almost coeval with the emplacement of the Semail ophiolite. We conclude that the lower plate blueschists and eclogites formed by intracontinental thrusting and subduction of the thinned leading edge of the Oman continental margin in an east dipping subduction zone. The upper plate rocks which were part of the hanging wall of this subduction zone, were metamorphosed by tectonic loading by the ophiolite. Entrance of thicker portions of the positively buoyant continental crust into this subduction zone choked it, and caused the ductile thinning of mantle lithosphere in its hanging wall. This initiated the rapid exhumation of the blueschists and eclogites from $>$ 40 km to 14 km $\sim$ 78 Ma, and led to their juxtaposition by the lower grade upper plate rocks. Erosion and crustal extension led to the final exhumation of all high P/T rocks in Saih Hatat.

V42F-06 1505h INVITED

Formation and Segregation of Melts in the Continental Crust: Time Scales From Trace Element Modeling of Rocks From the Sikkim Himalaya, India

Sumit Chakraborty[1] (+49-234-3224395; Sumit.Chakraborty@ruhr-uni-bochum.de)

Sudipta Neogi[1]

Edward W Bolton[2]

[1]Institut fuer Geologie, Mineralogie und Geophysik, Ruhr-Universitaet Bochum, Bochum, NRW D-44780, Germany

[2]Department of Geology and Geophysics, Yale University, Kline Geology Laboratory, P.O. Box 208109, New Haven, CT 06520-8109, United States

It is difficult to quantify the distribution of trace elements during crustal melting because equilibrium partitioning of these elements is often not attained. But modeling the distribution is crucial for understanding intracrustal differentiation (into upper, middle, and lower crust) as well as the nature and timescale of melt formation and segregation in the crust. To address this problem, we have developed a numerical model to simulate the evolution of trace elements in a system undergoing melting. The model accounts for equilibrium partitioning as well as kinetic processes such as dissolution, crystal growth, and diffusion along arbitrary temperature - time paths. In this project we have field tested the model on rocks from the classic inverted metamorphic sequence in the Sikkim Himalaya. The geological and petrological history of the area has been well constrained in a parallel project. Our study material consists of a sequence of prograde metamorphic rocks with rather similar bulk compositions that have been subjected to progressively increasing pressures and temperatures to ultimately undergo melting by well defined mica dehydration reactions. Using measured protolith and reactant mineral compositions, inferred balanced reactions, petrologically constrained peak temperatures, and known partition and diffusion coefficients in our model we reproduce observed mineral and melt compositions for any one element (e.g. Sr) by varying the thermal history. Once a good fit was observed, the same thermal history was then used to predict other trace element distributions (e.g. Rb, Ba) with a high degree of success. In our simulations so far we have ignored minor phases (e.g. apatite) and back reactions during cooling. Consequently, fits for elements that are known to reside primarily in minor phases (e.g. La) are poor, indicating that our model does indeed capture the essence of processes taking place in nature. Protolith bulk composition, stoichiometry of melting reaction, and partition and diffusion coefficients are found to be the key parameters controlling the distribution of trace elements. Our results so far indicate that the time scales of melting and melt segregation in such a continental collisional setting where dehydration melting reactions are taking place are on the order of 100,000 years.

V42F-07 1525h

Modeling Lithospheric Isostatic and Thermal Evolution: Application to the Proterozoic Orogen of the Southwestern United States

Rebecca M Flowers[1] (617-253-7993; rflowers@mit.edu)

Leigh H Royden[1] (lhroyden@mit.edu)

Samuel A Bowring[1] (sbowring@mit.edu)

[1]Massachusetts Institute of Technology, Dept. of Earth, Atmospheric and Planetary Sciences, 77 Massachusetts Ave., Cambridge, MA 02139, United States

The integration of high-resolution cooling histories with exhumation constraints and thermobarometric, heat production and heat flow data can be used to understand long-term lithospheric thermal and isostatic evolution. Cratonic lithosphere retains a record of the net temperature dependent lithospheric density change, as net lithospheric heating causes density decrease, uplift and erosion, while net cooling causes density increase, subsidence and sedimentation. We use this to construct isostatically consistent primary lithospheric geotherms, and use a finite-difference model to compute the time-dependent change of the geotherms following assembly to steady-state. The Proterozoic orogen of the southwestern U.S., characterized by disparate crustal domains with distinct cooling records, levels of exposure, and peak metamorphic conditions, is an ideal location to evaluate the controls on lithospheric thermal and isostatic evolution. In West-central AZ, apparent protracted cooling (1°C/m.y.) in 3-4 kbar exposed rocks of the Hualapai block contrasts with rapid cooling (25-100°C/m.y.) in 1-2 kbar exposed rocks of the Ash Creek block. Our thermal analysis indicates that observed differences in radiogenic heat production (3.1-5.2 microW/m^3 for Hualapai vs. 0.7-1.4 microW/m^3 for Ash Creek), but similar initial lithospheric mantle temperatures (900-1000°C), can explain the distinct thermal and isostatic records of the two blocks. Thus, heat production variation not only significantly influences crustal cooling histories, as has been previously documented, but also can induce diverse isostatic responses during geotherm evolution. The approach applied in this study can place important constraints on feasible, isostatically consistent models for cratonic lithosphere, and provides a framework with which better understand its assembly, stabilization and preservation.

V42G MCC: 3006 Thursday 1600h

Modeling Metamorphism III *(joint with T)*

Presiding: **M Brown,** University of Maryland**; B Dutrow,** Louisiana State University

V42G-01 1600h INVITED

Cenozoic and Mesozoic metamorphism in the Longmenshan orogen: Implications for geodynamic models of eastern Tibet

Simon Richard Wallis[1] (+81 52 789 3558; swallis@eps.nagoya-u.ac.jp); Tatsuki Tsujimori[2] (tatsukix@rins.ous.ac.jp); Mutsuki Aoya[1] (f030402r@mbox.nagoya-u.ac.jp); Tetsuo Kawakami[3] (tetsuo@cc.okayama-u.ac.jp); Kentaro Terada[4] (terada@letitbe.geol.sci.hiroshima-u.ac.jp); Kazuhiro Suzuki[5] (suzuki@nendai.nagoya-u.ac.jp); Hironobu Hyodo[2] (hhyodo@rins.ous.ac.jp)

[1]Nagoya University, Department of Earth and Planetary Sciences, Nagoya University, Nagoya 464-8602, Japan

[2]Okayama University of Science, Research Institute of Natural Sciences, Okayama University of Science, Okayama 700-0005, Japan

[3]Okayama University, Department of Earth Sciences, Faculty of Education, Okayama University, Okayama 700-8530, Japan

[4]Hiroshima University, Department of Earth and Planetary Systems Science, Hiroshima University, Hiroshima 739-8526, Japan

[5]Nagoya University, Nagoya Univeristy Center for Chronological Research, Nagoya University, Nagoya 464-8602, Japan

The Tibetan Plateau is characterized by both its great height (much of it above 5,000 m) and flatness. It has been proposed that the flat topography is due to ductile flow of highly mobile lower crustal rocks. This idea has lead to a radical new idea in continental tectonics that horizontal outflow of mobile lower-crustal rock from topographic highs is one of the principal mechanisms by which plateaus grow laterally. It has been proposed that the large-scale topography of the whole of the SE Asian continent has been strongly influenced by this process. The best case for such a mechanism is made in the eastern border of Tibet in the Longmenshan orogen. The Longmenshan region lies on the western fringe of the S-China craton and has been involved in two stages of orogenesis: one event at 200 Ma associated with the collision between the N- and S-China cratons and a second, the Cenozoic Himalayan orogeny related to the collision between India and Asia. However, a number of studies have emphasized that the upper crustal deformation in the Longmenshan is almost entirely Mesozoic and, therefore, unrelated to the India-Asia collision, which began around 54 Ma. This discrepancy can be explained if the crustal thickening in the Longmenshan was caused by solid-state inflow of mobile lower-crustal metamorphic rocks from a topographic high. New zircon U-Pb and mica $^{40}Ar/^{39}Ar$ dating combined with structural studies confirm that most of the upper crustal deformation in the eastern margin of Tibet is Mesozoic. The deepest exposed parts of the orogen have undergone Barrovian facies metamorphism with estimated peak conditions around 8 kbar and 725°C (Huang et al, 2003) and associated deformation generally thought to have occurred around 200 Ma. However, new apatite U-Pb and monazite electron microprobe dating in the sillimanite zone give ages around 65 Ma. Metamorphic minerals occur both surrounding and as inclusions of the dated monazite suggesting 65 Ma is the age of metamorphism. The main phase of syn-metamorphic deformation is overprinted by a phase of folding associated with N-S fold axes and steep axial planes with geometries that indicate an E-W shortening of 10 - 50%. The evidence for originally thick crust existing around the time of the India-Asia collision and the presence of moderate amounts of Cenozoic E-W shortening can account for most if not all of the present thickness of the continental crust in the Longmenshan area. These results do not, therefore, support models of crustal thickening in the region caused by solid-state lateral flow of mid-crustal metamorphic rocks. Reference: Huang, M.-H., Buick, I. S. & Hou, W. 2003. Tectonometamorphic evolution of the Eastern Tibet plateau: evidence from the central Sogpan-Garze orogenic belt, western China. Journal of Petrology, 44 255-278

V42G-02 1620h

Deformation Structures and Geochronology of the Deformation-Metamorphism Event of the South Sulu High-Pressure Metamorphic belt

Zhiqin Xu[1] (xuzhiqin@ccsd.org.cn)

M. McWilliams[2] (mac@pangea.stanford.edu)

Haijun Qiu[1] (qhj@ccsd.org.cn)

Jingsui Yang[1] (yangjsui@ccsd.org.cn)

J. G. Liou[2] (liou@pangea.Stanford.EDU)

[1]Laboratory of Continental Dynamics, Institute of Geology, CAGS, Beijing 100037, China, Beijing 100037, China

[2]Dep. of Geological and Environmental Sciences, Stanford University, Stanford, California 94305, United States, Standford 94305, United States

The present structure of the Sulu HP-UHP belt in east China is a product of subduction and exhumation, resulting in a foliation parallel to the trend of the HP-UHP metamorphic belt, SE-ESE dips of 20-30æ, with NW-SE stretching lineation. The Sulu HP-UHP belt has two parts: a southern stacked set of HP tectonic slices overlain by a northern stacked set of UHP slices. Previous studies indicate that the northern UHP slices is the product of Indosinian continental deep subduction and exhumation. SHRIMP ages indicate UHP metamorphism at 220-245 Ma and exhumation at 202-220 Ma. The HP belt is further subdivided into high-pressure (HP) and low-temperature (LT) slices in the southeast and the HP and medium-temperature (MT) slices in the northwest. The HP/LT slices have P-T estimates of 0.70-0.85 GPa and 300-360°, and contain characteristic minerals such as winchite, barroisite, phengite and aragonite. These rocks are strongly sheared and individual tectonic slabs are separated by mylonitize zones. During exhumation, HP-LT rocks underwent continuous retrograde metamorphism from blueschist through laucophane-greenschist to greenschist facies. Retrographic metamorphic minerals are developed on regional strong penetrative shearing foliations and have inferred P-T conditions at 350-410 $^{\circ}$ and 0.2-0.4 GPa. The HP-MT belt is composed of kyanite-topaz quartzite (500 to 600 $^{\circ}$) kyanite-bearing albite-quartz schist, marble, phosphatic marble and phosphorite. The HP-MT rocks experienced retrograde metamorphism from epidote-amphibolite to greenschist facies (350 to 410° and 0.2 to 0.4 GPa). The LPO of quartz from mylonitized gneiss and schist constrains LPO models of the prism {1010} <a> and base {0001}<a>, which reflects the MT (450-650 $^{\circ}$) and LT ($<$ 400 $^{\circ}$)shear strain conditions. Shear strain and LPO of quartz indicate that shearing vector was from ESE to WNW. Three biotite samples yielded a weighted mean (WM) age of 232.5 $\pm$ 2.4 Ma and an isochron age of 232.9 $\pm$ 2.5 Ma, a plateau age of 253.9 $\pm$ 2.6 Ma and an isochron age of 254.0 $\pm$ 2.7 Ma and a plateau age of 243.9 $\pm$ 2.6 Ma and an isochron age 244.2$\pm$2.6 Ma. Two muscovite samples have a WM age of 214.2 $\pm$ 2.3 Ma and an isochron age of 213.8 $\pm$ 2.7 Ma and a WM age of 218.7 $\pm$ 2.3 Ma and an isochron age of 218.8 $\pm$ 2.4 Ma. Two K-feldspar samples yield WM ages of 173.1 $\pm$ 2.0 and 180.5 $\pm$ 2.0 Ma and an isochron age of 180.5 $\pm$ 2.2 Ma, and one hornblende has a WM age of 208.5 $\pm$ 2.2 Ma and an isochron age of 207.5 $\pm$ 2.6 Ma. All are the products of ductile

shear and retrograde metamorphism. These ages represent deformation-retrograde events during exhumation. In contrast with the UHP ages of 242-220 Ma and the exhumation ages of 200-220 Ma, the HP metamorphic rocks apparently were exhumed since 250 Ma. Protolith for the HP rocks was Neoproterozoic metavolcanic basement of the Yangtze plate, whereas the UHP protolith was Meso- to Neoproterozoic paragneiss and granitic gneiss of the Yangtze plate. We infer that prior to 250 Ma, both continental basement slabs had been subducted northwards beneath the north China plate simultaneously. After reaching 20-30 km depth, HP metamorphic rocks were formed and soon after exhumed, while the incipient UHP rocks continued to be subducted to about 100 km depth and were later exhumed and appear at the surface with HP slabs.

V42G-03 1635h INVITED

Porphyroblast Microstructures and the Coupling of Deformation and Metamorphism

Scott E Johnson[1] ((207) 581-2142; johnsons@maine.edu)

Peter O Koons[1] ((207) 581-2158; peter.koons@maine.edu)

[1]University of Maine, Department of Earth Sciences, Orono, ME 04469, United States

Evidence suggesting that metamorphic reactions can be driven by deformation is ubiquitous. The example we discuss here is the spatial and temporal correlation between deformation and porphyroblastic mineral growth. Many porphyroblasts show synkinematic microstructures, and in general the evidence favors growth relative early during the deformation. These microstructural observations have been with us for decades, but mechanical descriptions of the coupling are lacking. We explore the relations between deformation and porphyroblast growth by employing three-dimensional coupling among diffusion, reaction and deformation. Both linear and non-linear coupling can significantly reduce the characteristic times of these processes, leading to enhanced strain-rate partitioning and porphyroblast growth rates. Porphyroblast growth is inherently a non-equilibrium process, controlled by the rate and distribution of strain. Correlatively, strain and strain-rate distribution are inherently controlled by porphyroblast growth and other microstructural changes associated with metamorphism. Results of linked mechanical and microstructural modeling show coupling between deformation and porphyroblast growth, as well as associated microstructural changes that occur in the surrounding matrix. Feedbacks among the various processes involved can follow many paths leading to the finite state preserved in the field.

V42G-04 1655h

Deciphering Metamorphic Processes Through 3D Visualization of Thermal and Textural Modeling

Barbara Dutrow[1] (225-578-2525; dutrow@geol.lsu.edu)

C.T. Foster[2] (tom-foster@uiowa.edu)

Carl W. Gable[3] (gable@lanl.gov)

Bryan Travis[4] (bjtravis@lanl.gov)

[1]Louisiana State Univ., Dept. Geology & Geophysics, Baton Rouge, LA 70803, United States

[2]Univ. of Iowa, Dept. of Geosciences, Iowa City, IA 52242

[3]Los Alamos Ntl. Lab., EES-6, Los Alamos, NM 87545, United States

[4]Los Alamos Ntl. Lab, EES-2, Los Alamos, NM 87545, United States

Mineral assemblages and textures associated with regional contact metamorphic events provide a natural laboratory for analyzing the effects of heat and fluid transport. Typically these include the maximum temperature, T_{max}, (or pressure) attained by the rocks. Early progression to T_{max} is often obscured in the rock record, as is the retrograde path. Similarly, thermal modeling of these systems provides a controlled laboratory for deciphering important geologic processes and their magnitude over the aureole's entire metamorphic history. Numerous previous modeling studies focus on extracting snapshots in time (t) by plotting temperature (T) at some time (t_i), often with velocity vectors at (t_i) if fluid flow is included. However, contained in these four dimensional calculations is much more information that provides insights into the spatial and temporal aspects of a metamorphic event. Advanced visualization and analyses tools permit extraction and analyses of that diagnostics data. For example, one of the fundamental controls on crystal size distribution and porphyroblast growth in metamorphic rocks is the heating rate (dT/dt) experienced by the rocks. The rate at which the rocks traverse a reaction boundary (analogous to an isotherm) dictates the number of nuclei that form. Textural modeling based on thermal profiles demonstrates that rapid heating produces many small nuclei whereas lower dT/dt produce fewer, larger nuclei. Various thermal scenarios display contrasting dT/dt. If permeability is sufficient for fluid circulation to develop, rapid heating is followed by a continuous T decrease to a local minimum, with reheating as warm fluids infiltrate; in contrast to single heating and cooling scenario (conductive regime). Visualization techniques allow 3D spatial mapping of dT/dt throughout the metamorphic event to permit analyses of the distribution of fast vs. slow heating rates, and hence nucleation. By tracking the time spent in specific T intervals, the resultant porphyroblast size can be estimated.Our modeling studies suggest that mineral growth may take place during periods of cooling, within a specific T intervals that post-date T_{max}.In addition, by examining dT/dt at one spatial location through time, sequential periods of porphyroblast nucleation and growth can be observed and crystal size distribution predicted. Additional and non-traditional diagnostic output allows analyses and visualization of model behavior and provides new insights into processes controlling the development of metamorphic rocks.

V42G-05 1710h

Unexpected Temperature-Fluid Composition Paths in Kinetic Models of Contact Metamorphism of Siliceous Dolomites

Edward W. Bolton[1] (1-203-432-3149; edward.bolton@yale.edu)

Andreas Luttge[2] (1-713-348-6304; aluttge@mail.rice.edu)

Danny M. Rye[1] (danny.rye@yale.edu)

Jay J. Ague[1] (jay.ague@yale.edu)

[1]Yale University, Dept. Geology and Geophysics, P.O. Box 208109, New Haven, CT 06520-8109, United States

[2]Rice University, Dept. Earth Science, P.O. Box 1892, Houston, TX 77251-1892, United States

We present new results from our two-dimensional kinetic model of contact metamorphism. The model includes 8 minerals and 15 reactions in the system defined by CaO-SiO_2-MgO-H_2O-CO_2. Initially, a matrix of dolomite and quartz is present in a vertical 2D cross section at a depth equivalent of 3 kbar at the top of the layer. The model pluton is introduced by gradually heating, then cooling, a portion of the lower boundary. Overall reaction rates are based on experimental data and depend on the departure of the Gibbs free energy from equilibrium as calculated from the Berman thermodynamic database along with data for supercritical CO_2-H_2O mixtures from Kerrick and Jacobs. Reaction rates also depend on the evolving mineral surface areas, and both stable and metastable reactions are necessarily included in this kinetic model. In addition to reaction and fluid generation rate calculations, we model the fluid flow, dispersion, thermal evolution, compaction, grain-size changes, and dynamic permeability. We primarily consider no fluid expulsion from the pluton itself, although, within the layer, reaction induced fluid release due to decarbonation reactions can be dramatic. Key factors that influence the style of flow (buoyancy drive verses drive from reaction induced fluid release-devolatilization) are the grain size and heating rates. The grain size effect is dominated by permeability dependencies, and to a lesser extent by the influence of surface areas on reaction rates. As has also been observed by other field and modeling studies, several styles of flow around the pluton are realized, including up temperature flow toward the pluton (buoyancy drive), and down-temperature flow away from the pluton (devolatilization drive). Several unexpected T-X paths (temperature-fluid composition) are generated by the kinetic model within the 2D domain. In some cases, dramatic overstepping of univariant curves is observed, even though kinetic rates of metamorphic reactions from the experimental studies are considered fast. In other cases, fluid rich in CO_2 created in one zone is driven toward neighboring zones where T-X evolution paths lie below univariant curves while temperature increases. Needs for future models include better data for kinetics of mineral dissolution and precipitation, solubilities in CO_2-rich fluids, and nucleation kinetics, as well as models for matrix fracture and improved numerical resolution.

V42G-06 1725h INVITED

Dehydration, Earthquakes, and the Co-seismic Switch

Stephen A. Miller (+41-1-633-2621; steve@erdw.ethz.ch)

Geophysics Institute, ETH-Hoenggerberg, Zurich 8093, Switzerland

The pressure of fluids produced in metamorphic reactions must necessarily be at least as high as the rock pressure. If the fluid produced at individual reaction nuclei is less than the porosity created, the pore space collapses and brings the fluid to rock pressure. If more fluid is produced than porosity, then the fluid pressure exceeds the rock pressure and may promote hydrofracture. Reaction-induced hydrofracture is then responsible for the evolving permeability structure of the dehydrating horizon and controls the nature of fluid expulsion if a low pressure boundary is breached. The introduction of a low-pressure boundary sparks rapid changes. Recent studies show that earthquakes can breach seals that separate hydrostatic and lithostatic fluid pressures. The co-seismic rupturing of the seal induces the propagation of a high pressure pulse and large-scale fluid flow. In the hydrostatically pressured regions, a large influx of fluid can induce melting, while in the lithostatically pressured region, a rapid reduction in fluid pressure accelerates dehydration reactions. To understand how these processes are linked, a model is developed that couples dehydration kinetics to a non-linear diffusion model where permeability is a strongly non-linear function of the effective normal stress acting on new fractures. Since opening and closing of fractures is strongly influenced by the fluid pressure, the hydraulic properties of the media change in space and through time. If a hydrostatic boundary is breached (i.e. through hydrofracture or an earthquake), fluid expulsion is controlled by the permeability evolution of the dehydrating system prior to the event.

V42G-07 1745h

The structural evolution of carbonaceous material during metamorphism : a geothermometer

Olivier Beyssac[1] (Olivier.Beyssac@ens.fr); Bruno Goffe[1] (goffe@geologie.ens.fr); Fabrice Brunet[1] (brunet@geologie.ens.fr); Laurent Bollinger[2] (bollinge@gps.caltech.edu); Jean-Philippe Avouac[2] (avouac@gps.caltech.edu); Jean-Noel Rouzaud[3] (rouzaud@cnrs-orleans.fr)

[1]Laboratoire de Geologie - Ecole Normale Superieure, 24 rue Lhomond, Paris 75005, France

[2]GPS Department - Caltech, 1200 E. California Bvd, Pasadena, CA 91125, United States

[3]Centre de Recherche sur la Matiere Divisee - CNRS, 1b rue de la Ferollerie, Orleans 45000, France

With increasing metamorphic temperature, the organic matter present in sedimentary rocks is progressively transformed into graphite (graphitization). The degree of organization of this carbonaceous material (CM) as characterized by Raman spectroscopy (RSCM) , can be used as a geothermometer which yields the maximum temperature reached during the metamorphic cycle (Beyssac et al., 2002). We used this RSCM geothermometer to map the maximum metamorphic temperatures through the Lesser Himalaya (LH) in Nepal. This study provides a large dataset (80 samples) to estimate uncertainty of this method and to ascertain its reliability by comparison with conventional petrological investigations. We show that the RSCM geothermometer might be used to detect inter-samples temperature variations as small as 10°C or so, but absolute temperatures are only loosely determined to +/- 50°C due to the uncertainty on the calibration. This successful application of the RSCM geothermometer confirms that, at the timescale of regional metamorphism (several My), the transformation of CM is mainly controlled by temperature. However, laboratory investigations suggest that, in addition to temperature, pressure should also play a role (Beyssac et al. 2003). As a matter of fact, high degree of organizations encountered in natural CM cannot be reproduced in laboratory without pressure, even at temperatures as high as 3000°C. In addition to the data acquired on natural CM, we will discuss laboratory experiments performed up to 8 GPa which show that (1) a few kbar of hydrostatic pressure are required to initiate microtextural and subsequent structural transformations within CM and (2) the overall effect of increasing pressure is to speed up graphitization process. Beyssac, O., Goffe, B., Chopin, C., and Rouzaud, J.N., 2002, Raman spectra of carbonaceous material in metasediments: a new geothermometer. Journal of Metamorphic Geology, 20, 859-871. Beyssac, O., Brunet, F., Petitet, J.P., Goffe, B., and Rouzaud, J.N., 2003, Experimental study of the microtextural and structural transformations of carbonaceous materials under pressure and temperature. European Journal of Mineralogy, in press.