and plagioclase (oligoclase-andesine) in textural equilibrium appear to have postdated the porphyroblastic garnet and inferred omphacitic pyroxene. In this regard, the garnet amphibolite must have been eclogite(s) overprinted by variant degrees of granulite- and amphibolite-facies metamorphism. A clockwise P-T path thus can be reconstructed. Such a finding confirms that the lack of ultrahigh-pressure (UHP) metamorphic records in the NOU and AU, in contrast to the wide distribution of eclogites and associated rocks in the southeastern part of the Dabie block, is best explained by post-UHP mid-to-high temperature metamorphic overprint involving hydration reactions during slab exhumation. The tectonic configurations of regional geologic units based on previous work thus need to be reconsidered.

V32C-0984 1330h POSTER

Metamorphism and Exhumation of Very High-Pressure Eclogites, North Qaidam, China

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The North Qaidam metamorphic belt (38°N , 95°E) is located within the Early Paleozoic Qilian Shan orogeny. Here mafic eclogite occurs as discrete blocks in leucocratic gneisses of epidote-amphibolite grade. The gneisses contain the assemblage: K-feldspar, quartz, plagioclase, garnet, muscovite, biotite, hornblende and epidote. The eclogite blocks are not of uniform grade; they vary in extent of retrogression and fluid alteration with no apparent correlation to structural position. The most retrograded blocks do not contain eclogite facies minerals and are amphibolite to epidote-amphibolite grade. They have the assemblage: garnet, Ca-amphibole, plagioclase, sphene, chlorite \pm white mica, epidote. In blocks which display only partial replacement of the eclogite facies assemblage, three phases of mineral growth can be identified. The first defines the prograde path and is found as inclusions in garnet (quartz, amphibole, plagioclase, rutile, epidote, sphene, ilmenite \pm pyroxene, apatite, zircon, white mica and K-feldspar). Based on textural evidence, the main eclogite facies assemblage is garnet, omphacite, rutile, quartz, \pm phengite. The garnets contain abundant inclusions, but omphacite is inclusion free. The final stage is marked by the retrograde introduction of fluids while still in the eclogite facies leading to the growth of high-pressure amphiboles, taramite and katophorite zoned to pargasite, containing inclusions of omphacite. Upon further decompression, fine-scale symplectites of albite and augite followed by albite and hornblende grew in grain boundaries. The garnets exhibit numerous micro-fractures implying brittle deformation occurred during exhumation aiding fluid flow. The prograde path corresponds to the epidote-blueschist facies ($< 625^\circ\text{C}$, 2.4-1.5 GPa). Peak eclogite conditions are just below the coesite-quartz phase boundary (700°C , 2.4 GPa). Final reequilibration conditions correspond to the epidote-amphibolite facies ($550-450^\circ\text{C}$, 1.0-0.8 GPa), which is the same as in the surrounding gneiss. The P-T path defines an open clockwise loop with nearly isothermal decompression. The variability observed in the eclogite blocks can be explained by discrete, non-uniform fluid influx during exhumation and probably does not represent different P-T histories. Our data are consistent with deep burial of continental materials during south-dipping subduction of the North China plate beneath the Qilian terrane and rapid exhumation from 80 km to mid-crustal levels, perhaps by diapiric flow. Based on regional correlation this event occurred during the development of the Ordovician-Silurian Qilian magmatic arc, and is apparently unrelated to continent-continent collision.

V32C-0985 1330h POSTER

U/Pb Zircon Geochronology of an Ultrahigh-Pressure Eclogite From the Western Gneiss Region, Norway

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The Western Gneiss Region (WGR), southern Norway, contains the largest tract of ultrahigh-pressure (UHP) eclogites on Earth. At present, the major limitation on unraveling the exhumation history of the WGR is a dearth of well-constrained ages of peak metamorphism. Eclogites of the WGR have been long considered to have formed at 425 ± 12 Ma, based on Sm-Nd isochron ages. However, assessing isotopic equilibration for these ages is impossible, as all are two-point or poorly fit three-point isochrons.

To better constrain the age of UHP metamorphism (UHPM) in the WGR, we performed SHRIMP and TIMS U/Pb analysis on zircons from a coesite-bearing eclogite at Flattraket. For this sample, it is possible to relate zircon growth to UHPM. In thin sections, almost all zircon is included within omphacite, garnet, sideromagnesite and symplectite after omphacitization. In the latter, zircon growth predates symplectitization. Zircon is not observed in the matrix, and only rarely within quartz.

SHRIMP results from Flattraket, in conjunction with CL imagery, indicate a minor inherited component. One of 17 grains analyzed contains a core with mottled CL; spot analyses reveal lower U contents, slightly higher Th/U ratios, and $^{206}\text{Pb}/^{238}\text{U}$ ages between 437 and 423 Ma. Excluding these spot ages, and

those exhibiting post-Caledonian Pb loss, we calculate a weighted mean of $^{206}\text{Pb}/^{238}\text{U}$ spot ages of 406 ± 4 Ma (MSWD=2.7; n=21). As the MSWD is larger than expected, it is unclear if the spread of the SHRIMP data is due to diachronous zircon growth or unresolved mixing.

For the TIMS analysis, two size fractions (<80 μ and 80-180 μ) were annealed at 850°C prior to multi-step partial dissolution analysis (PDA). One unannealed fraction was subjected to single dissolution analysis, yielding a $^{206}\text{Pb}/^{238}\text{U}$ age of 404.4 Ma (uncertainties for all TIMS $^{206}\text{Pb}/^{238}\text{U}$ ages are ± 0.8 Ma) and a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 411.8 ± 1.0 Ma.

For both PDA fractions, the A (first, lowest temperature) steps reveal minor Pb loss. Both B steps yield $^{206}\text{Pb}/^{238}\text{U}$ ages of 400 Ma. As little material was extracted in these steps, $^{207}\text{Pb}/^{206}\text{Pb}$ uncertainties are large and concordance is uncertain. For the fine fraction, $^{206}\text{Pb}/^{238}\text{U}$ ages from the remaining PDA steps increase from 404.2 to 406.7 Ma, while $^{207}\text{Pb}/^{206}\text{Pb}$ ages, other than from two poorly constrained steps, range from 411.1 ± 0.9 to 413.1 ± 1.1 Ma. The remaining PDA steps from the coarse fraction yield $^{206}\text{Pb}/^{238}\text{U}$ ages between 403.4 and 405.2 Ma, and $^{207}\text{Pb}/^{206}\text{Pb}$ ages between 407.9 ± 1.0 and 411.2 ± 0.9 Ma.

With decay constant errors taken into account, all well constrained PDA steps and the single dissolution analysis overlap or lie just above concordia, implying mixing of a minor older component and a dominant component of roughly 400 Ma. The narrow spread of PDA ages and relatively large decay constant errors preclude determination of intercept ages via linear regression. Given the SHRIMP results, the older component is inferred to be ca. 430 Ma, while the younger component may be represented by the 400 Ma B steps, if concordant, as well as an existing concordant U/Pb zircon age of 402 ± 2 Ma from the Ulsteinvik eclogite. The fine PDA fraction contains a slightly greater proportion of the older component, given its consistently 1-2 m.y. older step ages.

V32C-0986 1330h POSTER

Dating high-grade metamorphism: constraints from zircon and garnet REE compositions

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We present high spatial resolution ion microprobe REE analyses of zircon and garnet from pelitic granulite adjacent to the Ronda peridotite, Betic Cordillera, southern Spain. The zircons exhibit polyphase growth, with thick structureless (in cathodoluminescence) overgrowths over detrital cores. These overgrowths yield a U-Pb age of 21.3 ± 0.3 Ma [1, unpublished data] which we interpret as dating an episode of zircon growth during the Alpine orogeny. REE analyses of the dated portions of these zircons reveal profound differences between cores and rims. Cores show patterns typical of magmatic zircon (steep upward slopes from La to Lu with marked positive Ce anomaly), while the overgrowths are characterised by flat or even negatively sloping HREE profiles (Gd - Lu). Garnet, which occupies ca. 30 % by volume of the rock, is the most likely phase to host the HREEs in the rock and has been the subject of further ion-microprobe REE, textural and trace element investigations. The garnets are themselves zoned, with dominant central regions that are relatively free of inclusions overgrown by inclusion-rich, more calcic rims. Inclusions of kyanite + rutile in the central regions and sillimanite + ilmenite in the rims suggests that the garnets grew during decompression, and the Ca-enrichment in the rims suggests that their growth coincided with the initiation of partial melting. The presence of rimmed zircons only in the garnet rims and the matrix further suggests that the zircons also grew during this late decompressional history. An REE traverse of the garnet from core to rim reveals marked HREE depletion in the rims relative to the cores which we suggest is consistent with the textural evidence and probably results from early garnet core growth strongly depleting the HREEs available to subsequent growth. This mechanism can also be invoked to explain depletion in the zircon rims and more closely ties their formation to this stage of garnet growth. We therefore interpret the 21.3 ± 0.3 Ma U-Pb age from the zircon rims as dating a point on the decompressional path rather than peak metamorphic pressure.

[1] Platt, J.P. and Whitehouse, M.J. (1999) EPSL 171, 591-605.

V32C-0987 1330h POSTER

Geochronology and P-T Constraints on the Exhumation History of an UHP Eclogite from Northern Greece

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The recent discovery in northern Greece of metamorphosed crustal rocks units which had been transported to depths well within the diamond stability field provide concrete proof of a hitherto unknown UHP (ultrahigh-pressure) metamorphic event in the Aegean region (Kostopoulos et al., 2000, Mposkos and Kostopoulos, 2001). We investigated in detail the P-T path an UHP eclogite from the Galarinos area ca. 20 km SE of Thessaloniki in order to place constraints on its metamorphic and uplift history.

The rocks studied belong to the Serbo-Macedonian Massif, which along with the Rhodope Massif, form the major tectonic units of northern Greece and constitute the internal part of the Hellenides. Its main lithotypes include amphibolites, amphibolite-facies para- and orthogneisses and schists, marbles, and a variety of granitic intrusions. We selected an eclogite lens and its surrounding trondhjemite envelope from the so-called Galarinos Unit. The latter comprises (garnet-) amphibolites, garnet-biotite-plagioclase gneisses, garnet-biotite-kyanite gneisses, phengite marbles and quartzites, pyroxene-zoisite-carbonate rocks, orthogneisses, and migmatites. The UHP stage is documented by cubic and octahedral graphite pseudomorphs after diamond in both the eclogite and trondhjemite (Kostopoulos et al., 2001), strongly suggesting that the trondhjemite originated from the eclogite via partial melting. Inferred temperature and pressure conditions for the UHP event are in excess of 800°C at 4 GPa, sufficient to induce (wet) partial melting during or shortly after diamond formation. Single zircon Pb-Pb determinations for the trondhjemite indicate an age of ca. 185 Ma, which is interpreted as best approximating the age of the UHP event. High-Si phengite (Si=3.5 a.p.f.u.), high-Ti biotite inclusions in amphibole totally replacing pre-existing omphacite, and the formation of high-Al titanite and zoisite at the expense of garnet, rutile and silica in the presence of water record early stages of exhumation at 800-750°C 3-2 GPa. Subsequent exhumation to lower crustal levels and annealing occurred at amphibolite-facies conditions of 1.0 GPa 670°C. This phase is dated at ca.145 Ma by Sm-Nd in garnet, amphibole, biotite and whole rock. Cooling to 500°C occurred at ca. 118 Ma, dated by Rb-Sr in amphibole and whole rock. The eclogite eventually reached greenschist-facies conditions of 0.5 GPa 400°C by ca. 60 Ma, determined by Rb-Sr in biotite and whole rock. The geochronological results of our study suggest an Early Jurassic collision event as the cause of the UHP metamorphism and its subsequent Cretaceous uplift history, which has not yet been reported for other parts of the Aegean region.

Kostopoulos, D.K. Ioannidis, N.M. and Sklavounos, S.A., 2000, International Geology Review, v. 42, p. 545-554. Mposkos, E.D., and Kostopoulos, D.K., 2001, EPSL, in press.

V32C-0988 1330h POSTER

Effects of Compositional and Structural Variations on Log Responses in Igneous and Metamorphic Rocks

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Petrophysical in-situ data of several boreholes drilled igneous and metamorphic rocks of continental and oceanic basement were analyzed in order to characterize and classify the occurring rock types. Since physical properties of crystalline rocks are controlled by both, compositional and structural features, one objective of this study was to develop methods to detect and quantify matrix effects. The comparison of mineralogical and geochemical core data with wireline data reveal following systematic observations:

(1) Mafic rocks (e.g. oceanic basalts, volcanic island basalts, gabbros and amphibolites) generally have

low contents of radioactive minerals. This is in particular valid for mafic rocks from the upper and lower oceanic crust. Slight increases in gamma-ray are related to an enrichment in potassium due to seafloor alteration. In contrast to this uniform, mantle source controlled rocks, extrusives and re-sedimented material from ocean islands and large igneous provinces show a large scatter in gamma-ray responses as a result of their more complex evolution. Mafic rocks recovered from boreholes into continental crust, are characterized by high gamma-ray values, due to enrichment of thorium and uranium during regional metamorphism. In contrast to the mafic plutonic and metamorphic rocks, where the density and p-wave velocity is controlled by the mineralogical composition, the physical parameters of mafic volcanic rocks are strongly affected by fracturing and vesicularity. Density, p-wave velocity and electrical resistivity logs are significantly lowered depending on the degree of vesicularity and fracturing.

(2) Acid to intermediate igneous rocks and orthogneisses are distinguishable from paragneisses by their log responses despite showing a similar geochemical composition. The main difference occurs for the relation of the gamma-ray log to the density and neutron porosity log. The gamma-ray in paragneisses is controlled by the amount of phyllosilicates, which is dependent on the initial input of pelitic material of the educt. This produces a typical log signature, which shows a positive correlation of the gamma-ray with the density and neutron porosity log. In contrast, the gamma-ray in igneous rocks and orthogneisses follows the magmatic differentiation trend with an increase of potassium-feldspar with rock acidity causing a negative correlation of the gamma-ray log with the density and the neutron porosity log. These relations were observed up to higher amphibolite facies conditions and hold true if metamorphic overprint took place in a more or less closed system.

Based on these relations in physical rock properties classification diagrams for the crystalline rock types were established. They will help to separate matrix effects from structural properties and thus to improve the estimation of porosity from density, velocity and neutron porosity measurements.

V32C-0989 1330h POSTER

Distribution and concentration of microdiamond in UHP dolomite marble

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Abundant microdiamond occurs in dolomite marble in the Kokchetav massif, northern Kazakhstan. The concentration of diamond in this rock is extremely high in some domains in some samples; whereas some domains lack diamond although their mineral assemblages of silicates and carbonates are same with each other. The distribution and concentration of diamond in dolomite marble may give some keys to understand the formation mechanism and conditions of microdiamond in carbonate rocks. The continuous banded sample of the Kokchetav marble indicates the local heterogeneity of XCO₂ during UHP conditions; forsterite-bearing assemblages in dolomitic marble is stable under extremely low XCO₂ condition (e.g., XCO₂=0.01), but diopside-dolomite pair in dolomite marble is stable at a little higher XCO₂ conditions (e.g., XCO₂=0.1). Forsterite-bearing dolomitic marble lacks diamond and graphite and is an indicator of the infiltration of H₂O-rich fluid. Diamond occurs in dolomite marble whose mineral assemblage is dolomite-diopside-garnet (+ aragonite), and is mainly included in garnet and slightly in diopside. The shape of microdiamond can be divided into three types: (1) star-shaped diamond which consists of core and surrounding subhedral part (type-S), (2) rugged surface diamond which consists mainly of core with minor amount of surrounding parts (type-R), and (3) very small-grained transparent diamond without core (type-T). These morphological features with the results of our micro-Laue diffraction and laser-Raman studies suggest that microdiamond formed as core at the 1st stage and then surrounding subhedral part overgrew on the core at the 2nd stage to form rugged surface diamond and star-shaped diamond. Type-R is an embryo of type-S. Diamond at the 2nd stage probably formed from CO₂-H₂O-bearing multi-component fluid, and type-T may be evidence for the precipitation of diamond from fluid without core as an seed crystal. We estimated the concentration of diamond in the highest domain of dolomite marble by microscopic observation of 3,447 grains of microdiamond in one thin section. Considering the error in volume estimation of each diamond grain, the concentration of diamond for the highest domain is about 2,700 carat/ton. In this domain, the population of type-T is 15. The extremely high concentration of microdiamond, high population of type-T and the strong heterogeneity of diamond distribution indicate (1) close relations between microdiamond formation and fluid, and (2) the local heterogeneity of the fluid effects in UHP dolomite marble.

V32C-0990 1330h POSTER

Are UHP Rocks in Norway Allochthonous? A Major Revision of the Tectonostratigraphy.

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Ultrahigh pressure (UHP) rocks in the Norwegian Caledonides formed during the Caledonian collision between the Baltica and Laurentia continental plates in the Late Silurian/Early Devonian. Most geological maps show the UHP rocks as part of the Western Gneiss Complex, which lies beneath a stack of allochthonous nappes. Because the Western Gneiss Complex is correlated with autochthonous Baltica basement farther east, previous tectonic models have thus assumed that the UHP province is the leading, western edge of the subducted Baltica basement. In our view, one weakness of this interpretation is that the magnitude of both coaxial and non-coaxial deformation during the Devonian late-orogenic extension is insufficient to have exhumed the UHP rocks from mantle depths.

To resolve this issue, we conducted detailed structural and lithological mapping over the last two summers. Our mapping has carried the well-defined sequence of Western Gneiss Complex and overlying allochthonous sheets in the non-UHP Sandane area northward into the UHP Stadlandet area. We find that at least the Stadlandet area of the UHP terrane lies structurally above the Nordfjord-Sogn Detachment and the Western Gneiss Complex, and may be correlated with rocktypes of the Middle Allochthon farther south. This revision of the tectonostratigraphy has several important implications regarding the formation and exhumation of UHP rocks: 1) The trailing edges of nappes belonging to the Middle Allochthon were subducted to mantle depths, overturning a long-held belief that they remained at crustal levels. 2) The problem with the magnitude of the extensional event is alleviated, as the UHP rocks now must lie in a) the footwall of an (unidentified) large-scale normal fault, and b) the hangingwall of a large-scale thrust fault, perhaps the precursor of the Nordfjord-Sogn Detachment. 3) Exhumation of the UHP rocks from the mantle may have been coeval with thrust emplacement of the Middle Allochthon over Baltica.

V32C-0991 1330h POSTER

Foreland to Hinterland Regional Variation in Pressure-Temperature-Deformation Histories of the Norwegian UHP-HP Terrane

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The Scandinavian Caledonides of Norway consist of stacked thrust sheets emplaced to the SE onto the Precambrian Baltic Shield during the Silurian/Devonian(?) collision between Baltica and Laurentia. The Western Gneiss Complex (WGC), the parautochthonous equivalent of the Baltic Shield, is the subducting equivalent to epidoteamphibolite-facies orthogneisses, structurally overlain by allochthonous rocks of predominantly oceanic affinity. The allochthons can be traced from their low-grade type sections in the foreland, westward into the UHP core of the orogen. Eclogites crop out in both the WGC orthogneisses and in the overlying allochthonous rocks. Eclogites and granulites show an eastward decreasing PT gradient. This study focuses on the regional variation in PT deformation histories of rocks along a 160-km long transect from the foreland into the core of the orogen. Such a wide-scale study will assist in answering the larger questions of the Scandinavian UHP exhumation, such as: What mechanism drove the UHP exhumation? By what method were the UHP rocks ultimately exhumed?

Our structural studies reveal the order of deformational events along the EW transect: 1) emplacement of thrust sheets onto the Baltic Shield; 2) folding of allochthonous material into the basement in overturned, W-vergent synforms; 3) folding of EW trending isoclines; 4) amphibolite-facies metamorphism; 5) late-stage brittle/ductile faulting, and 6) broad open folding.

Our thermobarometry on pelitic rocks shows surprising results: 1) structurally higher allochthonous rocks record higher pressures (1.2 GPa) than basement rocks (0.6 GPa); 2) allochthons record isothermal decompression, while basement rocks indicate iso-

baric cooling, and 3) the pelitic P gradient increases to the SE, opposite to the regional eclogite P gradient. This significant difference in the P gradients of the pelitic rocks and the eclogites implies crustal imbrication, and hence negates the simplest model of UHP exhumation, the coherent-slab rollback model. UThPb dating of monazites will divulge the relative timing of the HP metamorphism of the allochthons and the HT metamorphism of the basement rocks, providing additional means for constraining other existing exhumation models.

V32C-0992 1330h POSTER

Pressure-Temperature-Time-Strain Path of Eclogites and Gneiss from the Ultrahigh Pressure Province of Western Norway:

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The UHP province of Western Norway is the part of the Baltic shield subducted to more than 100 km depth during the Caledonian orogeny. Field study in the Nordfjord area, north to the Hornelen Devonian basin reveals the heterogeneous behavior of the continental crust during its exhumation. Crustal-scale boudinage occurs during ductile constrictional stretching in amphibolitic conditions, preserving UHP and protolith in the core of boudins. The rims of the Nordfjord area boudins are characterized by a pervasive migmatization during exhumation, that lowers the average viscosity of the subducted crust. Top-to-the-west shearing associated to the Nordfjord-Sogn detachment overprints this constrictional fabric. Dating of a UHP eclogite in Stadlandet area by U-Pb method on rutile and omphacite fractions gives an age of 389.4±3.4 Ma for the crystallization of the UHP paragenesis. The same method used on titanite and Kfeldspars fractions from the surrounding migmatitic gneisses gives an age of 369.2±3.9 Ma for the end of the migmatitic event. Those calibrations added to P-T estimations allow to deduce exhumation rate of 2.5 and 3.7 mm±yr or the two successive stages of exhumation from UHP to amphibolitic depths and from amphibolitic depths to the surface respectively. The present age for UHP eclogite leads to some new considerations about the Caledonian history: (1) the ages of eclogites in the WGR scattered from 420 to 389 Ma can only be explained by a continuous exhumation of continental crust during subduction (2) most of extensional structures dated between 407 and 389 Ma are necessarily syn-orogenic (3) the deposition of the Devonian basins occurred while eclogites were still exhuming between 390 and 370 Ma.

A new scenario is proposed for the latest stages of the Caledonian orogeny, where exhumation of crustal lenses in a subduction channel lubricated by migmatization occurs at depths while transtension controls the deposition of conglomerates at the surface. Overall extension, probably correlated to plate divergence, is then responsible for the last stages of exhumation associated to the detachment system.

V32D MC: Hall D Wednesday 1330h

Magmatic Evolution of Volcanic Systems

Presiding: J B Lowenstern, U.S.

Geological Survey

V32D-0993 1330h POSTER

Evolution of rhyolitic magma from Ata caldera: progressive melting model for chemical variation

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In order to understand a magmatic evolution of caldera forming rhyolitic eruption, essential fragments from Ata caldera, which is one of the four gigantic Quaternary caldera in Kyushu Japan, have been analyzed on bulk rock and glass chemistry. Rhyolitic magmas formed Ata caldera have two different rock types: pyroxene dacite and hornblende rhyolite. Phenocrystic minerals of hornblende rhyolite consists hornblende, plagioclase, and quartz. On the other hand, pyroxene dacite is plagioclase as a main phenocrystic mineral, accompanied by small amounts of fine grain pyroxenes.

Concentration of LIL elements, such as K₂O, Ba, Na₂O, Rb, in both types are the same level, but concentration of HFS elements, such as Nb, Y, Zr and Zn, decrease with increasing SiO₂. Geochemical contrast between them are also obvious in the diagram of REE abundance pattern. REE patterns of hornblende rhyolites have lower than basaltic rocks and are depleted in MREE. REE patterns of pyroxene dacite are equal or even lower than that of basalt and higher than hornblende dacite. The REE patterns imply that hornblende, which has high distribution coefficients in MREE should be residual mineral for hornblende dacite and is not liquidus facies in pyroxene dacites.

Rhyolitic magmas are produced by the dehydration melting reaction which can be drawn as following equation: Pl(1) + Bi + Qz + K-feld + Hbl to melt(1) + Pl(2) + Qz + Hbl + Opx. In this reaction, accessory minerals may not be involved due to their small solubility such low temperature. When the source region become hotter, then the reaction advance further. Above equation will change to following one: Pl(2) + Qz + Hbl + Opx + Mt to melt(2) + Pl(3) + Cpx + Opx + Mt Incompatible elements may increase in the melt due to breaking down of hornblende and dissolving accessory minerals in more higher condition, both minerals have high distribution coefficients for HFSE. Geochemical characteristics of essential fragments from Ata caldera arranged in the volcano stratigraphic sequences can be explained reasonably by dehydration melting process in the source region than fractionation and contamination in the magma chamber.

V32D-0994 1330h POSTER

The Shevlin Park Tuff, Central Oregon Cascade Range: Magmatic Processes Recorded in an Arc-Related Ash-Flow Tuff

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The circa 260 ka Shevlin Park Tuff is found throughout an area of some 400 square km west of the city of Bend, OR. The tuff is composed of several flow units, the lowest of which was mapped separately in the past as the Century Drive Tuff. We have found the Century Drive to be chemically and paleomagnetically similar to the Shevlin Park. The spatial distribution and pumice imbrication of the Shevlin Park suggest a source at an elevation near 2000 m on the Bend Highland 5-6 km east of Broken Top volcano. Deposition of the Shevlin Park may have been preceded by a Plinian airfall eruption, now mainly preserved in the Columbia Canal irrigation ditch, which is likely equivalent in the distal tephra record to the Summer Lake NN layer. Despite our extensive database of bulk pumice and glass geochemistry, we cannot corroborate an earlier correlation of the Shevlin Park with the Summer Lake JJ tephra.

The Shevlin Park Tuff is compositionally bimodal, with black pumice ranging from 55-62% silica, and commonly paler silicic pumice from 64-68%. Lower flow units appear to contain proportionally more silicic pumice and slightly more fractionated (lower MgO) mafic pumice. Mafic pumice is much more heterogeneous for a given silica percentage than silicic pumice, especially in P, Fe/Mg, and Sr. Both types of pumice are crystal-poor, and thus the bulk pumice and glass compositions are similar. Phenocrysts present in pumice include plagioclase (dominantly reversely zoned An₃₀₋₄₀, but ranging up to skeletal An₈₂), two pyroxenes (typically reversely zoned), olivine (Fo₇₁₋₇₆), magnetite, and ilmenite. The phenocryst assemblage and mineral chemistry of the Columbia Canal pumice are similar, with the exception of slightly more Fe-rich opx.

Mixing of mafic and silicic magma appears to be the dominant process in the generation of the wide compositional range within the Shevlin Park. A simple mixing model can account for most of the major and trace