and Hilina slump regions in which hyaloclastite and fragmental debris are dominated. The debris avalanche deposits are prevailing only in the lower submarine slope. The second is the sequence of landslide events. Base on the topographic and geologic investigations major landslide events can be redefined in the sequence from early to late: South Kona Slide 1(South Kona slump and Ka Lae west debris-avalanche), South Kona Slide 2 (South Kona slide), North Kona Slump (North Kona slide + Alika 1 debris-avalanche), Ka Lae slump (newly defined), Ka Lae debris-avalanche (Ka Lae East debris-avalanche), Alika debris-avalanche (Alika 2 debris-avalanche). It is concluded that these slope failures were probably result in the rift propagation rather than instability of the slope itself which made of unstable fragmental lavas. Therefore, the pillow lava model is more suitable for present case. However, the fragmental lava model is also correct in other case, such as Nuuanu landslide and Hilina slump. Each cross section can not represent as a general model, because the growth conditions differ in the directions.

V22C-0602 1330h INVITED POSTER

Dynamic Submarine Flanks of Hualalai Volcano, Hawaii

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Four remote and manned submersible dives examined the Hualalai midslope bench scarps, NW rift zone, and an elongate ridge cresting at 3900 mbsl during 2001 and 2002 JAMSTEC cruises. Here we report the results of stratigraphic, petrographic, and geochemical studies of the latter feature (dive S692). The ridge is 2x8 km, 300-700 m above datum, oriented parallel to the midslope bench, and 1 km east of the Mauna Loa Alika 2 landslide chute and levee deposit. Although the vast majority of the ridge is sediment covered, dive videos and sampling of the steep seaward side of the ridge revealed the following in-place lithologies, from base to crest: (1) bedded, landward dipping glass sandstones consisting of arcuate, angular to subangular glasses, moderately vesicular, tholeiitic and fairly uniform in composition, dominantly low in S, and intensely chemically altered toward the base, (2) olivine basalt breccia with fresh tholeiite glassy matrix, including S-rich grains, (3) dense olivine basalt lava blocks, (4) coarsely crystalline, vesicular, and oxidized lava, and (5) a capping unit of layered, volcaniclastic siltstone beds rich in radiolarians. Finally, an apron of talus and a superficial coating of muddy clastic materials drape the base of the ridge. Samples of this material are compositionally distinct from the in-place samples: they include transitional basalt and S-rich hawaiite. Key inferences about the ridge deposits are: (1) glass sands were produced as shield stage Hualalai lava erupted subaerially or in shallow water, (2) sands were cemented and overlain by breccia and lava blocks following minimal transport as grain flows to a depth that allowed incorporation of high-S grains; the entire sequence was transported to its current deep water location as a coherent package, (3) the zone of intense hydrothermal alteration and mineralization at the base is consistent with fluid flow in a region of distributed strain, possibly associated with gravitational spreading of Hualalai volcano, (4) the alkalic and transitional materials may represent pre-shield Hualalai volcanism. Alternatively, they could represent pre-shield Mauna Loa lavas excavated and transported to their present location by the Alika 2 landslide, which truncated the package, exposed the observed outcrop, and capped the sequence with fossiliferous glassy silt.

V22C-0603 1330h POSTER

Obscure Subaerial Evidence for Landslides From West Maui Volcano and Haleakala, Island of Maui, Hawai'i

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We propose two moderate-sized landslides from the Island of Maui. The submarine evidence for one is buried and for the other may be difficult to interpret in the narrow deep trough that contains it. On West Maui volcano, the herein-named Waikapū landslide chopped off the volcano's east flank. Subaerial evidence is an 18-km-long, linear eastern mountain front defined by an eastward limit of lava-flow exposures owing to alluvial onlap. Microgravity profiles show no abrupt change across the sediment-lava flow contact; instead, the Bouguer-anomaly trend defines monotonically diminishing gravity values eastward away from the volcano's core. Therefore the alluvial onlap is interpreted as a depositional contact over east-dipping lava flows, not a headwall scarp at currently exposed altitudes. The Waikapū landslide, comparable to or slightly larger than the Pololū slump on the Island of Hawai'i, must have occurred during the shield-building stage prior to 1.4 Ma; its headwall subsequently was draped by tholeiitic lava late in the shield stage. Submarine evidence lies buried within the edifice of nearby Haleakalā volcano, which became emergent through the surf zone soon after the landslide. On East Maui volcano, or Haleakalā, the evidence for the herein-named Pāhihi landslide is found on the south flank, where the slopes are substantially steeper, 31-38%, than elsewhere on the volcano. The area of steepest slope coincides with the extent of a normal fault exposed in the south wall of the erosional summit valley, Haleakalā Crater. At the 2300-m altitude, this south-side-down fault juxtaposes reversed-polarity 0.9-Ma transitional basalt (north) against postshield basanite (south) younger than 0.78 Ma. Postshield lava flows have subsequently draped the south flank, masking any truncation of older flows. Bouguer gravity contours along this flank of the volcano are similar in form to free-air data, owing to the overwhelming correlation of topography and mass. The Pāhihi landslide may have matched the Waikapū in volume, depending on the extent of volcano sector involved, but direct comparison is difficult because their remnant subaerial geomorphic forms differ. Pāhihi debris presumably mantles the steep submarine south flank of Haleakalā or lies in the 2-km-deep trough beneath the 'Alenuihāhā Channel.

V22C-0604 1330h POSTER

Volcanic Features in the Northwestern Hawaiian Islands Revealed by SWATH Mapping

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The Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve (NWHICRER) has only recently been established, and has already caused an infusion of interest and funds for studies to assess what is there to preserve and how best to do it. The Northwestern chain stretches over 2200 km to the northwest of the 775 km-long Main Hawaiian Islands (MHI). The MHI have only in recent years been systematically mapped with modern multibeam swath sonar systems and the work is not yet complete. With these southeastern islands being the population center, it is easy to imagine the lack of coverage along the Northwestern chain where no one lives except those stationed at remote outposts for scientific study. Manned and robotic submersible studies and limited multibeam mapping have been carried out by the Hawaii Undersea Research Lab every year in the NWHICRER for the past several years though focused on relatively shallow water biological sites. In late 2002, the first dedicated exploratory multibeam mapping expedition took place aboard the new University of Hawaii SWATH ship R/V *Kilo Moana*. While the primary mission was shallow mapping on carbonate platforms in support of the NWHICRER boundaries, a large amount of data were collected over the deeper volcanic foundations of the atolls. These surveys revealed dramatic rift zones on the same scale as those in the MHI, sea level terraces, submarine canyons cutting through the platforms with debris chutes continuing down to base of the islands, additional submarine landslide scars and debris fields in more detail than the USGS GLORIA sidescan program of the previous decade, and previously unmapped seamounts with some likely resulting from Hawaiian hot spot activity while others formed during creation of the Pacific Plate. A diving program is planned on many of these features in late 2003 and preliminary results will be presented.

V22C-0605 1330h POSTER

Revised Calculated Volumes Of Individual Shield Volcanoes At The Young End Of The Hawaiian Ridge

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Recent, high-resolution multibeam bathymetry and a digital elevation model of the Hawaiian Islands allow us to recalculate Bargar and Jackson's [1974] volumes of coalesced volcanic edifices (Hawaii, Maui-Nui, Oahu, Kauai, and Niihau) and individual shield volcanoes at the young end of the Hawaiian Ridge, taking into account subsidence of the Pacific plate under the load of the volcanoes as modeled by Watts and ten Brink [1989]. Our volume for the Island of Hawaii (2.48 x10^5 km^3) is twice the previous estimate (1.13 x10^5 km^3), due primarily to crustal subsidence, which had not been accounted for in the earlier work. The volcanoes that make up the Hawaii edifice (Mahukona, Kohala, Mauna Kea, Hualalai, Mauna Loa, Kilauea, and Loihi) are generally considered to have formed within the past million years and our revised volume for Hawaii indicates that either magma-supply rates are greater than previously estimated (0.25 km^3/yr as opposed to 0.1 km^3/yr) or that Hawaii's volcanoes have erupted over a longer period of time (>1 million years). Our results also indicate that magma supply rates have increased dramatically to build the Hawaiian edifices: the average rate of the past 5 million years (0.096 km^3/yr) is substantially greater than the overall average of the Hawaiian Ridge (0.018km^3/yr) or Emperor Seamounts (0.012 km^3/yr) as calculated by Bargar and Jackson, and that rates within the past million years are greater still (0.25 km^3/yr). References: Bargar, K. E., and Jackson, E. D., 1974, Calculated volumes of individual shield volcanoes along the Hawaiian-Emperor Chain, Jour. Research U.S. Geol. Survey, Vol. 2, No. 5, p. 545-550. Watts, A. B., and ten Brink, U. S., 1989, Crustal structure, flexure, and subsidence history of the Hawaiian Islands, Jour. Geophys. Res., Vol. 94, No. B8, p. 10,473-10,500.

V22D MCC: Level 1 Tuesday 1330h

Modeling Metamorphism I Posters
(joint with T)

Presiding: **J Liou,** Stanford University**; N Petford,** Kingston University

V22D-0606 1330h POSTER

Melt Redistribution During The Bending Of A Porous, Partially Melted Layer

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A numerical, poro-viscoelastic finite element flow model has been developed to simulate the redistribution of partial melt during the folding of a horizontal layer. Important mechanical properties governing the overall rheology of the buckling layer including porosity, matrix viscosity, melt pressure and changes in deviatoric stress are tracked simultaneously with deformation. Melt migrates down gradients in melt pressure to the outer hinges of the folds, away from sites of compression to regions of local extension. For a matrix with dynamic power law rheology, deformation results in the formation of low viscosity, strain weakening zones that coincide with zones of enhanced deviatoric stress that are potential sites for plastic deformation. During fast deformation of layers with large width to height ratios, the more rapidly bending material splits into domains of higher viscosity separated by lower viscosity zones. Porosity (melt fraction) distribution patterns do not appear to be controlled by the matrix rheology. The numerical results and predictions of melt distribution and geometry during deformation corresponds well with data from some physical (analogue) laboratory experiments and field observations. The quantitative nature of our results should help refine more qualitative models for the rates and mechanisms of melt extraction and transport in folded crustal migmatite terranes.

V

V22D-0607 1330h POSTER

A Two-Stage Model for Origin of Al-rich Crustal Xenoliths in Miocene Andesite, Diablo Range, West-Central California

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Miocene (~ 8-10.5 Ma) andesite exposed as small plugs and dikes in the Diablo Range of west-central California encloses scattered xenoliths with diverse compositions and textures. The andesite is part of the Diablo Range Volcanics (DRV), a mafic to intermediate suite that is broadly coeval with and may be erosional remnants of the more extensive Quien Sabe Field located to the south and east. The DRV suite is inferred to be part of a northwestwardly younging sequence of volcanic fields that may be related to migration of the Mendocino Triple Junction (MTJ). Two basic categories of xenoliths are present: (1) metasedimentary rocks including quartzite, biotite schist, garnet-clinopyroxene gneiss, and distinctive sillimanite-corundum rocks; and (2) gabbroic and dioritic rocks exhibiting plutonic textures. Preliminary analysis has focused on aluminous xenoliths in which blocky porphyroblasts consisting of intergrown plagioclase, corundum, and hercynite ± sillimanite ± alkali feldspar up to ~ 2 cm in length are surrounded by a very fine-grained granoblastic matrix of plagioclase, orthopyroxene, and hercynite ± biotite ± alkali feldspar ± minor quartz. Glass is present both within the inclusions and in the surrounding matrix. The square to elongate outlines of the plagioclase-corundum inclusions suggest that they are pseudomorphic after andalusite. The corundum-bearing xenoliths are interpreted as the products of two stages of high T-low P metamorphism. The first event involved mid-crustal metamorphism (reflecting cessation of outboard subduction/refrigeration?) to produce andalusite-bearing hornfels; other phases probably included K-feldspar, Na-plagioclase, muscovite, biotite, and quartz. The second stage of recrystallization took place when the previously metamorphosed wall rock was incorporated in andesitic magma, possibly during passage of the MTJ. In response to heating by the magma, andalusite was replaced by corundum, plagioclase ± sillimanite, muscovite and quartz broke down to produce more K-feldspar and sillimanite, and most of the biotite decomposed, forming abundant hercynite.

V22D-0608 1330h POSTER

Modelling retrogressive reaction microstructures: a case study concerning staurolite to sericite reaction and the control of matrix composition on it

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Pseudomorphic sericite aggregates after staurolite have been observed in garnet + staurolite ± kyanite micaschists from the Austroalpine basement outcropping in the Quaira (Karbach) Valley (Eastern Alps, Bolzano, Italy). Microstructural analysis, mineral assemblages and geothermobarometry give constraints on the Variscan metamorphic peak conditions (T = 600-650°C; P = 0.7-0.8 GPa) and on the subsequent retrogressive P-T path. Reaction microstructures have been analysed by optical microscopy and SEM, and a developing model has been proposed. Such a model resulted to be satisfactory although some approximations have been introduced. These are related to inhomogeneous distribution of mineral phases in the matrix and to the exclusion of some mineral phases (garnet and plagioclase) believed to be not relevant to the pseudomorph formation. The following reaction is predicted by the model: 1.00 St + 2.42 Bt + 4.76 Qtz + 26.2 H2O = 2.73 Ms + 3.56 Chl + 0.24 Ilm. Congruently to observations, this reaction predicts that staurolite porphyroblasts decomposition to sericite is strictly connected to biotite decomposition to chlorite + ilmenite in the matrix. In fact, although channelised fluids probably drove the reaction, the extent of staurolite decomposition resulted to be controlled by the availability of biotite in the matrix.

V22D-0609 1330h POSTER

Oxygen Isotope Thermometry and Speedometry

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Oxygen isotope fractionation depends on temperature and has been extensively applied to geothermometry. However, unless the cooling is rapid enough, formation or peak temperature may not be recorded, and retrograde reaction and diffusion among minerals may lead to inconsistent temperatures for different mineral pairs. Dodson (1973) examined the isotopic exchange of a single crystal with an infinite reservoir and developed the concept of closure temperature (Tc). Giletti (1986) treated closure temperature as an innate property of a mineral and examined the isotopic exchange in a closed system. Eiler et al. (1992a, b, 1994) pointed out that this method is not strictly correct, and developed an FGB model for isotopic evolution of a multi-mineral system. They concluded that the apparent equilibrium temperature (Tae) calculated from isotopic fractionation between two phases is strongly dependent on mineral proportions and could even be negative. Although the FGB model can in principle be applied to determine the cooling history by matching observed and calculated isotopic compositions of the minerals by varying the cooling history, in practice the application is very difficult. In this contribution, we apply the FGB model to look for a simple method for oxygen isotope thermometry and speedometry. Our results can be summarized as follows. For a multi-mineral system, it is best to use two minerals with the greatest isotopic fractionation (such as quartz and magnetite, or quartz and rutile) to calculate Tae. Tae obtained from such a mineral pair almost always lies between the closure temperatures of the two minerals. The significance of this thermometry (calculation of Tae) is actually in speedometry: Using Tae as a proxy for Tc of each of the two minerals, the range of cooling rate can be estimated using the method of Dodson. If the two minerals happen to have diffusion properties so that they have similar closure temperatures (e.g., quartz and magnetite), Tae would be an excellent approximation of Tc of both minerals, from which cooling rate of the rock can be estimated. In summary, a mineral pair with the largest fractionation and similar closure temperatures is the best for obtaining cooling rate. San Jose tonalite (Giletti, 1986) serves as a good example to apply this method. It contains 5 minerals: quartz, plagioclase, hornblende, biotite, and magnetite, in the order of oxygen isotopic ratio (hornblende, quartz, magnetite, biotite and plagioclase, in the order of decreasing closure temperature). Tae between quartz and magnetite is 817 K (Zheng, 1995). Using diffusion data from Giletti and Yund (1984) for quartz and from Giletti and Hess (1988) for magnetite, the cooling rate at Tae ranges from 16 to 65 K/Myr.

V22D-0610 1330h POSTER

Experimental Investigation of Reaction and Fluid Transport in Dolomite Rock

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Metamorphism of carbonate rock is commonly the result of reaction between the minerals in the rock and an H_2O-rich fluid. One example is the breakdown of dolomite, producing calcite + periclase. The reaction results in a reduction of the solid volume of the rock and a production of CO_2. Both contribute to the increase in permeability during reaction, permitting continued ingress of H_2O. We have attempted to determine some of the processes that occur during infiltration and reaction experimentally. We cut 4 mm diameter cores of dolomite rocks with a variety of textures ranging from fine-grained sedimentary dolostones to coarse-grained dolomitic marbles. Experiments are carried out using a conventional cold-seal hydrothermal apparatus. The dolomite rock cores were sealed in gold capsules with an aliquot of isotopically enriched water of composition $HD^{18}O_{0.5}\,{}^{16}O_{0.5}$. The samples were held at a $P = 100$ MPa and $T = 650$–$700\,^{\circ}C$ for durations ranging from a few days to a few months. After experimentation, the cores were sectioned and examined by XRD, EMP, SIMS, and CL techniques. All experiments show some reaction, even in experiments lasting for only two days. In samples with a large water-rock ratio, complete reaction occurred within 30 d at 700 °C. Crystallization of new mineral phases within coarse samples is concentrated along fluid infiltration pathways, such as grain boundaries and fractures. Smaller grain size samples show more pervasive crystallization, with original dolomite nearly completely replaced by calcite. Although periclase is the stable phase for the conditions of these experiments, extensive brucite is observed and is believed to be the result of rapid hydration of periclase upon quench. SIMS ion imaging shows extensive enrichment of ^{18}O along dolomite grain boundaries and in fractures. There is little evidence in the short-duration experiments for any exchange between fluid and the dolomite, but the newly formed products of reaction are strongly enriched in ^{18}O. Under the conditions of the experiments with water–rock ratios ≥ 1, grain-boundary transport readily occurs over the sample distances of 2–4 mm.

V22D-0611 1330h POSTER

Very Low Solubility of Rutile in H_2O at High P and T

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Rutile (TiO_2) is a common accessory mineral in high-pressure rocks and contains high concentrations of high field strength elements (HFSE) such as Nb and Ta. Understanding the solubility behavior of rutile is necessary in order to interpret the characteristic HFSE depletion of island arc basalts. Previous study (Ayers and Watson, 1993, Contrib. Mineral. Petrol., 114, 321) suggests increasing solubility in H_2O with T at 900-1100 °C, 1 and 2 GPa, reaching 0.246 molal at 1100 °C, 1 GPa. These results imply significant solubility and mobility of aqueous Ti at mantle conditions. However, this conclusion depends on the interpretation that newly formed rutile crystallites in the experiments grew during quench rather than during the runs. In order to place additional constraints on the solubility of rutile in H_2O at these P-T conditions, we carried out weight-loss experiments on synthetic rutile single crystals in a piston-cylinder apparatus. Our main objective was to explore the effects of minor temperature gradients in the charges on rutile crystal growth. T gradients were minimized by using thick-walled graphite furnaces and small, horizontal Pt capsules (OD=3.5 mm). Experiments were conducted with and without inner Pt envelopes to contain crystals. Preliminary results showed that in the absence of the Pt-envelopes, significant aqueous Ti transport and newly formed, blocky rutile crystals occur in the capsule ends, presumably due to slight temperature gradients in the charges. Longer run times result in increased mass of these rutile crystallites. By contrast, new rutile growth is suppressed in the presence of a Pt envelope containing the crystal. Evidently, the inner capsule has a thermal baffling effect which reduces temperature gradients. In all runs, morphologically distinct rutile needles form on the capsule walls upon quench. Only experiments yielding no growth of new, blocky crystals during the run can provide accurate solubility measurements from the weight change of the starting crystal. At 1 GPa, we find rutile solubility at 800 °C and 900 °C to be <0.0007 molal, and at 1100 °C, it is 0.0028 molal. At 2.0 GPa, the solubility at 1000 and 1100 °C is also very low (0.0018 and 0.0030 molal, respectively). These data indicate that the solubility of rutile in H_2O at $\geq$1000 °C is up to 75 times lower than previously reported. Our results reduce significantly the solubility gradient that would be experienced by aqueous fluids in the mantle wedge above subduction zones, implying that such fluids are inefficient agents for the redistribution of HFSE in this environment.

V22D-0612 1330h POSTER

Solubility of Anhydrite ($CaSO_4$) in NaCl-H_2O Fluids at High T and P

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Weight losses of single crystals of a very pure natural anhydrite exposed to NaCl solutions of 0-0.3 mol fraction were measured at 600-800 °C and 6-14 kbar. Experimental charges were contained in welded Pt capsules in 1.91 cm-diameter piston-cylinder apparatus with NaCl pressure medium for 5-72 hr. Measurements in initially pure H_2O were made with HM, NNO, and MnO_2 buffers, as well as without buffering. At 800 °C and 10 kbar, $CaSO_4$ molalities are:

MnO_2, 0.014 mol/kg H_2O; HM, 0.017; NNO, 0.148; and unbuffered, 0.026. Variation in oxygen fugacity thus has a large effect on $CaSO_4$ solubility, increasing with H_2S/SO_2 in the fluid. Unbuffered (self-buffered) charges gave solubilities much closer to HM than NNO. Melting occurred in the NNO experiment at this P and T. NaCl increases $CaSO_4$ solubility enormously, with m($CaSO_4$) reaching 5.4, or 23.5 wt. %, at 800 °C, 10 kbar and X(NaCl)=0.3. There is also a very large increase with temperature. Regression of all the data give: log(m-m_o) = -1.533 + 0.00291T + (1.441 + 0.00016T)logX(NaCl) + 0.0413(P-10) where m_o is molality in pure H_2O, P is in kbar, and T is in Kelvins. The very large carrying capacity for sulfate in even mildly saline fluids at high P and T, together with the high oxygen potential generated when these solutions react with FeO in rocks to yield pyrrhotite, indicates that such fluids should be considered as principal agents in S-rich, highly oxidizing processes such as Pinatubo-type volcanic eruptions, certain deep-crustal granulite facies metamorphism, as in Bamble, Norway and Shevaroy Hills, S. India, and the anhydrite-related, oxidized Au ore deposits like Abitibi, Ontario, and Kalgoorlie, Australia.

V22D-0613 1330h POSTER

Solubility of Albite + Paragonite ± Quartz in H_2O at 1 GPa, 580°C: Implications for Metamorphic Fluids

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One of the most common mineral assemblages in crustal metamorphism is feldspar + quartz; however, little is known about the solubility of this assemblage in metamorphic fluids. We measured the solubility of albite and albite+quartz in H_2O at 580°C and 1.0 GPa using a piston cylinder apparatus. Experiments were conducted using Amelia albite in NaCl-graphite assemblies. Experiments were conducted using a double capsule arrangement. Inner capsules consisting of perforated 1.6 mm OD Pt capsules containing a single albite crystal were load in 3.5mm OD outer capsules containing ultra pure H_2O ± quartz. Solubility was determined by the weight loss of single albite and quartz grains after 8 hr runs. Time series experiments on this system show no variation in fluid composition or solubility after 4hrs. Albite exhibited incongruent dissolution, yielding paragonite as a husk that mantles the albite grain. The composition of the fluid was determined by mass balance as determined by the weights of albite, quartz, and paragonite. In the albite-only experiments, the concentration of total dissolved solids (TDS) were 0.628 molal, with Na, Al and Si in the fluid of 0.137, 0.081, and 0.41 molal, respectively, and Na/Al of 1.691. In the presence of quartz, there is an increase in the overall TDS to 0.777 molal. Albite-quartz experiments produce an increase in Si concentration to 0.628 molal, with lower Na and Al concentrations of 0.098 and 0.051 molal, respectively, and Na/Al of 1.922. The aqueous Si concentrations in the albite-only experiments are higher than those in fluid equilibrated with quartz (Manning, 1994, GCA, 58, 4831) at the same conditions. This is consistent with the data of Anderson and Burnham (1983, Am. J. Sci., 283-A, 283) on albite. In the quartz-present experiments results show still higher Si concentration in the fluid phase. Our results demonstrate enhanced solubility of silica in the presence of albite and albite+quartz, relative to quartz alone, suggesting that the additional components promote complexing, perhaps through polymerization. This solubility enhancement has implications for the nature of transport in deep crustal pelitic systems, allowing for a greater abundance of silica to be removed by a fluid phase during metamorphism. The enhancement of silica solubility indicates that models of simple, aqueous metamorphic fluids must account for silica polymerization, and that such fluids may carry a substantially greater solute load than has previously been recognized.

V22D-0614 1330h POSTER

Thermal structure of pumpellyite-actinolite facies regions in the Sanbagawa belt, Shikoku, SW Japan

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On the basis of the mineral assemblages of pelitic rocks, the Sanbagawa belt in Shikoku, SW Japan, has been divided, from low- to high-grade parts, into the chlorite, garnet, albite-biotite and oligoclase-biotite zones (Higashino, 1990). Also, the mineral assemblage of pumpellyite + actinolite + epidote + chlorite or epidote + actinolite + hematite + chlorite, which defines the pumpellyite-actinolite (PA) facies (e.g., Banno, 1998), is widely recognized in metabasites in the chlorite zone (e.g. Banno & Sakai, 1989). However, the detailed study on the PA facies regions has been done only in the Omoiji-Nagasawa area (Nakajima et al., 1977) and Asemigawa-Shirataki area (Nakajima, 1982) in central Shikoku, and thus, it is still hard to solve the regional thermal structure of the PA facies region. This study is aimed to reveal the thermal structure of the PA facies region of the Sanbagawa belt in Shikoku by analyzing the mineral assemblages and mineral chemistries of metabasites from the nine newly studied areas. The studied areas studied belong to the chlorite zone in the Oboke and Besshi units; the Oboke unit structurally underlay the Besshi unit. The mineral assemblages include pumpellyite + epidote + actinolite, epidote + actinolite hematite and epidote + Na-amphibole + actinolite + hematite. The metabasites from some areas involve Na-pyroxene-bearing assemblages, but the analyses of the Schreinemakers bundle of Tagiri et al. (1992) show that these assemblages do not define the Na-pyroxene-chlorite subfacies. As the low-grade metamorphic rocks do not have the hematite + pumpellyite paragenesis, its metamorphic temperature is estimated to be higher than the discontinuous reaction temperature of pumpellyite + hematite + quartz = epidote + actinolite + H2O, as shown by Nakajima et al. (1977). It is difficult to detect the difference in temperature in the PA facies regions by analyzing mineral assemblages. To detect the difference in temperature, and then to reveal thermal structure, I attempt here to analyze the Fe3+-values of epidote and pumpellyite in the pumpellyite + actinolite + epidote + chlorite assemblage, because these values, if coexisting chlorite has the fixed value of Fe*, have a tendency to decrease with increasing metamorphic temperature (Nakajima et al., 1977). The results show that, if coexisting chlorite compositions are fixed within XFe* = 0.45 - 0.56, Fe3+ values of epidote have the systematic variation as compared each areas, and at least three zones can be divided such as high (minimum XFe3+=0.13-0.19), medium (= 0.21), and low (= 0.25) temperature zones. The lowest temperature zone in the Sanbagawa belt is located at the Omoiji-Nagasawa area. The metamorphic temperature in the Besshi unite is decreasing away from the high grade zone, but it is not clear whether the temperature decreases continuously or discontinuously. The structural evidence indicated that the Oboke unit is the lowest horizon in the Sanbagawa belt, but the metamorphic temperature of the Oboke unit is higher than those of same areas belonging to the Besshi unite. The Oboke and Besshi units are separated by ductile thrust, and radiometric ages of thermal peaks are different between these units as reported by Takasu & Dallmeyer (1990). Therefore, although the chlorite zones of the Besshi unit and Oboke unit belong to the similar PA facies regions, it is not contradictory that the thermal structure from the Oboke to Besshi units is not continuous. These results could be important to adjust the Sanbagawa metamorphic history.

V22D-0615 1330h POSTER

Ultrahigh pressure eclogites of the North Qaidam and Altun Mountains, NW China and their protoliths

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An Early Paleozoic ultrahigh pressure metamorphic belt occurs in the Qilian-Altun Mountains and is offset about 400 km westward by the Altyn Tagh strike-slip fault. Eclogites in the belt consist of major basaltic and minor picritic rock types and can be subdivided into three groups: high TiO2 (2-5 wt%), medium TiO2 (1-2 wt%) and low TiO2 (<1 wt%). Geochemical evidence shows that the protoliths of the eclogite were basaltic rocks from different tectonic environments, including mid-ocean ridge basalt, island arc basalt and ocean island basalt. The Nd isotopes of these rocks are similar to those of MORB, characterized by mainly positive and minor negative eNd(0) values, providing further evidence that the eclogite protoliths were ocean floor basalts, to which minor crustal components were added during subduction to form UHP metamorphic rocks. Geochronological data indicate that the UHPM occurred about 500-440 Ma, and that there were two eclogite protoliths with ages of 800-750 Ma and about 1000 Ma. Geochemically and isotopically, the eclogites are similar to basaltic rocks in Luliangshan, North Daqaidam Mountains, which have Sr and Nd ages of 768 +/- 39 Ma and 780 +/- 22 Ma. The age and composition of these volcanic rocks suggest that they were one of the protoliths for the eclogites. A later series of calc-alkaline island arc volcanic rocks was formed at about 500 Ma, essentially contemporaneously with the UHP metamorphism. Based on the available geochronological and geochemical data, we suggest the following tectonic model for the evolution of the UHP belt in the North Qaidam Mountains. At about 1000 Ma the area was amalgamated to form the Rodinian continent, which contained some oceanic volcanic rocks, possibly as ophiolitic fragments. This part of Rodinia was then rifted at about 800-750 Ma to form an oceanic basin with a variety of MORB and ocean island basalts. Closure of this ocean basin produced the Neoproterozoic ophiolites and granitic gneisses in the North Qaidam Mountains. In the Early Paleozoic a new Qilian ocean basin formed and subduction of this oceanic lithosphere formed the island arc volcanic rocks at about 500 Ma and the subduction-related granites. Once the oceanic lithosphere was consumed, continent-continent collision led to deep subduction of continental crust, which was tectonically mixed with the eclogites.

V22D-0616 1330h POSTER

Chemistry and its implication of Ultrahigh-Pressure Peridotites from Pre-pilot hole of Chinese Continental Scientific Drilling Project (CCSDP)

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The Chinese pre-pilot hole (PP1) is located at Zhimafang village, Donghai of the Sulu UHP terrane, east China. Peridotite of 115 m thick within gneiss from the PP1 is composed of abundant lherzolite, harzburgite, and minor wehrlite and dunite. Peridotite at the contacts with gneiss is strongly serpentinized. More than 90 vol% peridotites contain garnet and phlogopite; some contain magnesite and Ti-clinohumite. The PP1 peridotites were recrystallized at 780-950oC and 4.5-7.0 +/- 0.2 GPa in the subduction zone environment. Major, REE, trace elements and O, Sr and Nd isotope compositions of peridotites were analyzed by XRF, ICPMS and mass spectrum. Mineral oxygen isotope has the mantle value of +4e - +6e, indicating that O isotope equilibrium between minerals has been reached. All peridotites contain lower "fertile element" concentrations than those of the primitive mantle. Mg number ranges from 90.29 to 92.66 (three down to 81.93-86.61). MgO content (41-48 wt%) has negative correlation with Na2O (0.01-0.24 wt%), Al2O3 (0.42-3.55, most < 2 wt%) and CaO (0.23-2.41wt%, one up to 3.15 wt%) contents, and moderately positive correlation with compatible element Ni and Co. These major element data suggest that the PP1 peridotites were derived from a depleted upper mantle resulting from partial melting of primitive mantle and melt removement. Among them, the most depleted rock is Grt-free dunite. The PP1 peridotites show slight to moderately fractionated REE pattern with (La/Yb)N ratios of 0.66-12.36 with a few exceptions. In spidergrams, conspicuous positive Ba and Sm, and negative Nb, Zr and Ti anomalies are observed. Whole rock has high present 87Sr/86Sr ratio of 0.7104-0.7227 and 143Nd/144Nd ratio of 0.51209-0.51254. These trace element and isotope data suggest that these rocks were probably derived from long-term enriched mantle or were subjected to crustal contamination. These characteristics described above and lack of correlation between refractory degree and enrichment of incompatible trace elements are attributed to metasomatism by various melts or H2O-CO2 fluid derived from both mantle and subducting slab.

V22D-0617 1330h POSTER

Diamond-free UHP garnet-clinopyroxene rock from Kumdy-kol in the Kokchetav Massif

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Diamond-free garnet-clinopyroxene rock that looks like 'skarns' occurs at the Kumdy-kol in the Kokchetav Massif, northern Kazakhstan. This rock is distinguished from eclogites by lack of diamond and from the garnet-pyroxene rocks previously reported by the chemical compositions of garnet and clinopyroxene. It was unclear whether this garnet-clinopyroxene rock was a

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product of the Kokchetav UHP metamorphism or not. Recently, we found coesite exsolution needle/plates in titanite and K-feldspar/phlogopite needles or prisms in clinopyroxenes in this rock. These findings indicate that diamond-free garnet-clinopyroxene rock is also a product of UHP metamorphism. The descriptions in detail are as follows. Diamond-free garnet-clinopyroxene rock consists mainly of garnet (40 vol.%), clionopyroxene (45 vol.%), quartz (5 vol.%), amphibole (<5 vol.%) and K-feldspar (< 5 vol. %) with minor amounts of titanite, calcite, plagioclase, chlorite and zoisite. Chemical compositions of garnet were plotted in two ranges: grossular-rich (Grs: 66.0-85.5, Pyp: 1.2-8.6, Alm: 21.4-26.8) and relatively pyroperich (Grs: 46.6-48.1, Pyp: 17.4-20.7, Alm: 30.6-32.7). Clinopyroxenes fell in the field from salite to ferrosalite. Amphibole, chlorite and zoisite are the secondary products. No diamond found. Tiny coesite needles (10-20 μm in longer dimension) and plates (10 μm in longer dimension) were found in titanite in the sample nos. XX-06, -16 and were considered to be exsolved from supersilicic titanite during exhumation stage according to their textural relations. The mode of occurrence of coesite in titanite is similar to that reported in calcite marble from the Kumdy-kol area (Ogasawara et al., 2002); however, the present garnet-clinopyroxene rock is clearly different from the calcite marble by a modal composition of calcite marble (calcite: 40 vol.%, K-feldspar: 30 vol.%, diopside: 20 vol.%) and by the chemical compositions of clinopyroxenes. Coesite was identified by the laser Raman spectroscopy. The strongest Raman band of coesite was detected at 521 cm^{-1} with weak bands at about 119, 270 and 426 cm^{-1}. Clinopyroxene (0.3-2.0 mm in diameter) contains exsolved phases of K-feldspar and phlogopite in the sample nos. XX-04, -06, -16 and -22. These phases were identified by the laser Raman spectroscopy and an electron microprobe. K-feldspar shows needle shape (100 μm in longer dimension) or prismatic shape (20 μm) and the domain of host clinopyroxene near K-feldspar prism lacks needle-shaped K-feldspar and phlogopite. Such textures suggest that the exsolution of K_2O-bearing phases occurred at two stages. All these data described above showed diamond-free garnet-clinopyroxene rock had been subjected to UHP metamorphism together with other rocks, eclogite, gneisses and marbles. References: Ogasawara, Fukasawa and Maruyama (2002): *Am. Mineral.* **87**, 454-461.

V22D-0618 1330h POSTER

Significance of Diamond-free Heterogeneous UHP Dolomitic Marble From the Kokchetav Massif

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Local heterogeneity of fluid conditions during UHP metamorphism has been well demonstrated in a cm-scaled continuous sample of UHP marble (sample no. Y665) from the Kumdy-kol in the Kokchetav Massif. This banded carbonate rock sample consists of three zones; zone-A: dolomitic marble with abundant Ti-clinohumite, zone-B: dolomite marble, zone-C: dolomitic marble without forsterite and Ti-clinohumite. All three zones lack diamond. Zone-A consists of Ti-clinohumite, forsterite, diopside, Mg-calcite, dolomite, symplectite, and is characterized by the presence of Ti-clinohumite and by Ti-clinohumite-aragonite tie-line at the peak metamorphic condition. Diopside lacks lamella. Garnet is completely retrograded to symplectite (Di + Spl + Mg-Cal). Large-grained Ti-clinohumite shows clear compositional zoning of TiO_2 between core (1.5-1.8 wt.%) and rim (2.2-3.4 wt.%). Some Ti-clinohumite grains contain very thin needles with preferred orientations. Zone-B consists mainly of dolomite, diopside, phlogopite, symplectite (Di + Spl + Mg-Cal) with minor amount of Mg-calcite, and is characterized by the stability of dolomite-diopside tie-line and by lack of Ti-clinohumite and forsterite. No lamella was observed in diopside. Garnet is rarely preserved. Zone-C consists mainly of Mg-calcite, dolomite, diopside, garnet and phlogopite and is characterized by phlogopite lamellae in diopside that indicate high pressure conditions. Phlogopite lamellae in diopside were confirmed by the laser Raman spectroscopy (Raman bands: 681.3 cm^{-1} and 357.9 cm^{-1}) and by microprobe analysis. Lack of Ti-clinohumite and forsterite also characterizes this zone. Garnet has been well preserved from the retrograde reaction. High $MgCO_3$ calcite (originally aragonite + dolomite) with large-grained exsolved dolomite lamellae occurs. All three zones have different bulk compositions each other; however, the tie-line relations cannot be explained by their bulk compositions. In zones C and B, diopside-dolomite tie-line was stable, whereas aragonite-Ti-clinohumite tie-line was stable in zone-A. Aragonite-clinohumite pair is stable at very low Xco_2 and diopside-dolomite pair has wide stability range in Xco_2 and is stable at higher Xco_2 than that of aragonite-clinohumite (Ogasawara et al., 1998). Such paragenetic relations observed in the banded carbonate specimen (no.Y665) suggest the local heterogeneity and the gradient of Xco_2 from zone A (low) to zone C (high) during UHP metamorphism. The infiltration of H_2O-rich fluid might occur in some layers of the marble to form the difference in the mineral assemblages during UHP metamorphism. References: Ogasawara, Zhang and Liou (1998): The Island Arc, 7, 82-97. Ogasawara, Ohta, Fukasawa, Katayama and Maruyama (2000) The Island Arc, 9, 400-416. Ogasawara, Fukasawa and Maruyama (2002): Am. Mineral. 87, 454-461.

V22D-0619 1330h POSTER

Stability relations of Ti-bearing assemblages in UHP marbles from the Kokchetav Massif

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Stability relations of Ti-bearing phases (rutile, titanite, Ti-clinohumite) in UHP marbles from the Kokchetav Massif, northern Kazakhstan were well analyzed by the phase relations in the model system CaO-MgO-SiO_2-TiO_2-CO_2-H_2O. Three types of UHP marbles have been described in the Kumdy-kol area: diamond-bearing dolomite marble (type-A), diamond-free Ti-clinohumite-bearing dolomitic marble (type-B), and diamond-free calcite marble (type-C) (Ogasawara et al., 2000; 2002), and they contain a distinct Ti-bearing phase, rutile, Ti-clinohumite, and titanite, respectively. The characteristics of these three marbles are as in the followings. Type-A: Dominant carbonate is dolomite. Abundant microdiamonds are included in garnet and diopside. Diopside-dolomite tie-line was stable. Diopside contains K-bearing silicate lamellar. The peak assemblage was dolomite + diopside + aragonite + garnet + rutile + diamond. Type-B: High $MgCO_3$-calcite (originally aragonite + dolomite) is distinct. No diamond occurs. Diopside lacks lamellar texture. The peak assemblage was aragonite + dolomite + garnet + Ti-clinohumite or forsterite. Type-C: Only carbonate phase is calcite (originally aragonite). No diamond occurs. Titanite contains coesite exsolution lamellae and indicated supersilicic compositions stable at UHP conditions (P > 6GPa). Diopside contains phengite and K-feldspar lamellae. The peak assemblage was aragonite + diopside + K-feldspar + garnet + titanite. The solid-solid reaction, $CaTiSiO_5$ (titanite) + $CaMg(CO_3)_2$ (dolomite) = $CaCO_3$ (aragonite) + $CaMgSi_2O_6$ (diopside) + TiO_2 (rutile), controlled the stability of Ti-bearing phases in calcite marble and dolomite marble. At UHP conditions, aragonite + diopside + rutile assemblage is stable compared with titanite + dolomite, and divides the compositional space into dolomite-free and dolomite-bearing tetrahedrons in the model system CaO-MgO-SiO_2-TiO_2. The presence of titanite in calcite marble indicates that the P-T condition was located in the right-hand side of the decarbonation reaction aragonite + rutile + coesite = titanite + CO_2. The lack of rutile in calcite marble can be explained by low bulk TiO_2 contents of this marble. The mineral assemblages in dolomitic marble require extremely low-X_{CO2} conditions compared with those in dolomite marble because the aragonite + Ti-clinohumite tie-line was stable (Ogasawara et al., 2000). The continuous sample from the Kumdy-kol (sample no. Y665: dolomite marble and dolomitic marble) suggests X_{CO2} heterogeneity in cm scale under UHP conditions. The stability of Ti-clinohumite was controlled by the reaction: dolomite + diopside + TiO_2 + H_2O = Ti-clinohumite + aragonite + CO_2. All these results related with Ti-bearing phases were consistent with the previous works on the Kokchetav UHP carbonates (Ogasawara et al., 2000; 2002). References: Ogasawara, Ohta, Fukasawa, Katayama and Maruyama (2000) *The Island Arc*, **9**, 400-416. Ogasawara, Fukasawa and Maruyama (2002): *Am. Mineral.* **87**, 454-461.

V22D-0620 1330h POSTER

SIMS carbon isotope study of microdiamond in UHP dolomite marble from the Kokchetav Massif

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Carbon isotope of 10-20 micrometer-sized metamorphic diamond inclusions in garnet was analyzed with a SIMS at Tokyo Institute of Technology. The samples used for this SIMS analysis are UHP dolomite marble corrected at Kumdy-kol in the Kokchetav Massif, northern Kazakhstan. Typical microdiamond in this dolomite marble shows star-shaped morphology (S-type) measuring 10-20 μm in diameter and consists of single crystal core and polycrystalline rim having different orientations (Ishida et al., 2003). Cathode luminescence (CL) images and spectra of S-type microdiamonds also show the difference between core and rim; the peak intensity at 525 nm of the rim is significantly stronger than that of the core (Yoshioka et al., 2002). Their results in CL analysis supported the two-stage growth of S-type microdiamond in dolomite marble (Ishida et al., 2003). For the SIMS measurements, we prepared the samples in ordinary polished thin sections that were previously examined by other methods (e.g. CL). Three grains of S-type microdiamond and two grains of single crystal R-type diamond (single crystal with rugged surface, Ishida et al., 2003) are analyzed up to now. The ion beam spot of SIMS analysis is about 5 μmm in diameter. The analyzed spots were confirmed by secondary electron images after SIMS analysis. The sample of S-type microdiamond (no. XX01-1-13) showed $\delta^{13}C$ values ranging from -13 to -9$^o/_{oo}$ (average -10.4$^o/_{oo}$) for the core, and from -21 to -15$^o/_{oo}$ (average -17.2$^o/_{oo}$) for the rim. Such heterogeneous $\delta^{13}C$ distribution in S-type microdiamond was also detected in the other two samples that indicated significant gap of $\delta^{13}C$ range; the sample no. XX01-1-12: -20 to -18$^o/_{oo}$ (average -17.5$^o/_{oo}$) and -27 to -22$^o/_{oo}$ (average -23.9$^o/_{oo}$), and the sample no. XX01-1-15: -18 to -16$^o/_{oo}$ (average -17.1$^o/_{oo}$) and ranging from -27 to -23$^o/_{oo}$ (average -24.9$^o/_{oo}$). Two independent analyses of the same sample (no. XX01-1-16) of R-type microdiamond show good reproducibility in $\delta^{13}C$ values; analysis no. 1: -15 to -8$^o/_{oo}$ (average -11.5$^o/_{oo}$) and analysis no. 2: -13 to -9$^o/_{oo}$ (average -11.0$^o/_{oo}$). The other sample of R-type microdiamond (no. XX01-1-10) showed $\delta^{13}C$ values ranging from -16 to -11$^o/_{oo}$ (average -12.9$^o/_{oo}$). Summarizing these carbon isotope data hitherto obtained strongly support two-stage growth of microdiamond in UHP dolomite marble in the Kokchetav Massif. References: Ishida, Ogasawara, Osumi & Saito (2003) J. Metamorphic Geol. 21, 515-522 Yoshioka, Imamura & Ogasawara (2002) EOS Transactions AGU, 83, F1403

V22D-0621 1330h POSTER

Exsolution Textures and Zircon Geochemistry, North Qaidam UHP Terrane, NW China

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Eclogite, peridotite and pyroxenite (± garnet) enclosed in amphibolite-facies felsic gneisses of the North Qaidam Mountains preserve mineral exsolution textures probably formed during exhumation from ultra-high pressure (UHP) conditions. Garnet in eclogite, garnetite, and clinopyroxenite contains rutile rods aligned in multiple crystallographically controlled directions. Clinopyroxenites contain 4–6 mm diopside porphyroblasts in a 0.5–1 mm matrix of diopside, chlorite, amphibole, and Cr-magnetite. These porphyroblasts contain rods and plates of chromite or Cr-magnetite (18–22 wt.% Cr_2O_3, poorer in iron than matrix magnetite), ilmenite rods, chlorite plates, and sparse phlogopite. X-ray microdiffraction of exsolved chromite in one grain indicates the crystallographic orientation $(101)_{Chr}//(0\bar{1}0)_{Di}$, $(111)_{Chr}//(\bar{1}3\bar{1})_{Di}$, $(131)_{Chr}//(\bar{1}\bar{1}1)_{Di}$. One clinopyroxenite contains diopside with exsolved Cr-spinel and magnesiokatophorite, and diopside from another sample contains stubby rutile prisms. These exsolution features are similar to those reported from other UHP terranes and kimberlites, and are consistent with the increased solubility of Ti in garnet, and K, Ti, and Si (± OH) in clinopyroxene indicated by UHP experiments. Cathodoluminescence (CL) and SHRIMP-RG Th, U, and REE analysis of zircons from one amphibolitized eclogite reveals CL dark cores (probably magmatic) with high Th/U, moderate Th, U, and high REE concentrations, and a moderate Eu anomaly. Very bright rims (metamorphic) contain very low Th/U, Th and U concentrations, and much lower REE concentrations. SHRIMP U/Pb ages previously reported from eclogite are 443–496 Ma. Zircon cores (detrital) from two paragneisses contain high Th/U, moderate to high Th and U concentrations, and prominent Ce

and Eu anomalies. Rims (metamorphic) contain very low Th/U and Th, high U, and lower, flatter REE patterns; Ce and Eu anomalies are small or absent. Zircons (magmatic) from three orthogneisses lack distinct rims, contain moderate to high Th/U, Th, U, and REE concentrations, and have small to moderate Ce anomalies, and moderate to very large Eu anomalies. SHRIMP U/Pb ages previously reported from orthogneiss are 932–1011 Ma.

V22D-0622 1330h POSTER

SHRIMP U/Pb age of unusually large zircon in low-T jadeitite from the Osayama serpentinite melange, SW Japan

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Porphyroblastic zircons up to 3 mm occur in nearly monomineralic jadeitite vein from the Osayama serpentinite melange, SW Japan. The Zrn-bearing jadeitite consists mainly of subhedral to anhedral jadeite (Jd<100), with minor amount of grossular, Zrn and rutile as primary phase, and shows variable degrees of retrogression. Anhedral Jd crystals show oscillatory zoning with Ca-rich bands (Jd87-91) at the rims, suggesting crystallization from an aqueous fluid. Zrn occurs as discrete euhedral to subhedral crystals up to 3 mm in size or as twinned crystals or aggregates in the matrix; Zrn contains tiny inclusions of Rt and rare Jd. Tiny Zrn also occurs as inclusions in a single Jd crystal. This evidence indicates synchronous growth of Zrn and Jd. Phase equilibria and the existing fluid-inclusion data constrain P-T conditions to P > 1.2 GPa at T < 350 çC for formation of the jadeitite. Th-U chemistry and U/Pb ages were determined using the SHRIMP-RG. The Zrn crystals show remarkable internal zoning textures including fine, euhedral growth layers with sharp contrasts in CL brightness, and are characterized by both low Th/U ratios (0.2-0.8) and low Th- and U-abundances (Th = 1-81 ppm; U = 6-149 ppm). Most U/Pb ages are concordant, with a weighted mean 206Pb/238U age of 475.4 ± 9.8 Ma [MSWD = 5.2]. The investigated Zrns were directly crystallized from a hydrothermal alkaline fluid during the jadeitite-formation, and Zrn does not reach the closure T of the Zrn U/Pb system. Thus, it is interpreted the U/Pb ages, c. 475 Ma, as timing of crystallization of Zrn during HP-LT jadeitite-formation in serpentinites. The alkaline fluid with high Na- and Al-concentrations that resulted from subduction-zone metamorphism may have led to Zr concentration and the precipitation of Zrn in jadeitite. Consistent SHRIMP data for the blueschist-facies event suggest reliable dating of the LT Zrn in spite of its growth far below its closureT. The Zrn U/Pb age of this study provides likewise constraint for the timing of hydrothermal fluid-rock interaction related to serpentinization at HP-LT condition, establishing evidence for Ordovician subduction environments in SW Japan.

V22E MCC: 3004 Tuesday 1340h

Centennial Celebration of Radioisotopic Geochronology: Dates, Rates, and New Debates I

Presiding: **P W Reiners,** Yale University**; P R Renne,** Berkeley Geochronology Center

V22E-01 1340h INVITED

Earth accretion dynamics and time-scales

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The degree to which efficient mixing of new material, losses of volatiles to space and changes in oxidation characterize the impact-driven growth of Earth-like planets in unclear. These processes affect calculated time-scales and can be studied by parallel modeling of data from different radiogenic isotope systems. The W isotope composition of the silicate Earth yields a model time-scale for accretion that is faster than estimates based on terrestrial Pb and Xe isotope data and on Sr, W and Pb data for lunar samples. This is hard to explain unless refractory metals in impacting core material did not always mix efficiently with the silicate portions of the Earth before being added to the Earth's core. Agreement is obtained with a Moon-forming Giant Impact 50 Myrs after the start of the solar system if only a quarter of the W from Theia's core equilibrated with the silicate Earth assuming the Hf/W in silicate reservoirs remained constant. Both W and Sr isotope compositions of the Moon provide evidence that the average composition of proto-planets was in fact more like Mars, with a low Hf/W, volatile-rich, oxidized mantle. Growth from such protoplanets decreases to a few percent the calculated amount of equilibration between Theia's core and the silicate Earth during the Giant Impact.

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Dating Earth Core and Atmospheric Formation Through Hf-W and I-Pu-Xe Clocks

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It was the discovery of the radioactivities and nuclear energy at the beginning of last century that settled the long lasting debate about the ages of the Earth and the Sun, between elegant physical arguments advanced by Lord Kelvin favoring short timescale vs. Charles Darwin's trouble for not having enough time for evolution of species, hence resorted to geological observation of sedimentation rate favoring long-time scale. Claire Patterson's landmark work on Pb isotopes (1956) establishes the age of meteorites and the Earth at 4.56 Ga, albeit with somewhat wrong half-life of U and wrong sample (one ocean sediment landing on meteorite isochron). Modeling of planetary accretion rate via statistical approach pioneered by Safranov suggested planet formation lasted over 100 Ma. This long timescale was shaken by modern computer simulation. When actual orbital characteristics of the accreting bodies were considered (aided by ever-increasing computing power), the timescale for the inner planet formation is typically around 30 Ma. Discoveries of extrasolar planets place demanding constraints for the timescale of planet formation, i.e. gaseous giant planets must form before the disk dissipation (typically less than 10 Ma). No conventional long-lived isotopic systems are likely to place constraints for the planet formation with sufficient precision and resolution (30/4567), nor do we have 4.56 Ga-old terrestrial sample to work with. Modern approach to the problem is to exploit the now-extinct radioactive isotopes that were once extent at the beginning of the solar system, and look for radiogenic signatures of its daughter isotopes affected by planet wide fractionation. In this sense, we treat the Earth as one piece of whole rock; metallic core, silicate mantle and atmosphere are its mineral constituents. Both Hf-W and I-Pu-Xe clocks are uniquely affected by large-scale processes, core-mantle segregation in the Hf-W system and atmosphere-solid Earth segregation in the I-Pu-Xe system. And the ruler sizes are just right: 182Hf (9Ma); 129I (15.6 Ma); 244Pu (80 Ma). The first-discovered extinct-radionuclide (129I) by Reynolds (1960) played important role in planetary chronometry over the last four decades. The persistent timescale of 100 Ma provided by terrestrial I-Pu-Xe system all goes back to the influential paper by Wetherill (1975). We will show that the atmospheric retention age (Xe closure) is only 30 Ma, in remarkable agreement with the radiogenic 182W signature of the silicate Earth that argue for rapid core-mantle segregation of 30 Ma at most (Yin et al., 2002). Missing Xe event lasted another 90-120 Ma, possibly associated with early continental crust formation, a timescale consistent with 146Sm-142Nd clock. It is interesting to note in this regard that Xe could form silicate compound under lower crustal pressure and temperature, as shown by recent experiments at Geophysical Lab. What need to be shown are Kr, Ar, and Ne do not form silicates under the same condition, or released readily, in order to explain the fact the only Xe is missing.

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The Coupled Hf-Nd Isotopic Perspective on Crust-Mantle Evolution

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The Sm-Nd and Lu-Hf isotope systems have been valuable tools in trying to understand the differentiation and evolution of bulk silicate Earth (BSE). Together these systems allow us to constrain important processes such as the evolution of the crust and mantle as well as provide a basis for quantifying bulk Earth isotopic mass balance. Linking these systems is especially important for examination of the early Earth as they complement each other and provide independent records in rocks with long and complex tectonothermal histories. Ultimately, the utility of these systems in this regard will depend on how well we know both the decay constants for ^{147}Sm and ^{176}Lu as well as the Lu-Hf and Sm-Nd isotopic composition of BSE. Both sets of parameters, however, have been the subject of recent debate and this uncertainty has prevented these systems from achieving their full potential. Recent work on the ^{176}Lu decay constant by cross-calibration of U-Pb and Lu-Hf isotope systems on mineral isochrons in terrestrial rocks [1,2] have determined values (1.865 x 10^{-11}y^{-1}) considerably lower than the value currently in use (1.93 x 10^{-11}y^{-1}) and lower still than the value determined from examination of various meteorite groups [3,4]. The value of 1.865 x 10^{-11}y^{-1}, if true, would result in initial ϵ_{Hf} values for the Early Archean Greenland gneisses [5] to be on average chondritic instead of having a depleted mantle signature (ϵ_{Hf}=$^{+2}$-$^{+4}$). While this is certainly plausible, it conflicts with the dominantly depleted signature in the Nd isotopic record for these rocks. More significantly the lower value for λ^{176}Lu would result in the Jack Hills detrital zircons [6] having initial ϵ_{Hf} of $^{-}$2 to $^{-}$4 at 4.0 Ga which would have profound implications for the existence of continental crust at or near 4.4 Ga. One notable aspect of the existing Hf-Nd isotopic record from Earth's reservoirs is the apparent mismatch of ~3 ϵ_{Hf} units between the current BSE value (based on an average of ordinary and carbonaceous chondrites) and the center of the Hf-Nd terrestrial array, which would seem to require a hidden reservoir in order to achieve isotopic mass balance [7]. Recent work [8] has demonstrated a large range in Lu-Hf isotopic composition in chondrites and a systematic difference between carbonaceous and ordinary chondrites. Therefore, unlike the Sm-Nd system, there is considerable latitude in how the Lu-Hf chondritic parameters are chosen. The average of carbonaceous chondrites are ~7 ϵ_{Hf} units higher than ordinary chondrites and ~3 ϵ_{Hf} units higher than the current chondritic value. If BSE is closer to that of carbonaceous chondrites, the BSE point would lie in the middle of the terrestrial array and solve the Hf-Nd isotopic mass balance problem. A higher ^{176}Hf/^{177}Hf value, however, would have little effect on Archean initial Hf values because of the correspondingly higher chondritic ^{176}Lu/^{177}Hf. The lack of coherence between the Hf and Nd records for the early Archean demonstrates that there are still some critical unresolved issues that need to be addressed. [1] Scherer et al., 2001., Science, 293: 683-686. [2] Söderlund et al., in review, EPSL. [3] Bizzarro et al, 2003, Nature, 421: 931-933. [4] Blichert-Toft et al., 2002, EPSL, 204: 167-181. [5] Vervoort and Blichert-Toft, 1999, GCA, 63:533-556. [6] Amelin et al., 2000, GCA, 64: 4205-4225. [7] Blichert-Toft and Albarède, 1997, EPSL, 148: 243-258. [8] Patchett et al., in review, EPSL.

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The Geochronology of Terrestrial Meteorite and Cometary Impacts

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Geochronology has become a crucial part of the debate over the influx of extraterrestrial material and its long term importance to terrestrial life. Many of the known terrestrial craters have ages attached to them, but all too often the ages are imprecise and unfortunately some are inaccurate. Despite these problems the database of measured ages has been used to support hypotheses of clustering and periodicity in the impact record, and compare ages with those for mass extinctions in the fossil record. Over 170 craters have been identified on the Earth's surface, but the ages of less than half are known to better than 10 million years. The crucial question of peak eruption ages for large igneous provinces (LIPs) formed during the Palaeozoic, such as Deccan and the Siberian Traps, has been resolved using radiometric dating techniques such as Ar-Ar and U-Pb dating. The precision of measured ages for LIPs is better than 1% in most cases, but the precision and accuracy of ages determined for impact events is very variable. The ages of the largest 5 known terrestrial impact craters (>100 km diameter) have been established using radiometric dating techniques such as Ar-Ar and U-Pb and are known to precisions of better than 1%. However, the ages of many smaller craters,

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