

**21st Annual
Five College Geology
Faculty Symposium**
Amherst College
Amherst, Massachusetts

February 9, 2001

- 3:00 **Welcome/Introductions**
- 3:05 **John Brady, Smith College**
Whole-rock geochemistry and metamorphism of blueschist/eclogite-facies mafic rocks on Syros, Cyclades, Greece
- 3:25 **Tekla Harms, Amherst College**
An estimate of shortening in a penetratively deformed domain of the Cordilleran thrust belt
- 3:45 **Michelle Markley, Mount Holyoke College**
Are big faults weak?: Evidence from the Norumbega fault in Maine
- 4:05 **Steve Roof, Hampshire College**
Pleistocene high shorelines in Panamint Valley, California: Geologic Evidence
- 4:25 **Sheila Seaman, University of Massachusetts**
The origin of andesitic ignimbrites in subduction-free bimodal volcanic systems
- 4:45 **Mike Williams, University of Massachusetts**
Age mapping and dating of monazite on the electron microprobe: a powerful new tool for tectonic analysis

PIZZA TO FOLLOW IN GEOLOGY BUILDING

- 7:00 **“FOSSIL ART” talk in Pratt Museum**

WHOLE-ROCK GEOCHEMISTRY AND METAMORPHISM OF BLUESCHIST/ECLOGITE-FACIES MAFIC ROCKS ON SYROS, CYCLADES, GREECE

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The island of Syros consists largely of possibly-repeated sequences of glaucophane-bearing calcareous schists, mafic schists, dolomite marbles, and calcite marbles containing abundant aragonite pseudomorphs (Dixon, 1969; Hecht, 1984). Several discrete, fault-bounded packages of blueschist/eclogite-facies mafic rocks with minor serpentinite are also found on the island. Although the mafic rocks occur with a variety of textures and modes, most are either fine-grained, glaucophane-rich blueschists with a strong fabric or coarse-grained (>1cm), massive omphacite- or glaucophane-rich rocks. Based on textures and field relations, previous workers (e.g. Dixon and Ridley, 1987) have interpreted these rock types as meta-basalt and meta-gabbro, respectively. We have obtained 38 new whole-rock XRF and INAA analyses for 18 fine-grained and 20 coarse-grained samples. The fine-grained mafic rocks are chemically very similar and have basalt or basaltic andesite compositions compatible with an ocean floor or island arc origin. The coarse-grained mafic rocks vary more widely in composition and include samples that are significantly enriched or somewhat depleted in TiO₂, FeO, and V relative to the fine-grained mafic rocks. The chondrite-normalized REE patterns of the fine-grained mafic rocks are nearly flat with values in the range of 10 to 30. The REE patterns of 17 of the coarse-grained mafic rocks are depleted in LREE, have a clear positive Eu anomaly, and range in value from 5 to 20. We interpret these data to mean that the protoliths of the coarse-grained mafic rocks are indeed gabbros that have been chemically differentiated by fractional crystallization, whereas the protoliths of the fine-grained mafic rocks are largely undifferentiated ocean floor basalts. Our interpretation is consistent with the conclusions of previous workers based on field (Dixon, 1969), geochemical (Brocker, 1991; Seck et al., 1996), and isotopic (Putlitz et al., 2000) data. This result raises the interesting question of why a coarse-grained igneous protolith should lead to a coarse-grained metamorphic rock containing all new minerals. The massive character of the original gabbros appears to have had a strong influence on their metamorphism (coarse texture, little hydration) and deformation (little fabric, coherent blocks) during subduction and exhumation.

AN ESTIMATE OF SHORTENING IN A PENETRATIVELY DEFORMED DOMAIN OF THE CORDILLERAN THRUST BELT

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From retrodeformable cross sections constructed across the Canadian Cordilleran thrust belt, Price (1981) provided a well-constrained estimate for the amount of supracrustal shortening due to thrust faulting within the Front Ranges and Foothills of the Rocky Mountains. Price (1981) calculated 105 km or 55% shortening from the Bourgeau thrust to the undeformed foreland along an east-west section just south of 50° N latitude, using line-length balance on the well-grounded assumption that penetrative deformation was negligible in that area. This study asks if shortening can also be estimated in the thrust belt west of the Bourgeau thrust, where penetrative deformation within thrust sheets is widespread. Here, we present the results of quantitative strain analysis in a thrust panel of the eastern Kootenay arc in northeastern-most Washington - approximately 150 km west of the Bourgeau fault and 80 km south of Price's line of section.

This study was conducted in an intraformational limestone conglomerate of the Monk Formation, a unit in the Proterozoic Windermere Group (Miller, 1994), where it lies in a homoclinally west-dipping thrust stack (Miller, 1983). In this region, penetrative deformation is expressed as well developed cleavage (Miller, 1983), axial planar to outcrop scale folds that are also common, and by significant changes in bed thickness between the noses and limbs of these folds. The carbonate conglomerate occurs in two 2 m thick layers that are clast-supported with < 5% micrite matrix. Limestone clasts are sub-rectangular and range from < 5 mm to 15 cm in length. The Monk Formation carbonate conglomerate is ideal for strain analysis for several reasons: (1) both the pebbles and matrix are limestone, yielding no ductility contrast between different elements of the rock; (2) no evidence of pressure solution volume loss was observed; and (3) the unit is cut by two nearly perpendicular joint sets and a well-developed cleavage plane at high angles to the joints, providing the three necessary measurement planes for three-dimensional structural analysis.

A finite strain ellipsoid, representing the sum of all penetrative deformation experienced by the rock, was determined by an R_f analysis of deformed pebble shape conducted in the limestone conglomerate - both at the outcrop (with the axial ratio and orientation of ≥ 100 pebbles measured on each of three planar joint or cleavage faces) and on oriented, cut slabs (with ≥ 250 pebbles measured on each of three perpendicular planes observed in serial sections). Results obtained were very consistent between these two data sets, yielding a strain ellipsoid with an axial ratio of 1.7:1.0:0.2 (normalized to the intermediate axis) - a strongly oblate ellipsoid. As expected, the maximum (ϵ_1) and intermediate (ϵ_2) principal axes of the strain ellipsoid determined by this study lie within the local cleavage plane, and the minimum (ϵ_3) principal axis is perpendicular to cleavage. Notably, the maximum (elongation) strain axis is shallowly plunging ($\leq 22^\circ$) at azimuth 014° - parallel to the structural grain of the Kootenay arc and to the axes of minor folds in the study area. The minimum (shortening) axis plunges steeply ($\sim 45^\circ$) at 128° azimuth. Assuming no volume change and plane strain, this corresponds to 55% horizontal shortening across the Kootenay arc.

To what extent is the strain ellipsoid determined in this study more widely applicable in the region of the study area or throughout the Kootenay arc? Outcrop scale folds occur in the study area and regionally within the southern Kootenay arc (Miller, 1983). These are asymmetric, ESE-vergent folds with short, steeply E-dipping intermediate limbs and long, shallowly W-dipping limbs that parallel the general homocline of units in the Kootenay arc. We have attempted to assess whether or not there are significant differences in finite penetrative strain experienced in the regionally-

dominant homoclinal panels (such as the limestone conglomerate of the R_f analysis) versus localized zones in the nose or intermediate limbs of such folds. Just 20 m upsection from the limestone conglomerate in the study area, thinly bedded (5-45 cm), carbonate cemented quartz sandstone is folded in a 2 m amplitude, sinusoidal, asymmetric fold. Dip isogon analysis of the fold shape shows that some areas of the fold are similar to Class 2 but that most of the fold is Class 1C - characteristic of buckle folds moderately to strongly modified by flattening. Oriented samples were taken from 5 key positions around the limbs and nose of this fold and analyzed in the σ_2/σ_3 plane (perpendicular to the fold axis). Deformation in the sandstone was determined by the Fry method, with 800-900 data points included in each. The orientations of principal axes of the strain ellipses so determined vary from nose to limb around the fold. In the synclinal nose and on the long limb, strain axes parallel those determined downsection in the limestone conglomerate by the R_f method. In the intermediate limb and anticlinal nose, axis orientations vary in a pattern consistent with flexural slip buckle folding.

References

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ARE BIG FAULTS WEAK?: EVIDENCE FROM THE NORUMBEGA FAULT IN MAINE

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Can plutons record stress in the earth's crust? This study uses a technique called the anisotropy of magnetic susceptibility (AMS). AMS is a semi-quantitative method commonly used for mapping foliations and lineations in granite [Bouchez, 1997]. The purpose of this study is to characterize fabric in the Mount Waldo pluton by comparing (1) the foliation defined by porphyritic feldspar crystals and (2) the magnetic foliation and lineation defined by the orientation of magnetite crystals. The Mount Waldo pluton [Trefethen, 1944] is a late Devonian, medium-grained granite that shows a weak fabric. Our AMS data agree with previous studies of feldspar foliation in the pluton [Trefethen, 1944]. Here we extend foliation data to three dimensions, and we report a previously unrecognized lineation in the pluton. In the Mount Waldo pluton, foliation is steep and strikes north-south. The AMS data also reveal a previously undescribed weak lineation in the pluton. Lineation is shallow and trends north-south. These fabrics appear to be magmatic in origin and may record the late Devonian strike-slip stress regime that drove slip along the nearby Norumbega Fault. Such a stress regime is inconsistent with a "weak" Norumbega Fault. These data therefore provide further evidence that crustal scale strike slip faults are strong enough that they do not act as free surfaces with respect to local and regional stress fields.

PLEISTOCENE HIGH SHORELINES IN PANAMINT VALLEY, CALIFORNIA: GEOLOGIC EVIDENCE

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During cooler and wetter periods of Pleistocene time, the Owens River system in SE California successively filled Owens, Searles, China, and Panamint valleys, and ultimately Death Valley. While lacustrine deposits and shoreline features are abundant in Panamint Valley, evidence constraining overflow timing from Panamint to Death Valley remains elusive. Searles Lake deposits suggest that the last long-standing wet interval with definite overflow occurred over one million years ago. Yet cores from Death Valley show that a lake existed there from c. 180 to 130 Ka. Researchers thus assume a similar age for the prominent high shoreline in Panamint Valley. However constraining overflow timing in the lower Owens River system is crucial for tectonic reconstructions of the Panamint Range and other ranges, and paleoclimate interpretations for the Yucca Mountain project. If the Owens River did not contribute to Death Valley in the last 200 kyrs, then the Amargosa and possibly Mojave rivers must have played much greater roles than recognized by current models.

Our research team is pursuing two key questions: when was Panamint Valley filled to overflow levels, and what was the source of water?

Shoreline features in Panamint Valley, such as wave-cut terraces, depositional bars and spits, and tufa deposits, provide unambiguous evidence of former lakes. Unfortunately, the dating of shoreline formation is difficult. Radiocarbon dating provides ages only for the last 30,000 years. We have preliminary results from a newly-refined method for dating sediments older than 30,000 years: Optically Stimulated Luminescence dating (OSL). OSL dating measures the accumulation of dislodged electrons which occur over time in mineral grains. Sampling for OSL requires finding appropriate fine-grained sand deposits, then collecting the sand without exposing it to sunlight. Our initial OSL ages indicate the high shoreline features formed between 80,000 and 40,000 years ago, much younger than previously assumed. Additional OSL ages are being processed to confirm the age of high shoreline features elsewhere in Panamint Valley.

Gastropod assemblages found in Panamint Valley typically contain the pulmonate genera *Lymnaea* and *Helisoma* which are tolerant of brackish water, and the prosobranch genera (gilled) *Valvata* and *Amnicola* which are restricted to nearly pure freshwater. The Owens River has long been considered the obvious source of water to fill Panamint Valley and overflow in to Death Valley, but a recent analyses of fossil ostracodes (small bivalved crustaceans) from Panamint Valley suggests the lake may have been fed by groundwater springs rather than Owens River water. A groundwater-fed lake would imply vastly different precipitation patterns than previously envisioned. To test this new hypothesis, we will be analyzing Sr/Ca, Mg/Ca, and Ba/Ca ratios recorded in carbonate shells that can be related to the salinity and alkalinity of the water in which the shells were growing. We will also use strontium isotopes ($^{87}\text{Sr}/^{86}\text{Sr}$) to determine the source of water of Panamint Valley lakes. The Owens River, which drains the eastern Sierra Nevada, has a low $^{87}\text{Sr}/^{86}\text{Sr}$ ratio derived from the relatively young granitic rocks of the Sierra Nevada mountains, whereas regional groundwater would reflect higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of older rocks of the Great Basin.

THE ORIGIN OF ANDESITIC IGNIMBRITES IN SUBDUCTION-FREE BIMODAL VOLCANIC SYSTEMS

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Pyroclastic eruption of rhyolitic magma carrying basaltic magmatic inclusions may result in either deposition of mechanically hybridized andesitic ignimbrite, or in deposition of rhyolitic ignimbrite hosting preserved basaltic enclaves. Basaltic inclusions with lobate and wispy boundaries, interpreted as chilled magmatic enclaves that survived post-vesiculation fragmentation, occur in rhyolitic ignimbrites in two Silurian volcanic successions in coastal Maine. On Isle au Haut, minimally flattened, vesiculated basaltic inclusions occur in slightly welded ignimbrite. On Great Cranberry Island, strongly welded ignimbrite hosts mostly vesicle-free basaltic inclusions, flattened in the volcanic bedding plane. Both examples may represent enclaves that survived the vesiculation and fragmentation associated with explosive pyroclastic eruption. Inclusions similar in appearance, suggestive of the transport of basaltic droplets in pyroclastic flows, have been observed in a Krakatauan pyroclastic deposit (Steve Carey, pers. comm, 2000). Fragmentation and homogenization of these enclaves with the rhyolitic ash host results in andesitic ignimbrites, compositional hybrids of rhyolitic and basaltic compositions represented in the system.

The degree of fragmentation that a magma undergoes during an eruption depends on many factors, including: water concentration, viscosity, degree and speed of bubble growth and coalescence, degree of magma permeability, and on the shear strain applied to the magma. Basaltic magma droplets carried in rhyolitic magma may avoid fragmentation to ash-sized particles if 1) the basaltic magma is sufficiently non-viscous that vesicles forming in the rising magma can coalesce, permitting volatiles to escape the enclave (e.g., Klug and Cashman, 1996), or if 2) the basaltic magma is too volatile-poor for expanding gas bubbles to produce the .70-.80 void fraction that results in magma fragmentation. Typical rhyolitic magma (5.5 wt.% water, log viscosity = 4.8 Pa s) would begin to vesiculate at ~ 2970 m depth, while basaltic magma (2.0 wt% water, log viscosity = 1.0 Pa s) would begin to vesiculate at ~460 m depth. The depth at which 70-80% of the volume of the magma consists of bubbles, inducing fragmentation, if bubbles DO NOT coalesce sufficiently to prevent fragmentation, would be ~360 m for the rhyolitic magma, and ~160 m for the basaltic magma. The basaltic inclusions described above suggest that in some cases sufficient permeability develops in basaltic magmatic inclusions carried in rhyolitic magma to allow volatiles to escape the basaltic magma,

moving the fragmentation threshold to low enough pressures to avoid fragmentation. In instances where fragmentation of enclaves does occur, mechanical hybridization of basaltic and rhyolitic ash produces andesitic ignimbrite layers that are genetically unrelated to subduction.

AGE MAPPING AND DATING OF MONAZITE ON THE ELECTRON MICROPROBE: A POWERFUL NEW TOOL FOR TECTONIC ANALYSIS

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High-resolution X-ray mapping and dating of monazite using the electron microprobe offer a powerful geochronological tool for structural, metamorphic, and tectonic analysis. X-ray maps commonly show complex Th, U, and Pb compositional domains that reflect monazite growth and overgrowth events. Age maps can be constructed from the X-ray maps by applying the age equation to each pixel (after background correction and calibration). The age maps generally show less complexity than individual element maps, typically displaying older cores with one or more younger rims. Quantitative microprobe analysis of monazite offers a rapid, in situ method for establishing accurate ages of the mapped domains. The high spatial resolution of the compositional maps, speed of analysis, and in situ nature (allowing direct correlation with texture) give microprobe dating techniques a unique power for unraveling tectonic histories and for clarifying the interpretation of conventional mass spectrometric age data. Three specific applications will be illustrated:

- (1) Monazite inclusions in metamorphic porphyroblasts can be used to put specific time constraints on P-T paths and rates of metamorphic and deformational processes. For example, phase relationships in Archean/Proterozoic rocks of northern Saskatchewan may suggest a relatively typical, clockwise P-T-t path involving granulite facies metamorphism followed by exhumation. However, monazite analysis indicates that the 1.8 Ga exhumation event may have culminated a multi-stage or protracted history, involving an extended residence at deep-crustal levels.
- (2) Because monazite is commonly a fabric forming (and inclusion bearing) mineral, microfabrics and microtextures associated with monazite can help to constrain the age of deformation events and provide new links between metamorphism and deformation. For example, aligned, tabular monazite inclusions in staurolite and andalusite from Proterozoic rocks of northern New Mexico indicate that deformation and regional triple-point metamorphism occurred at ca. 1.4 Ga, not during the Mazatzal orogeny (1.7-1.65 Ga) as previously thought.
- (3) Age mapping and dating can provide insight into complex results from other geochronologic techniques. For example, previous monazite dates from the Lower Gorge of the Grand Canyon tend to spread over several tens of millions of years. Age mapping reveals that most monazite grains have a euhedral core domain that is ca. 1.69 Ga with overgrowths ranging from 1.67 to 1.64 Ga. We interpret the euhedral core to represent the

time of migmatization, and the overgrowths to represent subsequent thermal or hydrothermal events during slow cooling. Single whole-monazite dates would yield an average of these domains.

Monazite age mapping and dating on the microprobe allow geochronology to be an integral part of the petrological and microstructural analytical process rather than a subsequent activity. Dates can be obtained from a large number of samples rather than a small subset, and the interpretation of dates has immediate petrologic and structural context. Finally, informed decisions can be made about which samples require high-precision mass-spectroscopic analysis, and the results of those analyses can be better integrated with all other petrologic and structural data