Final Report for DOE Award DE-FG02-03ER-46041 to Louisiana State University

Thermal-chemical-mechanical feedback during fluid-rock interactions: Implications for chemical transport and scales of equilibria in the crust

Dr. Barb Dutrow, P.I., LSU

Covering the time period May, 2003 - May, 2008

2003/04 - $81,814; 2004/05 - $82,377; 2005/06 - $82,709; 2007/08 - no cost extn

Partnership with Los Alamos National Laboratory; Drs. Bryan Travis and Carl Gable

5. Brief description of project goal and objective:

Our research evaluates the hypothesis that feedback amongst thermal-chemical-mechanical processes operative in fluid-rock systems alters the fluid flow dynamics of the system which, in turn, affects chemical transport and temporal and spatial scales of equilibria, thus impacting the resultant mineral textural development of rocks. Our methods include computational experimentation and detailed analyses of fluid-infiltrated rocks from well-characterized terranes. This work focuses on metamorphic rocks and hydrothermal systems where minerals and their textures are utilized to evaluate pressure (P), temperature (T), and time (t) paths in the evolution of mountain belts and ore deposits, and to interpret tectonic events and the timing of these events. Our work on coupled processes also extends to other areas where subsurface flow and transport in porous media have consequences such as oil and gas movement, geothermal system development, transport of contaminants, nuclear waste disposal, and other systems rich in fluid-rock reactions.

Fluid-rock systems are widespread in the geologic record. Correctly deciphering the products resulting from such systems is important to interpreting a number of geologic phenomena. These systems are characterized by complex interactions involving time-dependent, non-linear processes in heterogeneous materials. While many of these interactions have been studied in isolation, they are more appropriately analyzed in the context of a system with feedback. When one process impacts another process, time and space scales as well as the overall outcome of the interaction can be dramatically altered. Our goals to test this hypothesis are: to develop and incorporate algorithms into our 3D heat and mass transport code to allow the effects of feedback to be investigated numerically, to analyze fluid infiltrated rocks from a variety of terranes at differing P-T conditions, to identify subtle features of the infiltration of fluids and/or feedback, and to quantify the importance of feedback in complex fluid-rock systems and its affects on time and space scales and rates of reaction. We have made significant contributions toward understanding feedback and its impacts by numerical experimentation using 3D computational modeling of fluid-rock systems and by chemical and textural analyses of fluid-infiltrated rocks.

6. Description of Accomplishments:

Accomplishments for this research involve computational experimentation and field and analytical investigations of rocks infiltrated by fluids.

Enhancements to computational code - MOR3D

Each of these modifications required original algorithm and code development, testing, verification and documentation. We developed a suite of unit tests and benchmark problems to verify and validate MOR3D during development. The following algorithms were added to the code.

- *Fluid production* - to more realistically model cooling intrusions by allowing a non-linear release of volatiles from the crystallizing magma, in the form of:

$$V_{fluidprodn} = \int_{T(t_1)}^{T(t_2)} e^{-\beta\,(T-T_m)^2} \;\; dT \tag{1}$$

- *Boundary conditions* - to maintain mass balance, in the presence of mass sources, commensurate with fluid production, side boundary conditions were modified to allow flow in and out of the sides and/or the top boundary.

- *Fluid release via dehydration reactions* - to more realistically model fluid production in the host rocks. Minerals contain hydroxyl $(OH)^-$ and/or water molecules (H_2O) and dehydrate with increasing temperatures. This fluid release can affect fluid dynamics, heat transport, and flow direction. Algorithms were implemented that incorporate dehydration reactions at specific temperatures and pressures, for specified water contents. Permeability and porosity of the rock are allowed to change and the enthalpy of the reaction is incorporated into the energy equation. These allow us to more realistically evaluate the many metamorphic systems with bulk compositions of a shale (metapelites). In addition, we can compare these calculations to those without mineral reactions to access the impact fluid production has on the 3D thermal and flow system.

- *Specific storage* - for compressibility of a rock matrix. Fluids expand when heated and pore fluid pressure becomes unrealistically large without matrix compressibility. At higher values of fluid production this is necessary for numerical convergence with fluid production. This is a necessary precursor to implement hydrofracturing, one of the important mechanical feedbacks.

- *Developed new (more accurate) mathematical method to determine the direction of fluid flow* - determining the direction of flow has major implications for transport of heat, fluids, and chemical components and, therefore, where the system is out of equilibrium such that chemical reactions will likely occur in the host rocks. In all previous studies, fluid direction has been tracked based on only a portion of the flow field. Our algorithm accounts for all components of the velocity field, that portion which moves mass but no energy and that portion which moves mass and energy. A paper is now in preparation covering this technique.

- *Algorithm for incorporate depth dependent permeability* - Permeability (K) exerts a dominant control on the dynamics of fluid flow. To date, most calculations use isotropic and constant, layered, or an anisotropic K structure. Here permeability decays from some nominal value with depth, generally given by the equation $K = f(z) = ae^{-\lambda z}$ where z is depth and a represents material properties (equation from Ingebritsen and Manning, 1999, Reviews of Geophysics.)

- *Extended Equation-of-State (EOS) tables* for H_2O to 10 kbar and 1200^oC - to permit calculations over a wider PT range. We continue development of EOS for NaCl-rich fluids at high PT.

- *Numerics for multiple magmatic intrusions over time* - many magmatic systems display pulses of intrusion, rather than a single magmatic pulse. This alters (preheats) the host rock, raising the background temperature and requires that the entire thermal and flow field as well as the extent of all reaction variables be preserved for a 'restart' in the calculation. Multiple smaller events also minimizes the 'space' problem of intrusions.

- *Complex intrusion geometry* - to calculate on more realistic intrusion morphology. MOR3D has been interfaced with the mesh generation and geometric modeling package LaGriT (http://lagrit.lanl.gov) to enable modeling of complex geometric shapes. Material properties can be set based on simple geometric shapes (box, cylinder, sphere). More complex shapes defined by arbitrary surfaces can also be used to set material properties. Complex geologic framework models can be imported from geologic characterization packages such as EarthVision and goCad.

- *Extended visual diagnostics* - the only viable method for analyzing large data sets produced by numerical experimentation is through visualization of the data. Our visualization routines have been extended to analyze several more parameters throughout the 3D spatial and temporal domain of the calculation. Additions to visualization modules include:

  1. those related to fluid production:

     (a) fluid of hydration remaining bound in the host rock
     (b) density of water of hydration bound in the rock
     (c) water of hydration remaining in pluton
     (d) initial density of water of hydration bound in pluton
     (e) rate of total water release/uptake
     (f) fraction of melt

     Release of magmatic fluid indicates that this is an important process early in the thermal history, when fluid production increases fluid pressure and thus acts to drive flow away from the intrusion displacing the location of isotherms. These features allow the fluid evolution to be tracked as a function of space and time, and their impact on heating rates, direction of fluid migration and thermal development to be evaluated. Ultimately this affects mineral nucleation and growth and the location of isotherms.

2. Heating rate (dT/dt) through time at specific spatial surfaces (to simulate an erosional level), contoured for domains of heating and cooling. This permits visualization of regions of two thermal events, multiple heating cycles, cumulative time rocks spend heating and allows one to predict the domains of equilibrium (Fig. 1).

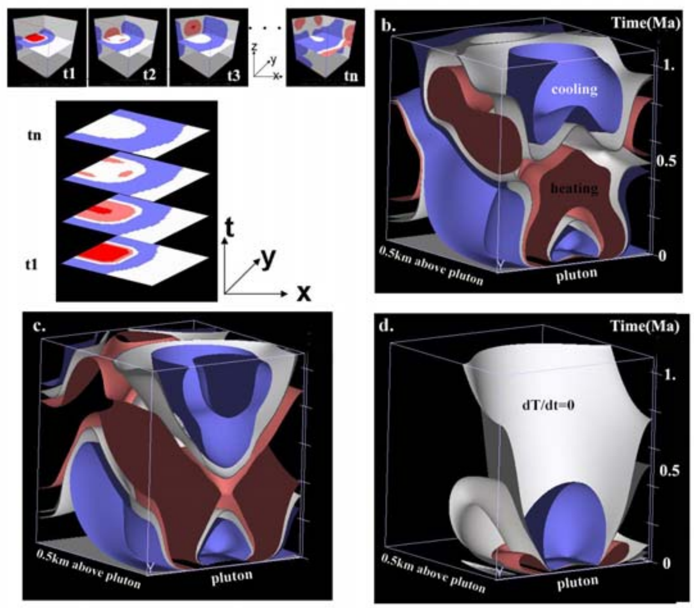

Figure 1: Visualizations developed from results of 3D computations of heat and mass transport surrounding igneous intrusions to display duration of heating and cooling. (A.) Construction of diagrams is done by extracting an x-y slice from a 3D volume at z' for specific time intervals ($t_1 ....t_n$), stacking planes with time increasing vertically, and coloring the volume with isosurfaces to highlight regions of heating and cooling. (B-D.) Variations in the diagrams developed by this method result from different permeability (K) values and geothermal gradients used in the calculations. (B.) 3 km thick intrusion emplaced at 12km depth, host rock K = $10^{-16}m^2$, $32^oC/km$. Note two thermal heating zones, one early one and a long-lived event later. (C.) same parameters as B. but emplaced at 9km depth. Note the shorter, and more restricted second thermal event. (D.) same parameters as in B. but with host rock K = $10^{-18}m^2$, $32^oC/km$. Note only a single, short-lived heating event.

3. Heating rate as rocks move across a reaction boundary (i.e. isotherm) which evolves through the region. This determines the number of mineral nuclei that form and the length scale of mineral equilibration.
4. Heating rate as a function of fluid field. Combining heating rates with velocity fields permits determination of heat carried by the fluid.
5. Maximum temperature at any time throughout a spatial domain T_{max}.
6. Time of T_{max} at any location throughout the field $t_{T_{max}}(x)$. This demonstrates the rate of isotherm advance and the time scales over which peak temperatures

are achieved.

Completed numerous scoping calculations to verify code development and to identify controlling parameters.

Calculations were completed for a 2D systems then a 3D domain. Key parameters that drive fluid flow were varied, including:

- intrusion thickness - 3 or 6km
- intrusion depth - 9, 12 or 15km
- multiple intrusions - 1 to 5 of various sizes
- variable shapes - sill, vertical sill, disks
- host rock geothermal gradient - 28, 32 or 36 $^oC/km$
- host rock permeability - homogeneous - $10^{-16}m^2$; $10^{-18}m^2$ and anisotropic - $10^{-15}_{x,y}$; 10^{-16}_{z}, depth dependent K, layered K
- magmatic fluid production - 0, 2.5% and 5%
- dehydration reactions - discontinuous at 300, 400, 550, 600C

Completed computational experiments incorporating the thermal, chemical and mechanical processes for 3D systems that have been implemented.

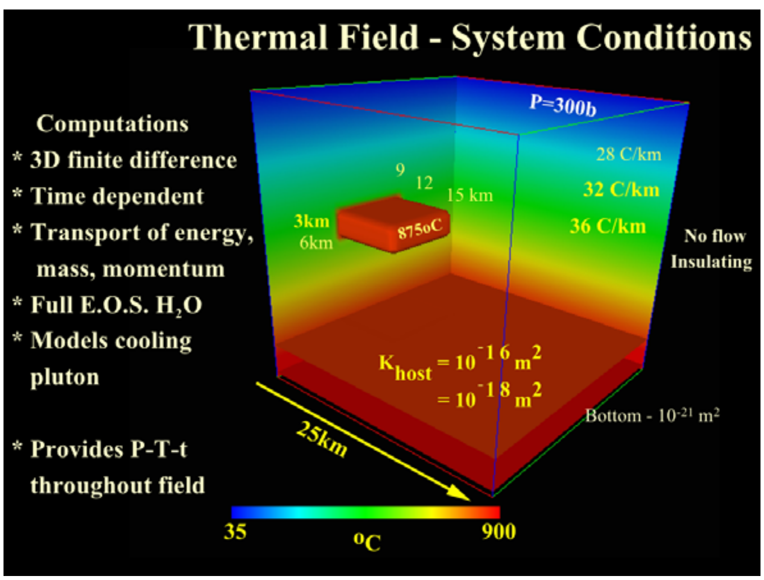

Figure 2: Computational domain showing variations in key parameters.

Produced animations of processes as a function of time. Movies were made to track the evolution of thermal and flow field and its dependence on parameters for the above calculations. These are available by request. They have been requested by a number of instructors for use in the classroom. A website is currently under development.

Visualization of these 3D fields throughout the duration of the calculation allows one to easily compare the difference in controlling parameters, to analyze the complete system, and communicate this information more readily. These animations have been very useful for both analysis of the calculations and communication of research results.

Significant accomplishments and results from calculations and field studies

Our numerous heat and mass transport calculations provided the framework on which we could analyze more complicated systems. Significant advances were made with respect to understanding the thermal field and the impact that fluid flow and mass transport have on thermal evolution (the subject of several papers in various stages of preparation). Our sophisticated 3D code, with its complexity, has allowed calculations heretofore untenable. Our exciting results use this groundwork to analyze the impact of feedback.

- *Feedback of the thermal and flow field on textural development of metapelitic rocks: Combining 3D thermal modeling with irreversible textural modeling*

  Mineral nucleation and growth are driven and controlled by thermally actived processes (Fig. 3; feedback loop developed for mineral texture formation). Two dominant controlling parameters are the heating rate of the rock, which controls the number of nuclei that form and the local reaction mechanisms, and the duration of heating, which controls mineral growth and equilibration. As such, the texture of a rock (the spatial location and size of minerals comprising the rock, crystal size distribution) should reflect the thermal and flow field. In turn, the thermal history should be recorded in the mineral texture if the textures can be deciphered. However, interpreting textures of rocks has long been inconclusive.

  Results of our computational experiments demonstrate that for contact metamorphic rocks, metamorphic heating rates vary by over four orders of magnitude during a single thermal event at a single location. Previously, reaction rates and kinetic parameters have been extracted from natural assemblages using constant heating rates which clearly leads to erroneous results. Our work has shown that it is therefore critical to use actual thermal paths of rocks for extracting accurate kinetic parameters from natural assemblages.

  To evaluate the impact that the thermal and flow field have on textural development, we combined our 3D heat and mass transport modeling with irreversible (time dependent) textural modeling of rocks undergoing thermal alteration. To our knowledge, this work remains unique in the world. Our textural modeling uses the actual P-T-t path calculated for any position in the 3D thermal field (Fig. 2) as input into time and temperature dependent equations for mineral nucleation and growth.

$$\frac{dN}{dt} = \left(\frac{dN}{dt}\right)_{t=0} \cdot exp\left[\kappa(T - T_{crit})^2\right] \tag{2}$$

$$R_i^{eq} = \left(\int_{t_1}^{t} D_r dt\right)^{0.5} \tag{3}$$

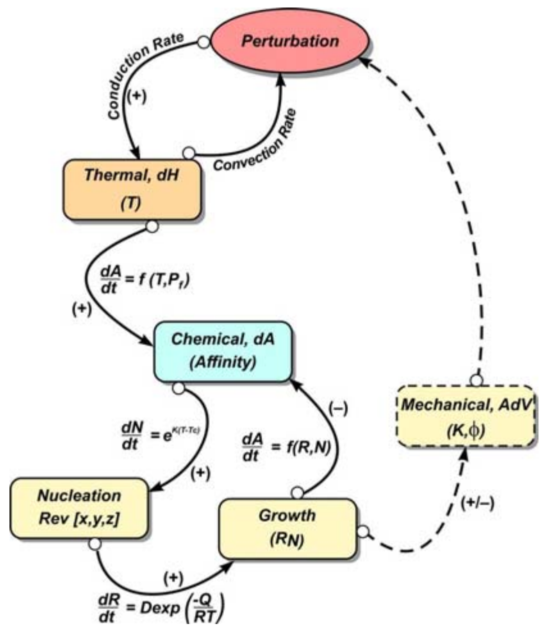

Figure 3: Schematic feedback loop showing the primary thermally driven processes involved in mineral textural development of metamorphic rocks. Arrows display the dependence of one process on another, equations show the mechanisms of change, +/- indicates a positive or negative feedback.

The result is a texture calculated for $1cm^3$ of rock (1 million nodes) for various locations in the 3D system (Fig.4, up rt). Our work demonstrates that rock textures record significant information on the heating rate and duration of time that the rock remains at elevated temperatures, previously unrecognized, and can be directly linked to the thermal and flow field (Fig.4).

The heating rate and the duration of time at high temperatures, fundamental controls on mineral textural development, are dramatically affected by the dominant heat transport mechanism. Thus, they depend on whether fluids flow and heat is transported by advection, or if heat transport is by diffusion only (Fig. 3). As such, different textures develop based on the heat transport mechanisms in addition to their location within the 3D thermal and flow field. We found that advective heat transport mechanism increases the scale of equilibrium and results in a rock with fewer nuclei, larger crystals and larger domains of equilibration (see Fig. 4, rt column). The reactions mechanisms are also dominated by more stable reactions. In some cases, the reaction mechanism controlling garnet growth may be completely different than the mechanism controlling e.g. staurolite and sillimanite growth. Consequently, extraction of kinetic parameters and reaction mechanisms from a single mineral could be problematic if related to the entire rock mass. Our work also demonstrates that different crystal size distributions (CSD) result from different thermal and flow fields, as shown in Figure 4. The actual CSD is dramatically different that one developed for a rock using a linear, or constant, heating rate as has been done previously. These calculations display the impact of fluids on chemical transport and scales of equilibria in the crust.

This work provides researchers with a new method to quantitatively understand textu-

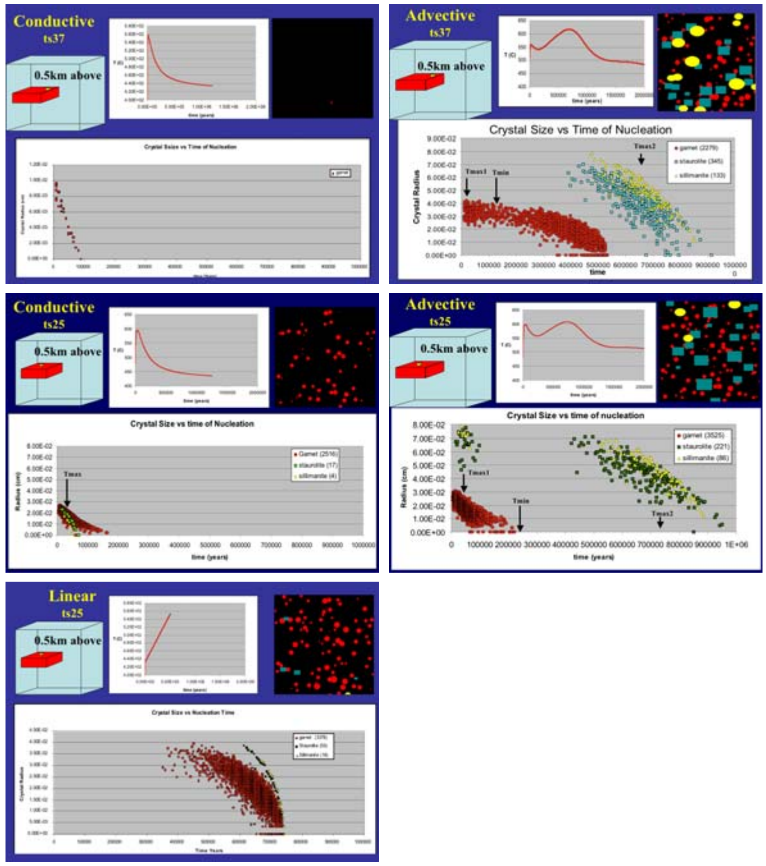

Figure 4: Comparison of rock textures and their crystal size distribution that result from variations in temperature time paths (location, heating rates and duration). Each diagram displays the location of the P-T-t path (up lf), T-t path (center), $1cm^2$ slice of rock with calculated texture (up rt), and crystal size vs. time of nucleation. Rows in diagram show the same spatial location in the thermal and flow field, columns reflect the dominant heat transport mechanism (lf = diffusion; rt = advection). Note the difference in textures and CSDs produced by varying P-T-t paths. See also Fig. 5.

ral formation in metapelitic metamorphic rocks. Previously most interpretations were qualitative only and had no basis for quantitative interpretations. Not only do we now have a method to quantitatively interpret mineral textures, but we can test this in various field locations.

- *Origin of regional-contact metamorphic terranes.*

  The outcome of our thermal and flow calculations provide a possible explanation for the development of regional-contact metamorphic terranes (e.g. NW Maine, USA), areas which have characteristics of both regional and contact metamorphism. These terranes have mineral zones that display a rough coincidence to exposed plutons (heat sources) but the mineral textures are regional in character (crystals are larger in size, nuclei are less abundant). The origin of these terranes has long been enigmatic.

  When thermal models of these terranes are combined with our textural models, the

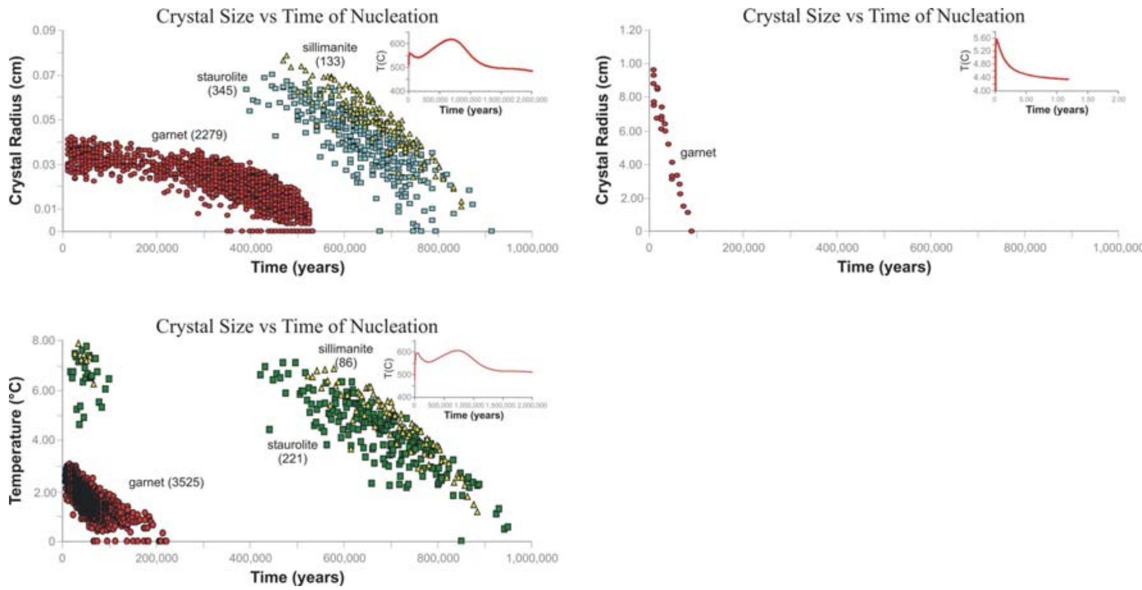

Figure 5: Comparison of crystal size distribution and mineral assemblage s due to fluid flow (left cf. right) and spatial location (top, bottom), taken from Figure 3. Upper left, convective system 0.25km from intrusion margin; upper right, same location for conductive system. Lower left, mineral distribution resulting at 0.25 km above center of pluton.

P-T-t paths resulting from advective dominated heat transport produce the mineral textures and spatial distribution patterns observed in NW Maine. Consequently, this suggests that fluid flow is required in the development of these terranes. Additional calculations are needed to verify this hypothesis, but it seems likely that fluid flow is required to develop these terranes in contrast to previous suggestions that they were due to multiple metamorphic events or diffusion dominated systems. This work underscores the importance of thermal-chemical feedback when interpreting geologic systems.

- *Prograde pseudomorphs as indicators of metamorphic conditions*

  Based on our computational work, it is suggested that rocks may contain subtle evidence in their textures of fluid-infiltration during prograde metamorphism. M.S. student J. Whittington analyzed a suite of rocks from NW Maine that contained prograde muscovite-rich pseudomorphs (muscovite replaces the former mineral staurolite but retains the earlier mineral's texture). These pseudomorphs developed as the rocks were heating and contain variations in mineral modes, despite their similar bulk composition. These differing mineral modes may reflect chemical transport and are hypothesized to contain information on metamorphic conditions along the prograde path. Because most prograde features are obliterated as the rocks recrystallize during heating, if this is the case, pseudomorphs represent a new method to decipher conditions along this portion of the P-T-t path.

  Using new techniques for image analyses (e.g. SEM-CL), she determined the modal mineralogy, analyzed mineral chemistry of minerals in the pseudomorphs and ma-

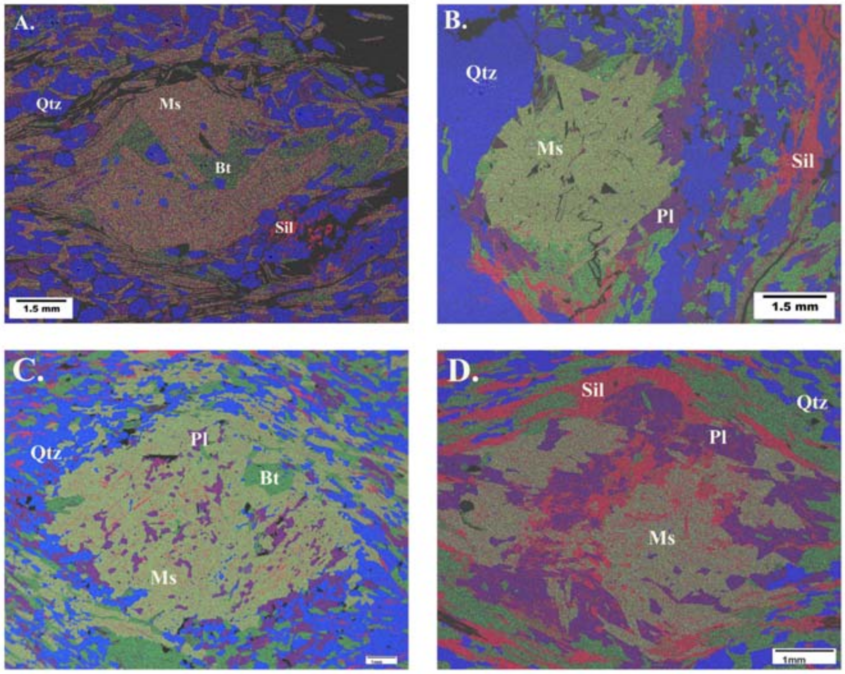

Figure 6: Four types of mica pseudomorphs found in NW Maine as shown by composite X-ray images. Slight color variations reflect differences in X-ray counts. Brown-brownish green = muscovite; bright green = biotite; blue = quartz; purple = plagioclase; red = sillimanite. (a) quartz-muscovite pseudomorph. (b) Muscovite pseudomorph. (c) Plagioclase-muscovite pseudomorph. (d) Sillimanite-plagioclase-muscovite pseudomorph. Each contains subtle information on thermal-chemical conditions during metamorphism.

trix (Fig. 6). This data, combined with irreversible thermodynamic models of texture development, were used to determine the mass transport and reaction mechanisms required to produce the pseudomorphs. Four different reaction mechanisms were proposed to explain the modal mineralogy, each representing a control during prograde metamorphism. Muscovite-rich and quartz-muscovite pseudomorphs likely reflect differing amounts of quartz in the original staurolite (bulk composition) (Fig. 6a,b); plagioclase-muscovite-rich pseudomorphs require the infiltration of Na-rich fluids (Fig.6c); sillimanite-plagioclase-muscovite pseudomorphs require a two stage process - the infiltration of Na-rich fluids during staurolite breakdown followed by heating and sillimanite growth (Fig. 6d). The subtle mineralogical differences recorded in pseudomorphs provide evidence of conditions along the prograde path, not previously recognized. This also demonstrates the utility of textural features to record conditions of metamorphism. This is the first quantitative study of its type and provides direct assessment reaction mechanisms and mass transport (Dutrow et al., 2008).

- *Tourmaline as indicators of fluid influx and chemical feedback*

Tourmaline has a wide range of chemical compositions that are extremely sensitive to their local environment (P-T-X). In some chemical environments such as evaporite deposits, there are few indicators in the geologic record of their former presence. Tourmaline from meta-evaporitic tourmalinites of the Duruchaus Formation of central Namibia reveal a common compositional trend that occurs in tourmaline from of other meta-evaporite localities. The meta-evaporitic tourmalines are generally magnesian, moderately-to-highly depleted in Al, enriched in Fe3+ and calculated WO2-. They typically follow this trend along a join between "oxy-dravite" $Na(Mg_2Al)(Al_6)(Si_6O_{18})(BO_3)_3(OH)_3(O)$ and povondraite $Na(Fe_2^{3+})(Fe_4^{3+}Mg_2)(Si_6O_{18})(BO_3)_3(OH)_3(O)$. Similar trends occur in the meta-evaporites at Alto Chapare (Bolivia), Challenger Dome (Gulf of Mexico) and Liaoning (China). This chemical feature is attributed to the influence of oxidizing, highly saline, boron-bearing fluids that are associated with these lithologies. Thus, tourmaline reflects the local evaporitic environment.

In the Namibian tourmalines, deviations from this trend are considered to be a consequence of subsequent overprints related to sulfate-silicate interactions and/or influx of reactive fluid. Tourmalines occurring in the highly magnesian high-pressure rocks (whiteschists and pyrope-coesite rocks) are distinctly more magnesian and fall close to the dravite and "oxy-dravite" compositions. These latter tourmaline compositions likely reflect the metasomatic processes that produced these unusual bulk compositions and/or the influx of a reactive fluid that eliminated any earlier chemical signatures of meta-evaporitic fluids.

7. Publications with DOE acknowledgments

Henry, D.J., Sun, H., Slack, J.F. and Dutrow, B.L., 2008. Tourmaline in meta-evaporites and highly magnesian rocks: perspectives from Namibian tourmalinites. European Journal of Mineralogy. Schreyer volume.

Dutrow, B.L., Foster, C.T.,Jr., Whittington, J., 2008. Prograde muscovite-rich pseudomorphs as indicators of conditions during metamorphism: An example from NW Maine. *American Mineralogist* C.V. Guidotti issue, v. 93, pp. 300-314.

Dutrow, B.L., Foster, C.T., Jr., and Gable, C., 2007. The Impact of Fluid Flow on Mineral Development: Three-dimensional modeling as a predictor of spatial distribution patterns. Fifth IMA Conference on Modelling Permeable Rocks, 1-4 p. Institute of Mathematics and its Applications, United Kingdom.

Dutrow, B.L., 2007. Visual communication: Do you see what I see? Elements, v. 3, no. 2, pp. 119-126.

Please note that our no cost extension came after LSU was severely impacted by Hurricanes Katrina and Rita. They dramatically impacted our work, students, and progress.

7a. Publications, in preparation or submitted, with DOE acknowledgments

Dutrow, B.L., Travis, B.J., and Gable, C.W. (in prep) A new quantitative method for determining the direction of up temperature fluid flow in hydrothermal systems.

Dutrow, B.L. (invited). Thermal-chemical-mechanical feedbacks during contact metamorphism. American Mineralogist.

Foster, C.T., Jr. and Dutrow, B.L. (in prep) Combining irreversible thermodynamic modeling of mineral textures with thermal models of metamorphism: Insights on textural development.

Dutrow, B.L., Gable, C.W., and Travis, B.J. (in prep). Effects of fluid flow, pluton fracture and permeability structure on the location of metamorphic isograds.

Dutrow, B.L., and Foster, C.T., Jr. (in prep) On the origin of regional-contact metamorphic terranes.

7b. Theses supported, with DOE acknowledgments

Sun, Haiting, 2007. Tourmalinites in the Neoproterozoic Metaevaporitic deposit of the Duruchaus Formation, Damara Belt, central Namibia. Ph.D. thesis, Louisiana State University, Baton Rouge, LA. 350 p.

Whittington, Jennifer, 2006. Muscovite pseudomorphs after staurolite as a record of fluid infiltration during prograde metamorphism. M.S. Thesis, Louisiana State University, Baton Rouge, LA. 119 p.

Armstrong, Corine, 2005. When bivalues get the blues: vivianite replacement of bivalves from the Kerch iron-ore deposits, Ukraine. Senior Thesis, Louisiana State University, Baton Rouge, LA 36 p.

Armstrong, Corine, 2008. Volcaniclastics as provenance indicators. M.S. Thesis, Louisiana State University, Baton Rouge, LA.

Metz, Kyle, in progress. Thermal evolution and contact metamorphism of roof pendants in the Sawtooth Batholith, ID. M.S. Thesis.

DOE was also acknowledged in several oral presentations, both invited and contributed. Many were accompanied by published abstracts of oral presentations.

Dutrow, B., Gable, C., Travis, B., and Foster, C.T., Jr. 2008. Numerical Experiments as a Guide to Rates of Metamorphic Processes. *Geological Society of America*.

Henry, D.J., Sun, H., Slack, J., and Dutrow, B., 2008. Tourmaline in Meta-Evaporites: Perspectives from Namibian Tourmalinites *Geological Society of America*.

Dutrow, B.L., Gable, C.W., Travis, B.J. and Foster, C.T.,Jr., 2008 Modeling Heat and Mass Transport in Metamorphic Systems. NSF-IGERT LSU-LANL Workshop on Computational Fluid Dynamics. Baton Rouge, March. Gable and Travis traveled to LSU and also made presentations.

Henry, D.J. and Dutrow, B.L., 2007. Sulfide-silicate interactions in medium grade metapelites, NW Maine. Frontiers in Mineralogy, Cambridge, England, June.

Henry, D.J., Sun, H., Dutrow, B.L.*, and Slack, J., 2007. Tourmaline in evaporites and metaevaporites: perspectives from Namibian Metasediments. Geochimica et Cosmochimica Acta, 71:A396 (Dutrow presented at: Goldschmidt 07, C ologne,Germany). INVITED - keynote *Presenter

Dutrow, B., Foster, C.T., Jr., and Gable, C.W., 2007. The Impact of fluid flow on mineral development: Three-dimensional modeling as a predictor of spatial distribution patterns. Fifth Institute of Mathematics and its Applications (of the United Kingdom) Conference on Modeling Permeable Rocks. March 26-29, 2007, Edinburgh, Scotland. INVITED

Dutrow, B.L., 2007. Introduction to the session in honor of Prof. Werner S chreyer: A U.S. perspective. Geochimica et Cosmochimica Acta, 71: "From field observation to experimental petrology and back in memory of Werner Schreyer" Goldschmidt 07, Cologne, Germany. INVITED - keynote.

Dutrow, B.L. 2007. MSA Presidential Address. Modeling Metamorphism: Energy, Fluids, and Feedbacks. *Geological Society of America, Abstracts with Programs*39. INVITED.

Dutrow, B., Foster, C.T., Jr., and Gable, C.W., 2006. Consequences of thermal input on metamorphic textures in contact and regional-contact terranes. 19th General Meeting of the International Mineralogical Association, Kobe, Japan. p. 173.

Whittington, J., Dutrow, B., and Foster, C.T., Jr. 2006. Prograde pseudomorphs as indicators of metamorphic processes. *Geological Society of America, Abstracts with Programs*, v. 38, p. 48.

Foster, C.T., Jr. and Dutrow, B., 2006. Porphyroblast spacing and nucleation time spans in well-equilibrated metamorphic rocks. *Geological Society of America, Abstracts with Programs*v. 38, p. 270.

Armstrong, C.*, Dutrow, B., Henry, D.J., 2005. When bivalves get the blues: vivianite replacement of bivalves from the Kerch iron-ore deposits, Ukraine. *Geological Society of America, Abstracts with Programs*, v. 37, p. 300. *Undergraduate researcher working on fluid-rock interactions at low T.

Dutrow, B., 2005. Evolution of thermal, mechanical, and chemical processes during contact metamorphism. *Geological Society of America, Abstracts with Programs*,v.37, p. 51. INVITED - keynote.

Foster, C.T., and Dutrow, B., 2005. Local reaction affinities and their effect on nucleation patterns in metamorphic rocks. *Geological Society of America, Abstracts with Programs*, v. 37, p.53.

Dutrow, B., Foster, C.T., Jr., Gable, C.W., Travis, B.J., 2005. Heat and Mass Transport Modeling and Rates of Metamorphic Processes. Goldschmidt Conference, May, Moscow, Idaho. *Geochimica et Cosmochimica Acta*.

Whittington, J., Dutrow, B., Foster, C.T., 2005. Muscovite-rich pseudomorphs after staurolite as a record of fluid infiltration during prograde metamorphism. *Geological Society of America, Abstracts with Programs*. v. 37, p. 227.

Dutrow, B., 2004. Thermal and mineral textural modeling of contact metamorphism as a guide to fluid-rock interactions and hydrothermal activity. Mineralogical Society Winter Meeting, p. 15. Bath, England. INVITED - Keynote.

Dutrow, B., Foster, C.T., Jr., Gable, C.W., Travis, B.J., 2004. Aspects of 3D heat transfer and fluid flow on mineral growth surrounding plutons. GSA Penrose Conference on Mass Redistribution in Continental Magmatic-Hydrothermal Systems. INVITED.

Clark, R., Foster, C. T., Jr. and Dutrow, B. L., 2004. MO) Garnet crystal size and spatial distributions in a staurolite schist. *Geological Society of America, Abstracts with Programs*(North Central meeting) , v. 36 , no. 3, p. 42.

Foster, C.T., Jr. and Dutrow, B.L., 2004. Modeling heterogeneous metamorphic reaction mechanisms and their relationship to textures and P-T-X-T paths. *Geological Society of America, Abstracts with Programs*v. 36, p. 202.

Dutrow, B., Foster, C.T., Jr., Gable, C.W., Travis, B.J., 2004. Advances in modeling contact metamorphism: 3D thermal and flow structure, mineral textural analyses and interpretive visualization. *Geological Society of America, Abstracts with Programs*v. 36, p. 338.

Dutrow, B., Foster, C.T., Jr., Gable, C.W., Travis, B.J., 2004. Heating rates and mineral textures as indicators of fluid flow during metamorphism. Goldschmidt Geochemistry Conference, June, 2004, Copenhagen, Denmark. *Geochimica et Cosmochimica Acta*68(11):A249 Suppl.S.

Dutrow, B., Foster, C.T., Jr., Gable, C.W., Travis, B.J., 2003. Metamorphic heating rates in contact aureoles: Consequences of intrusion depth and size, geothermal gradient and host rock permeability. *Geological Society of America, Abstracts with Programs*35:396.

Foster, C.T., Jr and Dutrow, B. L., 2003. The relations of multi-mineral crystal size distributions to rates of temperature change during metamorphism. *Geological Society of America, Abstracts with Programs*35:396

Dutrow, B., Foster, C.T., Jr., Gable, C.W., Travis, B.J., 2003. Deciphering metamorphic processes through 3D visualization of thermal and textural modeling. *Transactions of the American Geophysical Union*, 84:F1606.

Nine University/National Laboratory speaking invitations

8. People working on the Project; or who have worked on the project; percentage of support

UG = undergraduate, MS = Masters degree student, PhD = Ph.D. student; full time is 20 hrs/week.

- Dutrow, B., 1-2 month summer support.
- Four graduate students, four undergraduate students,
  - Haiting Sun, Ph.D. student, 100% support during one academic year.
  - Armstrong, Corine, U.G. - M.S. student (2005-present). UG Student researcher, academic year 2005-2006. 100% support She analyzed fluid infiltrated rocks in a low temperature environment that contain clam shells. This work presented new evidence on mineral replacement features in the solid state rather than reprecipitation/dissolution processes. Entered M.S. program in Fall, 2006. 1 month summer support, 50% support for academic year 2007-2008. Expected M.S. completion date is August, 2008.
  - Metz, Kyle, M.S. Student, 1 month summer support.
  - Sheldon, Nick, U.G. student. 20% support, work study student.

  - Jennifer Whittington, M.S. student (2004-2006). 50% during academic year; 100% support during summers.
  - Danielle Duhe, U.G. student worker (xerox, literature search, scanning, etc.) 0% DOE support; funded by workstudy.
  - Marc Cooper, U.G., 0% support (workstudy)
- Drs. Carl Gable and Bryan Travis, 0% support by this grant, as per requirements.
- Dr. Katherine Hosch, computer system analyst ($1000/yr)
- Dr. C.T. Foster, Jr., working with textural modeling algorithms, 0% support
- Dr. Denis Norton, feedback effects, 0% support
- Dr. Xiogang Xie, LSU electron microprobe technician, 0% support
- Mr. Richard Young, thin section technician, 0% support

9. Updated list of other support, current and pending

Frank's Foundation - pending. Purchase of electron microprobe for LSU Geology Department. $1,500,000. Only equipment money, no overlap, instrument needed for analyses.

Dominion Oil Co. - current. Provenance Studies of Volcaniclastics in the San Luis Basin, CO. $5,000. No overlap.

10. Cost Status:

Approved budget for full budget period: $ 246,900.
Actual costs incurred: $ 246,899.
Cost-sharing: LSU provided $21,022; used primarily for foreign travel to present invited lectures and equipment upgrades.