defines a clockwise P-T path characterized by (1) prograde garnet formation associated with crustal thickening and (2) staurolite growth during post-peak decompression. These porphyroblasts also preserve microstructural evidence for multiple episodes of deformation: (1) initial contractional deformation (Dn-1); (2) penetrative deformation (Dn) producing major foliation, Sn; and (3) extensional ductile shearing (Dn+1). In the garnet zone, microstructural relationship defines two distinct stages of garnet growth. First-stage garnet contains slightly-curved inclusion trails (Si) continuous with Sn, suggesting syn-Dn growth. In contrast, second-stage garnet is post-tectonic and grows at the expense of biotite. In the staurolite zone, garnet porphyroblasts containing planar Si oblique to Sn suggest inter-tectonic (Dn-1~Dn) growth, whereas staurolite overprinting the Sn is post-Dn. In the kyanite zone, garnet also appears to be inter-tectonic, but some garnet porphyroblasts with sigmoidal Si favor syn-Dn-1 growth. This interpretation is corroborated by progressive change in inclusion minerals from ilmenite to ilmenite+rutile within garnet. Pseudomorphic textures and inclusion assemblages further suggest that kyanite has formed at the expense of garnet and chlorite, and that staurolite has grown along decompressional P-T path in lieu of garnet and kyanite during Dn+1. Our results demonstrate not only crustal thickening process followed by extensional collapse in an orogenic belt, but also complex P-T-t-D evolution in Barrovian-type metamorphic terrane.

260-22 BTH 194 Cho, Moonsup

METAMORPHIC EVOLUTION OF THE OGCHEON METAMORPHIC BELT, KOREA

CHO, Moonsup and KIM, Hyeoncheol, School of Earth and Environmental Sciences, Seoul National Univ, Seoul, 151-742, South Korea, moonsup@snu.ac.kr

The Ogcheon metamorphic belt (OMB) is a northeast-trending fold-thrust belt, which is often correlated with the Dabie-Sulu ultrahigh-pressure (UHP) belt in China. The OMB comprises Neoproterozoic to Paleozoic meta-sedimentary and -volcanic sequences which are interpreted to represent a stack of syn-metamorphic nappes. Regional metamorphic grade increases north-westward to produce the assemblage, biotite + garnet +/- staurolite +/- kyanite + plagioclase + quartz. Garnet crystals show chemical zoning, typical for prograde metamorphism, with decreasing Mn, and increasing Fe and Mg from core to rim. P-T conditions were estimated as 4.2-9.4 kbar and 490-630°C, corresponding to the medium-pressure type. In addition, the GIBBS calculation suggests a clockwise P-T-t path corroborating the crustal-thickening event associated with regional metamorphism. Based upon U-Pb and Sm-Nd isotopic ages of garnet containing ilmenite inclusions as well as chemical ages of uraninite, the peak metamorphism has been dated at ca. 300-280 Ma. This result is supported by our SHRIMP U-Pb zircon ages obtained from a granitic gneiss pebble in meta-diamictite, defining a discordia with lower intercept age of ca. 300 Ma. It is thus likely that a significant Pb loss has occurred during the Ogcheon orogeny. Subsequent to this orogeny, the OMB has been affected to a lesser extent by greenschist to amphibolite facies metamorphism in the Triassic time. In summary, several independent sets of geochronologic data suggest that syn-tectonic regional metamorphism has occurred during Late Carboniferous to Early Permian time, in contrast to earlier considerations favoring either Silurian or Triassic orogeny in the OMB. Thus, the OMB is not exactly correlative with the Triassic UHP belt in China. It is noted, however, that the ca. 300 Ma event may correspond to an early stage of collisional episode recently reported from the Dabie belt in east-central China.

260-23 BTH 195 Booth, Amanda L.

U-PB ZIRCON CONSTRAINTS ON THE TECTONIC EVOLUTION OF SOUTHEASTERN TIBET

BOOTH, Amanda L.[1], ZEITLER, Peter K.[2], KIDD, W.S.F.[3], WOODEN, Joseph L.[4], IDLEMAN, Bruce[5], YUPING, Liu[6], and CHAMBERLAIN, C. Page[1], (1) Geological and Environmental Sciences, Stanford Univ, Stanford, CA 94305, mbooth@pangea.stanford.edu, (2) Lehigh Univ, 31 Williams Dr, Bethlehem, PA 18015-3188, (3) Univ Albany, ES 315, Albany, NY 12222-0001, (4) U.S. Geol Survey, 345 Middlefield Road, Menlo Park, CA 94025, (5) Dept. of Earth & Environmental Sciences, Lehigh Univ, 31 Williams Dr, Bethlehem, PA 18015-3188, (6) Chengdu Institute of Mines and Geology, Chengdu, China

The eastern syntaxis of the Himalayas is expressed in the crust as a rotation of topographic, structural, and lithologic features from dominantly east-west to approximately north-south trends. The axis of rotation of geologic features is coincidental with the high topography of the Namche Barwa region, the exposure of granulite-grade metamorphic rocks, and a major bend in the Tsangpo river. Within the Namche Barwa and subjacent terranes are numerous granitoids that are associated with various events contributing to the tectonic development of southeastern Tibet. Our combined geochronologic and geochemical investigation provides insight into mechanisms of granite formation and helps to constrain the distribution of terranes, timing of assembly, and magmatic processes operative in each. U-Pb SHRIMP ages establish a complex tectonic history for southeastern Tibet, with the presence of at least five magmatic episodes: ~250 Ma, ~120 Ma, 40-70 Ma, 18-25 Ma, and 3-10 Ma. Two lines of evidence suggest that the Namche Barwa massif is a product of local feedbacks between tectonic and surficial processes: 1) exceptionally young zircon ages (~2.8 - 9.5 Ma) for samples collected from the Tsangpo river gorge correspond to a period of rapid denudation; 2) granitoids within the massif core exhibit high Rb/Sr ratios (>1.4), suggesting a fluid-absent (decompression) melting regime dominates near the core of Namche Barwa.

260-24 BTH 196 Leech, Mary L.

NEW U-PB SHRIMP AGES FOR THE UHP TSO-MORARI CRYSTALLINES, EASTERN LADAKH, INDIA

LEECH, Mary L.[1], SINGH, Sandeep[2], JAIN, A.K.[2], and MANICKAVASAGAM, R.M.[3], (1) Geological and Environmental Sciences, Stanford Univ, Bldg 320, Stanford, CA 94305-2115, mary@pangea.stanford.edu, (2) Department of Earth Sciences, Indian Institute of Technology Roorkee, Roorkee, 247 667, India, (3) Institute Instrumentation Center, Indian Institute of Technology Roorkee, Roorkee, 247667

The Tso Morari Crystallines are a 100 x 50 km NW-SE-trending ultrahigh-pressure eclogitic subduction zone complex in the eastern Ladakh area in the western Himalaya, south of the Indus-Tsangpo suture zone. Estimates for the initiation of the Himalayan collision between India and Asia range from the Late Cretaceous (>65 Ma) and the latest Eocene (<40 Ma); the continent-continent collision is thought to have begun in the northwest part of the Himalaya <52 Ma based on collision-related sediments. U-Pb zircon SHRIMP data better defines three stages in the development of the Tso Morari complex and helps to constrain the timing of collision and subduction in the western Himalaya: the protolith age in zircon cores; the timing of Pan-African magmatism in the Indian sub-continent from analysis of zircon cores and mantles; and the timing of peak eclogite-facies metamorphism from analysis of metamorphic rims. Zircons for this study are from two samples of the country rock to eclogite that were metamorphosed at ultrahigh-pressure eclogite-facies based on P-T calculations (>560 ± 50° C, ~2.2 GPa) and the presence of coesite in related rocks. Precise new single zircon U-Pb ages for host rocks to eclogite in the Tso Morari crystallines indicate that peak eclogite-facies metamorphism occurred at 48 ± 1 Ma. Zircons include both euhedral and fairly rounded grains that display clear core/rim zoning relationships under CL. Zircons that yielded ca. 48 Ma rim ages occurred in rounded grains with dark cores and light-colored rims; these metamorphic rims had very low Th/U ratios (<<0.1). Many zircon mantles and cores gave ages ca. 400 Ma and have much higher Th/U ratios (>>0.1); these ages likely reflect a magmatic event that is recorded in many other areas throughout the Himalaya. A few zircon cores indicate a minor inherited component with Proterozoic ages (700 ± 6 Ma to 1668 ± 14 Ma). These new data show that eclogitization was ~7 m.y. later than other workers have reported from Sm-Nd, Lu-Hf, and U-Pb (alanite) dating; the 48 Ma ages correspond well with other Sm-Nd, Rb-Sr, and Ar/Ar dating which may indicate fast exhumation.

260-25 BTH 197 Yue, Yongjun

NEW EVIDENCE FOR TWO-STAGE EVOLUTION OF THE ALTYN TAGH FAULT AND ITS IMPLICATIONS FOR THE INDO-ASIAN COLLISION ZONE

YUE, Yongjun, Department of Geological and Environmental Sciences, Stanford Univ, Stanford, CA 94305-2115, yongjun@pangea.stanford.edu.

New geological and geophysical evidence supports the two-stage model for the Altyn Tagh fault (ATF) of Yue and Liou (1999 Geology 27; 227-230), which predicted: 1. 400±50 km of left-lateral offset at the present northeastern end of the ATF; 2. low post-Early Miocene slip rate along its eastern segment; 3. mid-Miocene exhumation of northern Tibet; and 4. Cenozoic age for the Alxa-East Mongolia fault. First, Paleozoic and Tertiary piercing points along the ATF constrain the left-lateral offset around the eastern end of the fault at 375±25 km. Second, a correlation between granitic boulders in the upper Lower Miocene strata of the Xorkol basin and their source terrane across the fault indicates that post-Early Miocene slip rate along the eastern segment of the ATF is less than 10 mm/year. Third, apatite fission-track analysis of the northern Qilian Shan (George et al., 2001, Geology 29; 939-942) and sedimentary basin analysis of the Subei basin indicate that exhumation of northern Tibet began between 10 and 20 Ma. Fourth, interpretation of seismic profiles demonstrates that the East Mongolia fault, previously considered a Paleozoic or Jurassic structure, is post-Late Cretaceous (Johnson, 2002, Stanford Ph.D. Dissertation).

Not only do these new data support the two-stage model of the ATF, but they shed new light on the tectonics of the Indo-Asian collision zone as well. The amount of extrusion during the Oligocene and Early Miocene along the ATF (375±25 km) and Red River fault (500±200 km) is able to accommodate most or all of the synchronous convergence between India and Asia (680-850km), suggesting dominance of extrusion over crustal shortening. The cessation of extrusion along the Red River fault at about 17 Ma and slowing down of slip on the ATF at the same time suggest that distributed crustal thickening has become dominant since the Early/Middle Miocene boundary.

260-26 BTH 198 Terabayashi, Masaru

THE DAULET METAMORPHISM: A CONTACT METAMORPHISM BY SOLID INTRUSION OF THE KOKCHETAV UHP-HP METAMORPHIC SLAB

TERABAYASHI, Masaru, Dept. Safety Systems Construction Engineering, Kagawa Univ, Takamatsu, 761-0396, Japan, tera@eng.kagawa-u.ac.jp and OTA, Tsutomu, Dept. Earth and Planetary Sciences, Tokyo Institute of Technology, Tokyo, 152-8551, Japan

Metapelites in the andalusite-sillimanite type Daulet Suite provide a good opportunity to reveal a new-type of metamorphism. The Daulet Suite, underlying the Kokchetav ultrahigh-pressure - high-pressure (UHP-HP) massif of northern Kazakhstan, is composed of pelitic-psammitic gneisses or schists and quartz schist with minor amounts of metacarbonate and metabasite. About 300 thin sections were examined from the Daulet metapelites; they were divided into two mineral zones. Zone A is characterized by an assemblage of andalusite + cordierite + biotite and zone B by sillimanite + cordierite + biotite with excess K-feldspar, quartz and plagioclase in both zones. Thermal structure of the Daulet Suite is subhorizontal and metamorphic grade increases upwards, i.e., towards the boundary with the UHP-HP unit. Observations in this study indicate that heat source for the Daulet metamorphism is not the Devonian granitoid but the "hot" Kokchetav UHP-HP unit. Since K-feldspar first appears with andalusite within zone A prior to appearance of sillimanite, pressure-temperature conditions of the Daulet metamorphism range from 580 to 680 °C at a nearly constant pressure of about 2 kbar; tectonic juxtaposition occurred at notably shallow crustal levels. Many UHP-HP rocks are partially hydrated during exhumation and are overprinted by the Barrovian-type metamorphism. It was considered that fluids from a subducting slab have will exert important effects on metasomatic and melting relations (e.g. Selverstone et al.,1984; 1992). The tectonic juxtaposition of dehydrated UHP-HP units on hydrous low-grade rocks would allow infiltration of fluids into the UHP-HP unit. Such a tectonic overlap would transport sufficient fluids from the underlying unit to the overlying UHP-HP unit and would effectively obliterate the UHP-HP mineralogy.

260-27 BTH 199 Aycenk, Mustafa Aydin

JUXTAPOSITION OF HP AND HT METAMORPHIC ROCKS IN TRANSTENSIONAL EXHUMATION, SIVRIHISAR BELT, WEST-CENTRAL TURKEY

AYCENK, Mustafa Aydin[1], WHITNEY, Donna L.[1], TEYSSIER, Christian[1], and UCTAS, Zeynep[2], (1) Geology & Geophysics, Univ of Minnesota, Minneapolis, MN 55455, ayce0001@umn.edu, (2) Geological Engineering, Istanbul Univ, Avcilar 34310 Istanbul - Turkey, Istanbul, Turkey

The Sivrihisar massif has been described as part of the Turkish blueschist belts (HP-LT) that formed by Late Cretaceous subduction, collision, and exhumation of a continental margin during closure of a Neo-Tethyan seaway. In the massif, however, HP-LT rocks are juxtaposed with high T (sillimanite-bearing) rocks. The HP-LT unit consists of sodic amphibole rocks occurring as meter scale lenses in marble with fibrous texture similar to marble described in other HP-LT terrains of the Aegean belt. The fibrous texture in marble gradually decreases and vanishes from north to south over ~1km of section towards the HT rocks; the HT zone consists of non-fibrous marble, schist, and andalusite+kyanite+sillimanite micaceous quartzite. A late-kinematic Eocene granite is emplaced and developed a narrow metamorphic aureole (< 4 m). Therefore, contact metamorphism may not account for the strongly lineated sillimanite that exists ~1km away from the contact. The Sivrihisar massif provides an excellent opportunity to understand the thermal/tectonic evolution of continental rocks at a converging plate boundary. Metasedimentary rocks of the paleo-margin are extensively deformed with a foliation complexly folded around a prominent lineation uniformly oriented ~N-S to NE-SW. This strong lineation characterizes both the HP-LT and HT rocks throughout the southern Sivrihisar massif. Outcrop-scale kinematic indicators in the schist and quartzite confirm a normal / left lateral sense of shear (top-to-north). The transition between HP-LT and HT domains occurs over the chloritoid, staurolite-garnet, and Al2SiO5 isograds that are compressed in a few hundred meters of structural section. These structural and metamorphic relations are interpreted as a transtentional system, possibly developed in the extensional jog of the metamorphic belt. This model explains the ubiquitous normal/sinistral sense of shear and the development of HT metamorphism in transtensional exhumation.

259-5 BTH 169 Johnson, Tim

MODELING METAMORPHISM IN THE VARISCIDES OF SOUTHERN BRITTANY - A QUANTITATIVE APPROACH USING PSEUDOSECTIONS

JOHNSON, Tim and BROWN, Michael, Laboratory for Crustal Petrology, Univ of Maryland, Department of Geology, College Park, MD 20742-4211, timj@geol.umd.edu

Previous studies of subsolidus to suprasolidus metapelitic rocks from southern Brittany have used reaction microstructures and conventional thermobarometry to suggest the Variscan lower crust followed a clockwise P-T evolution. We construct equilibrium phase diagrams (pseudosections) for the MnNCKFMASH system and use average P-T calculations to investigate in more detail the metamorphic evolution of these rocks. For migmatites, phase relations predicted based on the superimposition of the P-T path inferred from microstructural relations among mineral phases onto pseudosections calculated for an average metapelite composition, contoured for proportions of L and Grt, are broadly consistent with those inferred from petrography. The sequential occurrence of Ky, Ky + St and Sil suggests a prograde evolution to P > 8 kbar at 625ºC decreasing to P around 6 kbar at 650ºC, and followed by increasing P and T to the metamorphic peak. A major melting step occurred at 750ºC and 9 kbar by incongruent breakdown of Ms. At the metamorphic peak of 8 kbar and 800ºC, ~25 mol % L and >20 mol % Grt are predicted from volatile phase-absent melting that also consumed Bt.

The retrograde evolution began with decompression and cooling, allowing crystallization of melt and replacement of Grt by Bt + Sil; this was followed by a near-isothermal decompression segment from around 6 kbar to 4 kbar. The decompression segment was associated with widespread development of Crd associated with a second episode of melt generation, consistent with phase relations calculated for a melt-depleted, low-Mn effective bulk composition. Microstructural relations in upper amphibolite facies metapelites from the unit structurally overlying the migmatites suggest retrograde development of St, And and WM in these rocks. Based on a pseudosection contoured for the quantity of H_2O required to saturate the assemblage at P-T, we suggest that an influx of an H_2O-rich volatile phase is required, which we infer to have been derived from crystallising melt in underlying migmatitic and granitic rocks. The P-T-X evolution of a segment of Variscan lower crust is determined quantitatively using pseudosections in a model system in combination with thermobarometry, which enables better constraints than before to be placed on tectonic models for the Variscan evolution of Southern Brittany.

259-6 BTH 170 Powell, Roger

PROGRADE METAMORPHIC ASSEMBLAGE EVOLUTION DURING PARTIAL MELTING OF METASEDIMENTARY ROCKS AT LOW PRESSURES: MIGMATITES FROM MT STAFFORD, CENTRAL AUSTRALIA

WHITE, Richard W.[1], POWELL, Roger[1], and CLARKE, Geoffrey L.[2], (1) School of Earth Sciences, Univ of Melbourne, Melbourne, 3010, rogerp@unimelb.edu.au, (2) School of Geosciences F05, Univ of Sydney, Sydney, 2006

The Mt Stafford area preserves a low-pressure greenschist to granulite facies regional aureole. The metasedimentary sequence has been divided into 5 zones from greenschist (Zone 1) to granulite facies (Zone 4) and a zone of hybrid diatexite formed from the introduction of granitic magma into the high-grade migmatites (Zone 5). Melt production was dominated by a series of multivariant biotite breakdown reactions, not the univariant reactions suggested by previous studies. Though the three main metasedimentary rock types produced similar amounts of melt at the highest grades, their melt production histories differed markedly as a function of temperature. Aluminous metapelites produced more melt at lower temperatures (Zones 2 and 3), whereas metapsammite and cordierite granofels experienced an additional major melt producing step at higher temperatures (upper Zone 3 & Zone 4). This melting step involved the breakdown of biotite to produce garnet, K-feldspar and melt, and in some rocks the production of orthopyroxene. Melt production in Zone 4 exceeded 25 molar percent, resulting in the formation of in situ diatexites. The complex relationships involving aluminosilicate porphyroblasts resulted in the breakdown of biotite and aluminosilicate being drawn out over a wide temperature range, from subsolidus conditions to temperatures close to 750°C. Initially, much of the melting developed around the aluminosilicate porphyroblasts during the breakdown of coexisting biotite, aluminosilicate and quartz. However, much of the rock was chemically isolated from the porphyroblasts and could not react to produce melt. As temperatures increased, the presence of the large isolated aluminosilicate porphyroblasts controlled the spatial development of quartz-absent, spinel-present compositional domains, the formation of spinel being governed by the silica-undersaturated breakdown of coexisting biotite and aluminosilicate.

259-7 BTH 171 Dale, Jonathon

MODELLING AMPHIBOLE THERMODYNAMICS

DALE, Jonathon[1], POWELL, Roger[1], HOLLAND, Tim[2], and WHITE, Richard[1], (1) School of Earth Sciences, Univ of Melbourne, Melbourne, 3010, Australia, jdale@unimelb.edu.au, (2) Department of Earth Sciences, Univ of Cambridge, Downing Street, Cambridge, CB2 3EQ

Quantitative mineral equilibria modelling in metabasic rocks has long been intractable because the activity–composition (a–X) relationships in amphiboles are poorly understood. We present a powerful new a–X model for clinoamphiboles in the system Na2O–CaO–K2O–FeO–MgO–Al2O3–SiO2–H2O–O2 in terms of the independent set of end–members tremolite, tschermakite, pargasite, glaucophane, ferro–actinolite, K–pargasite and ferri–tschermakite. The model is calibrated by regressing natural assemblage data from well characterised rocks.

The model incorporates three key methodological advances. Firstly, we consider the possibility of asymmetric non–ideal mixing in multicomponent systems by using the recently reformulated van Laar model. This permits the complete description of mixing between the seven amphibole end–members in terms of 21 interaction energies and 7 asymmetry parameters. Secondly it utilises a robust non–linear regression approach (least median of squares) for fitting noisy data typical of natural assemblages, minimising the damaging effect of outliers on regression results. Thirdly the model incorporates dependent end–member constraints for several of the interaction parameters by considering the equivalence between alternative sets of amphibole end-members (e.g. the magnesian system described above, and the corresponding ferrous system). This provides valuable constraints for several of the interaction energies which are otherwise poorly determined by the regression.

The calibration of the model is based on two large natural–assemblage datasets collected from the literature involving two different mineral assemblages. The first dataset consists of 73 pairs of coexisting amphiboles (actinolite–hornblende, winchite–hornblende, and barroisite–glaucophane) equilibrated over the range 250–580ºC, 2–18 kbar. The second consists of 270 garnet–amphibole–plagioclase–quartz assemblages equilibrated over the range 400–900ºC, 3–17 kbar. Simultaneously regressing two different datasets increases the quality of control available in comparison with calibrations based on a single assemblage.

259-8 BTH 172 Steffen, Kurt J.

QUANTIFYING THE METASTABLE CHEMICAL ENERGY AVAILABLE TO METAMORPHIC ASSEMBLAGES

STEFFEN, Kurt J. and SELVERSTONE, Jane, Earth and Planetary Sciences, Univ of New Mexico, Albuquerque, NM 87131, ksteffen@unm.edu

Common thermodynamic models of metamorphic systems assume that chemical equilibration processes (crystal nucleation, growth and resorption) occur under reversible (near–equilibrium) conditions. In reversible thermodynamic models, mineral assemblages and compositions are not path or process dependent; mineral compositions and modes can thus be calculated for a given bulk composition and set of P-T conditions. Although the reversible thermodynamic assumption greatly simplifies petrologic modeling, these models cannot accommodate features such as mineral zoning, incomplete reactions, and variation in porphyroblast and matrix mineral textures.

This study determines the metastable chemical excess energy (MCEM, the difference between the equilibrium energy and the actual energy). In order to calculate MCEM, large numbers (grids of 1000-2000 points) of quantitative electron microprobe analyses are collected. These analyses are phase classified and the Gibbs free energy for each mineral composition is determined at P and T using a thermodynamic model that incorporates non-ideal mixing, heat capacity, thermal expansion and compressibility. The Gibbs free energy values for each mineral analysis are added together and normalized to create a Gibbs free energy for the actual assemblage and composition for any P-T condition. A bulk composition is determined by integrating and normalizing the analyses; the same thermodynamic model is used to determine the equilibrium Gibbs free energy for this bulk composition at any P-T condition. The difference between these energy values is the MCEM.

Preliminary calculated values of minimum MCEM are 1-50 kJ/m3. MCEM is similar to the value for surficial and deformational excess energies reported by Stunitz (1998). MCEM represents a significant amount of excess energy in metamorphic assemblages. MCEM may provide driving energy for rapid nucleation and growth when liberated by rapid kinetics (in many cases induced by deformational processes) and a major component of the non-reversible energy available for textural evolution.

SESSION NO. 260, 1:30 PM

Wednesday, November 5, 2003

T141. Phase Relations, High *P-T* Terrains, *P-T*-ometry and Plate Pushing (Posters): A Tribute to W.G. Ernst (*Mineralogical Society of America*)

Washington State Convention and Trade Center, Hall 4-F

260-1 BTH 173 Dobrzhinetskaya, Larissa F.

MICRODIAMONDS FROM ULTRA-HIGH PRESSURE TERRANES: FROM DISCOVERY TO SYNTHESIS IN A LABORATORY

DOBRZHINETSKAYA, Larissa F.[1], RENFRO, Alex P.[1], and GREEN II, Harry W.[2], (1) Department of Earth Sciences, Univ of California at Riverside, Riverside, CA 92521, larissa@ucrac1.ucr.edu, (2) Institute of Geophysics and Planetary Physics, Univ of California at Riverside, Riverside, CA 92521

The discoveries of microdiamond within collisional orogeneic belts of Kazakhstan, China, Norway, Germany, Indonesia, Greece, and Russia are the foci in understanding deep subduction zones 'marked' by explosive volcanic activity, earthquakes and fast geomorphological evolution. The critical role of fluids in subduction zones has been addressed since the early 1970s. Fluids promote mass transfer and energy release in both thermal and mechanical forms, perhaps controlling slab pull and buoyancy forces. Experimental data suggest that fluids at high pressures may dissolve a large amount of solid components (Kennedy et al., 1962; Nakamura & Kushiro, 1974), and conversely, melts dissolve large amounts of volatiles, leading to a poor distinction between fluid and melt phases (Boettcher and Wyllie,1996; Bureau & Keppler, 1999). Now microdiamonds from orogenic belts provide a unique opportunity to directly study fluid compositions occurring in a subduction zone at a depth of >120 km. It was observed that diamond-bearing multiphase pockets in garnets and zircons are frequently accompanied by hydrous phases. Molecular water and carbonate radicals are detected in Kokchetav diamonds by FTIR (De Corte et al.,1998), and nanometric inclusions of oxides of Si, Fe, Ti, Th, Cr, and cavities of former fluid phases were discovered in diamonds (Dobrzhinetskaya et al., 2000, 2003). On the basis of those observations two concepts were suggested for the explanation of the origin of such diamonds: (1) crystallization from a supercritical COH fluid; (2) crystallization from fluid-bearing alkaline-carbonate melt. Both concepts have been successfully confirmed by experimental synthesis of diamonds at high P & T (Akaishi et al., 2002, Dobrzhinetskaya et al., 2002, Pol'anov et al., 2001). Diamond crystallization from graphite in the presence of H2O at high P & T is the most realistic explanation of microdiamond formations within UHPM terranes because it is in agreement with observations on the natural rocks. Although concept #2 is also well verified by experiments, no rocks bearing direct evidence of a partial melt that occurred in the diamond stability field were found yet within diamondiferous formations. Additional research projects need to be focused on this problem.

260-2 BTH 174 Renfro, Alex P.

EXPERIMENTAL SIMULATION OF DIAMOND CRYSTALLIZATION IN QUARTZITE AT HIGH PRESSURES AND TEMPERATURES

RENFRO, Alex P.[1], DOBRZHINETSKAYA, Larissa F.[1], and GREEN II, Harry W.[2], (1) Department of Earth Sciences, Univ of California at Riverside, Riverside, CA 92521, tashalex@earthlink.net, (2) Institute of Geophysics and Planetary Physics, Univ of California at Riverside, Riverside, CA 92521

Microdiamonds occur within ultra-high pressure metamorphic rocks exposed within collisional orogenic belts in Kazakhstan (Sobolev and Shatsky, 1990), China (Xu et al., 1992, Yang et al., 2003), Norway (Dobrzhinetskaya et al., 1995, Van Roermund et al., 2002), Germany (Massonne, 1998) and other locations. Various researchers have demonstrated that such diamonds are crystallized from a multicomponent COH-rich supercritical fluid, and that their compositional diversity reflects an intermixture of crustal and mantle components (Stokhert et al., 2000; Dobrzhinetskaya et al., 2000), although some have postulated the diamonds grew from a carbonate melt (Shatsky et al.,2003). Diamond is an important indicator of pressure, which determines the depth to which sedimentary rocks could be subducted during continental collision, and

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