

Summary of Research Projects

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Igneous Petrology and Geochemistry

B.Sc., 1971, San Jose State University, California

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Research Areas: Petrology, major and trace element geochemistry of basic and intermediate igneous rocks. Continental volcanism, ophiolites and island arcs, mantle metasomatism, lunar petrology.

Ophiolites, Oceanic Crust, and Active Margin Processes

Ophiolites are distinctive assemblages of mafic, ultramafic, and felsic igneous rocks that are commonly thought to represent oceanic crust and mantle that has been accreted to a continental margin. The accretion of ophiolite and island arc terranes has been the primary mechanism of continental growth since the Proterozoic.

Is the Southern Farmington Canyon Complex a Late Archean/Early Proterozoic Accretionary Complex?

NSF EAR-0337334, Jan 04-Dec 05

One of the fundamental questions in the planetary evolution of Earth centers on when modern style plate tectonic processes, driven by the sinking of dense lithospheric plates, became the dominant mode of thermal convection and crustal deformation. This project examines rock assemblages in the Wasatch Mountains of northern Utah that may represent a late Archean to early Proterozoic accretionary complex formed by subduction of oceanic plates beneath the Archean Wyoming province. These rocks were modified by a later collisional event circa 1700 Ma and are now amphibolite grade gneisses.

Our reconnaissance studies of the southern part of the Farmington Canyon complex suggest that it may represent an subduction zone accretionary complex that has been overprinted by amphibolite facies metamorphism. The southern Farmington Canyon complex contains blocks of mafic metavolcanic rock (amphibolite, pyroxene amphibolite, garnet amphibolite), ultramafic rock, and quartzite – some of which may represent metachert associated with mafic metavolcanic rocks – in a matrix of quartzo-feldspathic gneiss with a chemical composition similar to greywacke. The combination of old Nd model ages and Archean inherited zircon components implies that this accretionary complex formed on the SW margin of the Wyoming province, in conjunction with a coeval continental margin arc represented in part by the northern portion of the Farmington Canyon complex (orthogneiss, migmatite, pegmatite). This continental margin arc apparently collided with the Santaquin arc in the mid-Proterozoic.

We have mapped selected areas of the Farmington Canyon complex in detail to demonstrate the distribution of exotic blocks within the gneiss, to compare block distributions to the Franciscan complex. Sampling has focused on the amphibolites (metabasalts), quartzites (metacherts), and ultramafic rocks. The mafic rocks will be studied using standard discrimination techniques developed for oceanic crust and island arc lavas. Quartzites will be compared to published analytical data for Mesozoic to recent cherts to determine if they are metacherts or detrital, using the signatures of hydrothermal metal deposits. In addition, the project will carry out a reconnaissance study of Sr-Nd-Pb isotopes (6-8 samples) to confirm the provenance of mafic blocks in the assemblage, and to determine whether more detailed studies are warranted. Finally, detailed paleo P-T investigations of garnet-clinopyroxene amphibolites will be carried out to determine if an earlier history of high-pressure metamorphism can be documented in any of the mafic blocks; this investigation will use x-ray mapping of relict mineral phases, reconstruction of primary phase compositions using image analysis techniques, and calculation of paleo P-T-time paths for allowable assemblages, using the electron microprobe.

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Masters Thesis Kyle Andreasen, Petrology and geochemistry of the Farmington Canyon complex, Utah, *M.Sc. Thesis*, Utah State University, *in progress*.

Summary of Research Projects

Geochemical Processes in Forearc Peridotites: Depletion, Enrichment, and Melt Reactions in the Mantle Wedge above Subduction Zones

The question of geochemical flux in the mantle wedge during subduction is critical to our understanding of arc volcanism, and forms an important aspect of the global geochemical flux. This is one of the first order problems identified by the “Geochemical Earth Reference Model” (GERM) initiative, and by the “subduction factory” focus of the NSF “MARGINS” initiative. Quoting from the MARGINS program announcement: “*At convergent margins, raw materials (sediments, oceanic crust and upper mantle) are fed into the "subduction factory" where many processes (including dewatering, metamorphism, melting) under changing physical and chemical conditions shape the final products (magma, volatiles, ore deposits, new continental crust, recycled materials) with significant environmental consequences. In practice, it has been difficult to investigate processes and estimate fluxes through the "factory" owing to poor constraints on the volumes of magmas, fluids, and volatiles produced.*” The MARGINS program attempts to understand these processes by studying active subduction zones, where the processes may be observed directly. This approach has much to recommend it, but it does suffer from the fundamental problems posed by poor exposure of lithospheric mantle derived from the supra-subduction zone wedge, and by the cover of several thousand feet of seawater.

An alternative approach is to examine outcrops of lithospheric mantle that underlie crust known to have formed by supra-subduction zone (SSZ) magmatism. This lithospheric mantle represents in part the source from which the overlying crust was extracted, and its mineralogy and composition reflect the processes that have affected it through time, including melt extraction, fluid phase enrichment, and subsequent interactions with melt derived from lower in the mantle tectosphere. These processes have been frozen in place by cooling and emplacement of the mantle lithosphere and its overlying crust. This approach offers some advantages over currently active subduction zones, such as on-land exposures, continuous outcrops that can be related structurally and stratigraphically to their overlying crust, and relatively low costs associated with the field studies. A primary advantage, however, is the fact that large tracts of supra-subduction lithosphere are commonly exposed at the base of many SSZ ophiolites, allowing us to examine their petrology and geochemistry on larger length scales than is currently possible in active systems.

The Coast Range ophiolite of California (CRO) is one of the most extensive tracts of oceanic crust in North America. Our recent work at three important CRO localities (Elder Creek, Stonyford, Cuesta Ridge), along with work by other investigators at Del Puerto, Llanada, Sierra Azul, Mount Diablo, Point Sal, has now established that the CRO represents, in large part, formation by fore-arc extension above an east-dipping, proto-Franciscan subduction zone, modified in part by subsequent ridge-trench interactions (Shervais, 2001; Stern and Bloomer, 1992; Shervais and Hanan, 1989; Shervais et al, 2004a,b,c).

We propose to study geochemical flux in the lithospheric mantle above the proto-Franciscan subduction zone, as represented by partially serpentinized harzburgite and dunite tectonites that underlie the Coast Range ophiolite of California. Our goal is constrain nature and extent of these fluxes, as documented by whole rock major element, trace element, tracer isotope, and stable isotope analyses, and by mineral analyses using electron and ion beam techniques. Major questions we will pose include the cumulative extent of melt extraction and the nature of the melt extracted, the nature, source, and extent of fluid flux to the mantle in the SSZ wedge, and the nature and extent of mantle-melt interactions subsequent to melt extraction (e.g., addition of melt from sublithospheric sources, or reaction of this melt with the previously depleted peridotites).

Shervais, J.W., Kolesar, P., and Andreasen, K., 2005, Field and Chemical Study of Serpentinization – Stonyford, California: Chemical Fluxes and Mass Balance., in W.G. Ernst, editor, *Serpentine and serpentinites: mineralogy, petrology, geochemistry, ecology, geophysics, and tectonics (a tribute to Robert G. Coleman)*, International Book Series, v. 8, Bellwether Publishing Ltd., Columbia, MD, 452- 474. [reprinted from International Geology Review]

Shervais, J.W., Kolesar, P., and Andreasen, K., 2005, Field and Chemical Study of Serpentinization – Stonyford, California: Chemical Fluxes and Mass Balance, *International Geology Review*, v. 47, 1-23.

Shervais, Kolesar, Andreasen, and Vetter, Compositional Variation in Serpentine as a Function of Primary Phase Chemistry: Coast Range ophiolite, California, *International Geology Review*, in preparation.

Shervais, Vetter, Kolesar, and Andreasen, Serpentinized Peridotites of the Coast Range ophiolite, Stonyford, California: Melt reactions in a fore-arc mantle wedge; in preparation.

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Petrology, Geochemistry, and Age of Accreted Oceanic Crust, California Coast Ranges

The western margin of North America is characterized by extensive tracts of ophiolitic basement with radiometric ages of 155 to 170 Ma. The regional extent of these ophiolite belts, and the narrow range in their ages of formation, make their petrogenesis one of the more important tectonic problems in the Cordillera.

The Elder Creek ophiolite comprises four magmatic episodes. The first is represented by cumulate dunite, wehrlite, and gabbro, and isotropic gabbro, and dike complex. The second magmatic episode consists of clinopyroxenite intrusions with less common gabbro and gabbro pegmatoid. The third magmatic episode is represented by isotropic gabbro, agmatite with xenoliths of cumulate or foliated gabbro and dike complex in an isotropic gabbro-diorite matrix, diorite and quartz diorite stocks and dikes which intrude all of the older lithologies, and felsite dikes which are marginal to the quartz diorite plutons. The fourth magma series is represented by basaltic dikes which cross-cut rocks of the older episodes. Geochemical data are consistent with formation of the first three series in a supra-subduction zone (arc) environment; dikes of the final magma series are characterized by MORB-like major and trace element compositions. U-Pb zircon ages of plagiogranites from stage 1 and the stage 3 quartz diorites require a narrow formation interval, from 172 Ma to 165 Ma.

The Stonyford volcanic complex (SFVC) consists of three distinct petrologic groups: (1) oceanic tholeiites, (2) transitional alkali basalts and glasses, and (3) high-alumina, low-Ti tholeiites. REE, trace element, and Pb data indicate that group 1 (OT) and group 2 (alkalic) lavas of the SFVC were derived from a heterogeneous mantle source with at least two components: (1) depleted MORB-asthenosphere and (2) an enriched OIB-like component. The group 3 (high-Al, low-Ti) lavas resemble second stage melts of MORB asthenosphere which form by melting plagioclase lherzolite at low pressures. These lavas also resemble high-Al island arc basalts. The trace element and isotope systematics show a OIB influence, which overprints generally depleted trace element characteristics.

$^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages for basalt glasses from four localities within the complex show that they were erupted over a short period of time, ranging from 163.0 ± 0.8 to 164.8 ± 0.6 Ma. U/Pb zircon ages for CRO diorites in the underlying melange are 166 to 172 Ma. This coincidence in ages, coupled with the occurrence of arc-like high-Al, low-Ti basalts and the structural position of the SFVC overlying dismembered CRO plutonics in the serpentinite melange, imply that formation of the complex may have occurred in the upper plate of the CRO "arc", probably in response to collision of the subduction zone with a spreading center.

The Cuesta Ridge ophiolite is dominated by two magma suites: an older boninitic suite, with refractory major and trace element compositions, and a younger diorite-quartz diorite suite that forms the sheeted complex. A final magma series is represented by olivine tholeiite dikes with MORB composition that cross-cut both of the older magma series. The entire ophiolite was emplaced over the Franciscan and Tertiary sediments by thrust faulting during the Pliocene.

Re-examination of volcanic glasses from Stonyford suggests that they contain abundant evidence for chemosynthetic bacterial processes, in the form of tubules that penetrate into the glass from fractures. We are currently studying these tubules with Dr. Neil Banerjee of Univ Alberta to establish if they are truly biotic and the nature of the biota.

Masters Theses

Cameron Snow, The Coast Range ophiolite at Cuesta Ridge, California; Utah State University, *M.Sc. Thesis*, Utah State University, 2002.

Joe Beaman, Petrology and geochemistry of cumulate plutonic rocks and dikes, Elder Creek Ophiolite, California, *M.Sc. Thesis*, University of South Carolina, 1990.

Marchell Zoglman, The Stonyford Volcanic Complex, California: A Jurassic intraplate seamount, *M.Sc. Thesis*, University of South Carolina, 1991.

Adele Simpson, Provenance and tectonic implications of volcanic sandstones in the Jurassic Great Valley Series near Stonyford, California, *M.Sc. Thesis*, University of South Carolina, 1999.

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Publications Resulting From This Project

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- Shervais, J.W.,** 2001, Birth, Death, and Resurrection: The Life Cycle of Suprasubduction Zone Ophiolites, *Geochemistry, Geophysics, Geosystems*, vol. 2, (Paper number 2000GC000080), 20,925 words, 8 figures, 3 tables.
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- Snow, C.A. and J.W. Shervais, 2002, Late Stage MORB Volcanism at the Cuesta Ridge Ophiolite Remnant: Evidence for Ridge Collision or Back-arc Basin Spreading? American Geophysical Union, EOS, v. 83.
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- Shervais, J.W., 2001, Birth, Death, and Resurrection: The Life Cycle of Supra-Subduction Zone Ophiolites. International Conference on the Geology of Oman, Sultan Qaboos University, Abstract volume, p. 80.
- Shervais, J.W., 2000, Multistage Origin of the Coast Range Ophiolite, California: Implications for the Life Cycle of Supra-Subduction Zone Ophiolites, Geological Society of America, Abstracts with Programs, 32/7, A47, Abs. #51967.
- Shervais, J. W. (1999) Birth, Death, and Resurrection: The Life Cycle of Supra-Subduction Zone Ophiolites, illustrated by the Coast Range Ophiolite. Geological Society Of America, Abstracts with Programs, 31/6, A##.
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- Shervais, J.W. and Beaman, B.J. (1991) The Elder Creek Ophiolite: Multi-stage magmatic history in a fore-arc ophiolite, northern California Coast Ranges. Geological Society of America, Abstracts, 23/5, A387.
- Zoglman, M.M. and Shervais, J.W. (1991) The Stonyford Volcanic Complex: Petrology and structure of a Jurassic Seamount in the Northern California Coast Ranges. Geological Society of America, Abstracts, 23/5, A395.
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Summary of Research Projects

Chemical Provenance and Tectonic Setting of Clastic Sedimentary Rocks

One of the central goals of sedimentary petrology is the identification of provenance. Provenance is critical for deciphering the tectonic history of ancient basins and has been applied to both terrane analysis and basin analysis (e.g., Dickinson et al., 1983; Ingersoll et al., 1990; Schwab, 1991; Marsaglia and Ingersoll, 1992). Provenance is also an important factor in petroleum exploration, because of the role provenance and tectonic setting play in controlling the distribution and quality of petroleum systems elements, particularly reservoir, within sedimentary basins.

Determining provenance is relatively straightforward for conglomerates and breccias, where large intact samples of source are preserved as clasts (e.g., Seiders, 1983; Seiders and Blome, 1988). For sandstones, the process is more cumbersome, and requires detailed point counts of lithics and mineral grains, partitioned into a range of categories (e.g., Dickinson, 1970; Ingersoll et al., 1984). These methods are not only time consuming, but are also distinctly subjective, requiring the petrographer to make judgment calls on the identification of lithics and the nature of different mineral grains. For siltstones, the prospects are even bleaker because grain size is too small for point count methods to be applied.

In the 1980's and early 1990's a number of investigators endeavored to apply various geochemical criteria to the determination of provenance, focusing largely on either the rare earth elements (e.g., Bhatia, 1985; McLennan 1989) or on the isotopes of elements that are thought to be stable during transport and diagenesis (e.g., Nd, Sr: Heller et al., 1985, 1992; McLennan et al., 1990; Linn and others, 1991; Linn and DePaolo, 1993). A few studies have looked at broader arrays of elements but are more limited in scope and application (Bhatia, 1983; Bhatia and Crook, 1986; McLennan et al., 1993). More recently, Nd isotopes and detrital zircon ages have been used to associate ancient sedimentary rocks with specific cratonic source regions, e.g., studies of Avalonian and related peri-Gondwanan terranes in the Appalachians (Nance and Murphy, 1996).

This proposal requests funding to develop and apply a systematic technique for using major and trace element whole rock geochemistry to determine the provenance and tectonic setting of sand and silt-sized clastic sedimentary rocks. We will use major and trace element analyses by x-ray fluorescence spectrometry and trace elements by ICP-MS analysis to characterize sandstones and siltstones from different basins of known provenance and tectonic setting. Our analytical techniques and data reduction will be based on work carried out by one of my former graduate students and myself as part of a master's thesis on mafic-rich sandstones of the lower Great Valley series (Seymore-Simpson, 1999), and extended to assess the methods of Bhatia and Crook (1985) and McLennan et al. (1993). We will supplement this work with classic Gazzi-Dickinson point counts on selected sandstones from the same sample suite for comparison of results.

Our approach is based on work of Dickinson et al. (1983), who defined three basic provenance categories (continental block, magmatic arc, recycled orogen), each of which is divided into three distinct subgroups (e.g., craton interior vs. basement uplift, dissected arc vs. undissected arc), resulting in nine combinations of provenance and tectonic setting for sandstones in the western United States. Our plan is to sample a selection of the sandstones and siltstones in the basins studied by Dickinson et al. (1983). These data will be supplemented with existing published chemical data on modern clastic sediments (e.g., Maynard et al., 1982; McLennan et al., 1990) and on clastic sedimentary rocks from well-defined ancient settings (e.g., Bhatia, 1983; Linn et al., 1991).

Our goal is to allow sedimentary petrologists and others working on the tectonics of sedimentary basins to determine provenance in using a systematic approach that minimizes individual bias in point-counting and maximizes efficiency and speed. This work should be of interest to petroleum geologists who need to understand fundamental characteristics of basin fill and the setting in which these basins formed. It also has broader application to a range of problems in basin analysis, terrane analysis, tectonics, and regional geology.

Masters Theses

Adele Simpson, Provenance and tectonic implications of volcanic sandstones in the Jurassic Great Valley Series near Stonyford, California, *M.Sc. Thesis*, University of South Carolina, 1999.

Aaron Peterson, Chemical Provenance and Tectonic Setting of Clastic Sedimentary Rocks, *M.Sc. Thesis*, Utah State University, *in progress*.

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Mantle Plumes and Continental Volcanism

Our current work in the Snake River Plain of southern Idaho focuses on the role of mantle plumes (“Hot Spots”) and their interactions with continental lithosphere. Mantle plumes are thought to represent the upwelling of hot, enriched material from the core-mantle boundary towards the surface. Volcanic rocks which form by passage of lithosphere over a mantle plume will display chemical and isotopic compositions which vary in response to plume dynamics and interactions between the plume and the overlying lithosphere. Our work in the Snake River Plain uses both surface samples and drill core samples from existing scientific and geothermal test wells. Our goal is to reconstruct the geochemical and geodynamical history of the Yellowstone plume and its interactions with the overlying continental lithosphere.

Plume Tails and Continental Lithosphere: A Petrologic Traverse of the Snake River Plain

This collaborative research project documents field, petrologic, geochemical, isotopic, and geochronological relationships of Neogene basaltic volcanism in the western and central Snake River Plain. This area lies at the critical junction of the eastern Snake River Plain (which may represent the track of the Yellowstone hotspot) with the western SRP, a structural graben that connects the eastern SRP with the Columbia River Plateau flood basalt province.

Most models for the origin and evolution of the Snake River Plain (SRP) volcanic province focus on the central role of the Yellowstone hotspot and its effects on the lithosphere of North America in response to plate motions relative to this hotspot. In these models, movement of the North American plate over the Yellowstone hotspot has resulted in a linear track of volcanism that parallels this plate motion, represented today by volcanic rocks of the eastern SRP.

The western SRP structural graben is oriented at a high angle to the trace of the Yellowstone plume and to the axis of the eastern SRP. It is filled largely with lacustrine sediments related to Pliocene Lake Idaho, a large, long-lived lake system that formed first at the northwestern end of the graben (near Oregon) and extended to the southeast along with the structural graben. Lake deposits extend back into the late Miocene, and are underlain by older basalts that are best known from deep drill core. High-temperature rhyolite lavas that mark the onset of extension also become younger to the southeast. Because the western SRP lies at an acute angle to the track of North American plate motion, it cannot be related to passage of North America over a fixed hotspot in any simple way.

Basaltic volcanism in the western SRP occurred in two distinct episodes. The first episode, represented by samples from a deep drill core near Mountain Home and by older surface outcrops that sit directly on rhyolite, is characterized by ferrobasalts that are distinct from other SRP basalts. The second episode is represented by surface flows of Pleistocene age that are intercalated with or overlie lacustrine and deltaic sediments of Lake Idaho. These basalts are associated with young faults that reflect basin and range extension. The younger basalts are similar to young basalts of the ESRP, but are generally more Fe-rich; they are distinct from lavas of the Basin and Range province in Nevada and elsewhere. At the SE end of our transect, in the Bruneau-Jarbridge eruptive center, younger basalts with western SRP affinities (e.g., Salmon Falls Butte) are chemically distinct from older basalts associated with formation of the eruptive center and the eastern SRP chemical trend.

Our data suggest that the western SRP graben represents an aulocogen-like structure formed in response to thermal tumescence above the Yellowstone plume head (?) as it rose under eastern Oregon and Washington, during and after eruption of the Columbia River Plateau and Steens Mountain basalts. The plume head was deflected northwards either by subduction of the Farallon plate (Geist and Richards, 1993) or by impingement of North American plate lithosphere (Camp, 1995). Basaltic volcanism in the western SRP may be related to the flow of depleted plume-source mantle along a sublithospheric conduit beneath the western SRP graben from the Columbia River Plateau toward the plume track. The basalts would form by pressure-release melting of this previously depleted material, along with the overlying mantle lithosphere. The younger volcanic episode apparently formed in response to basin and range extension, in a fashion analogous to young basaltic volcanism in the eastern SRP. The source of these basalts is uncertain, but may be plume-modified subcontinental lithosphere.

Well-characterized basalts from the Snake River Plain (SRP) were analyzed for Pb, Sr, and Nd isotopes. The purpose was to test the proposed connection between the Yellowstone Plume and the volcanic rocks of the SRP. Such a connection implies that the SRP basalts should display chemical and isotopic compositions that vary in response to plume dynamics and interactions with the overlying sub continental mantle lithosphere (SCML). The spatial and temporal variation of 28 basalts from INEL WO-2 core site in the northern SRP, 19 basalts from the

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Bruneau-Jarbridge and 5 basalts from the King Hill areas (B-J) in the central SRP, and 16 basalts from the Steens Mountain area (located between the Columbia River Basalt (CRB) province and McDermitt caldera in southwest Oregon, in collaboration with J. Johnson and P. Hooper) have been analyzed for Pb, Sr, and Nd isotopes. The Pb, Nd, Sr isotope relationships for the SRP basalts can be interpreted to define a mixing array between SCLM sources and a mantle source similar to OIB/plume mantle sources (Fig.1). The high $^3\text{He}/^4\text{He}$ ratios found along the plume track at Yellowstone and in the CRB and SRP support the interpretation that the SRP basalts represent regularly varying interaction of the Yellowstone plume with the SCML (Craig et al., 1978; Kennedy et al., 1985; Poreda and Cerling, 1992; Dodson et al., 1997). Spatial (and temporal) isotope variation along the SRP from the B-J area to Yellowstone is characterized by decreasing $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ and increasing $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. The average Pb, Sr, and Nd isotope ratios for locations along the SRP between the B-J area and Yellowstone are linearly

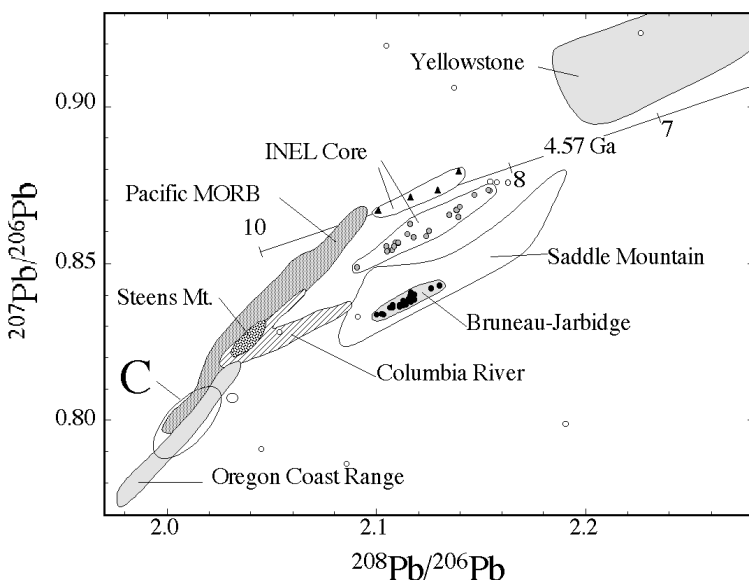


Figure 1. The SRP sub-populations (Bruneau-Jarbridge and INEL core) define linear arrays in $^{207}\text{Pb}/^{206}\text{Pb}$ - $^{208}\text{Pb}/^{206}\text{Pb}$ space between plume sources represented by the common plume component C (Hanan & Graham, 1996) and SCML mantle sources of varying age (Mesozoic – Archean). Published data for Yellowstone (Doe et al., 1982), CRB, and Saddle Mountains are shown for comparison (Tatsumoto and Snaveley, 1969; Church, 1985; Chamberlain & Lambert, ; Hooper and Hawkesworth, 1993; Carlson, 1984). The open circles represent SRP crustal xenoliths (Leeman et al., 1982). The 4.57 Ga geochron is shown for reference.

correlated with the square of the distance from the Yellowstone volcanic field. This suggests that the proportion of SCLM to plume source increases from west to east. The Pb isotopes for the Steens Mt. Basalts are consistent an oceanic-like mantle source.

Publications Resulting From This Project

Articles

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Shervais, J.W., Vetter, S.K., and Hanan, B.B. "Chemical stratigraphy of the WO-2 and NPR-E Deep drill cores, INEEL: Four million years of basaltic volcanism in the eastern Snake River Plain" *in preparation*.

Abstracts

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- Vetter, S., Shervais, J. (1997) Basaltic Volcanism of the Bruneau-Jarbidge Eruptive Center, Southwest, Idaho. Geol. Society America, Abstracts w/Programs, 29/6, A298.

Geologic Mapping

Eight USGS 7.5' quadrangles, all located in the Mountain Home area of Idaho, were mapped as part of this study: Mountain Home North, Mountain Home South, Teapot Dome, Crater Rings, Cinder Cone, Cinder Cone Reverse, and Cinder Cone Butte. Six quadrangles were mapped in the Shoshone area in 1998 and 1999 with USGS EDMAP funding (Dietrich, Dietrich Butte, Owinza, Owinza Butte, Star Lake, and Shoshone SW). In the Mountain Home area, the resulting composite map spans 30' of longitude (W115°30' to W116°0') and 15' of latitude (N43°0' to N43°15'), encompassing about 450 square miles (1,170 square kilometers). All of these map products have been prepared digitally using the GIS system MapInfo, which is fully compatible with ArcInfo and complies with Federal GIS standards. All of the completed maps will be assembled for publication by the Idaho Geological Survey as Technical Reports at 1/24,000 scale; the Mountain Home 30'x15' maps will also be compiled for publication as a Map Series map at approximately 1/50,000 scale. In addition, portions of quadrangles were mapped in the Mount Bennett Hills area as part of the Centenary College RUI effort: Deer Heaven Mountain 7.5', Dempsey Meadows 7.5', King Hill 7.5', Hog Creek 7.5', Davis Mountain SW 7.5'.

Graduate Student Research:

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|------------------|---|
| Meghan Zarnetske | Continental Volcanism in the western Snake River Plain, Idaho, <i>M.Sc. Thesis, in progress, 2004.</i> |
| Ruth Hobson | Remote sensing of basaltic volcanics, Central Snake River Plain, Idaho, <i>M.Sc. Thesis, in progress, 2004.</i> |
| Matthew Cooke | Petrology, Geochemistry, and Hydrology of basaltic volcanism, Central Snake River Plain, Idaho, <i>M.Sc., 1999.</i> |
| Scott Matthews | Petrology and Geochemistry of plume-related basaltic volcanism, Central Snake River Plain, Idaho, <i>M.Sc., 2000.</i> |

Summary of Research Projects

Island Arcs and Accreted Terranes

The formation of island arcs and their accretion to continental margins is the most fundamental process forming continental crust since the Archean. I am currently studying the formation and evolution of accreted arc terranes in two main areas, the Carolina arc terrane in the southern Appalachians, and the Kohistan arc terrane of NW Pakistan. I have also been involved in projects examining arc rocks in other parts of the world, including the Sierra Nevada Foothills of California and the Greater Caucasus Mountains of southern Russia.

The Carolina Terrane and a related Neoproterozoic Arc Complex Beneath the Atlantic Coastal Plain, South Carolina: The Savannah River Site Terranes

The hinterland of the Southern Appalachians, which lies SE of Grenville basement exposed in the Blue Ridge province, comprises a complex mosaic of exotic terranes of uncertain provenance. These terranes include (from NW to SE) the Inner Piedmont, the Carolina terrane (including the Carolina slate belt), and the Raliegh belt. Further to the SE, crystalline basement of the Laurentian margin is largely concealed beneath several kilometers of Mesozoic and Cenozoic sedimentary rocks, commonly referred to as the Atlantic Coastal Plain. The distribution and geologic history of this hidden crystalline basement can be inferred only on the basis of limited exposures at the margins of the Coastal Plain onlap, aeromagnetic lineaments that define basement trends in the subsurface, and core data from wells that penetrate basement.

Over the last 35 years more than 8000 meters of basement core has been recovered from 26 deep wells at the Department of Energy's Savannah River Site. This core provides the only known exposure of basement terranes that lie SE of the Carolina terrane in central South Carolina, beneath Cretaceous and Tertiary sediments the Atlantic Coastal Plain. Core from these wells, along with structural trends defined by aeromagnetic lineaments, allow us to define four distinct units within the basement beneath the Coastal Plain: (1) the Crackerneck metavolcanic complex, (2) the Deep Rock metaigneous complex, (3) the Pen Branch metaigneous complex, and (4) the Triassic Dunbarton basin series.

The Crackerneck Metavolcanic Complex underlies the NW quarter of the site. It is dominated by intercalated mafic greenstones, felsic tuffs, and lapilli tuffs, all metamorphosed under lowermost greenschist to subgreenschist facies conditions. The Deep Rock metaigneous complex consists of two units: the Deep Rock metavolcanic suite and the DRB1 metaplutonic suite. The Deep Rock Metavolcanic Complex comprises mafic to felsic metavolcanic rocks that have been metamorphosed under middle to upper amphibolite facies conditions. The DRB1 metaplutonic suite includes hornblende diorites, hornblende quartz diorites, and tonalites. Rocks of the Deep Rock metaigneous complex were metamorphosed under upper greenschist to lower amphibolite facies conditions. The Pen Branch metaigneous complex also consists of two units: the Pen Branch Metavolcanic suite (amphibolites, garnet amphibolites, and garnet-biotite schists, all metamorphosed under upper amphibolite to lowermost granulite facies conditions), and the PBF Metaplutonic suite. The PBF Metaplutonic suite were originally granodiorites metamorphosed under upper amphibolite to lower granulite facies conditions, but many metaplutonic rocks of this suite have undergone extensive hydrothermal alteration under greenschist facies conditions, during which potassic fluids infiltrating along fractures replaced calcic feldspar with K-feldspar, causing severe depletion of CaO and Sr, addition of K₂O and SiO₂, and coloring the rocks bright pink.

All of the metaplutonic and metavolcanic rocks have calc-alkaline fractionation trends, consistent with formation in active, subduction-related arc terranes. Reported crystallization ages of ≈ 619 Ma (Deep Rock Metaigneous complex) to ≈ 626 Ma (Pen Branch Metaigneous complex), however, show that these rocks do not correlate with accreted arc rocks that lie closer to the Grenville margin (Carolina terrane) because the latter are too young (≈ 535 to 570 Ma). The Crackerneck Metavolcanic complex may however, correlate with rocks of the Carolina Slate belt (Persimmon Fork formation). These ages may indicate that rocks of Deep Rock and Pen Branch metaigneous complexes are a continuation of Proterozoic basement which lies beneath, and is the older infrastructure of, the Carolina arc. This may also indicate that the contact between Crackerneck Metavolcanic Complex (\approx Persimmon Fork Formation) and Deep Rock/Pen Branch metaigneous complexes is equivalent to the angular unconformity between the Uwharrie Formation and the Virgilina sequence. Based on their compositions and ages, we tentatively correlate these rocks with the Hyco Formation in southern Virginia and central North Carolina. The Hyco Formation forms the infrastructure of the Carolina terrane in Virginia and North Carolina, where it was affected by the circa 600 Ma "Virgilina" orogeny. The Deep Rock/Pen Branch arc may represent the infrastructure of the Carolina slate belt in South Carolina, detached by later tectonic events, or it may represent late Proterozoic arc infrastructure from another location in the arc that has been moved into its current location by transcurrent motions.

Summary of Research Projects

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- Allen J. Dennis, **John W. Shervais**, Joshua Mauldin, and Harmon D. Maher, Jr., 2004, Petrology and Geochemistry of Neoproterozoic Volcanic Arc Terranes Beneath the Atlantic Coastal Plain, Savannah River Site, South Carolina, *Geological Society of America Bulletin*, v 116, 572–593.
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- Dennis, A.J., Secor, D.T., and Shervais, J.W., 2001, Constraints on Assembly of the Carolina Composite Terrane In The Southern Appalachian Piedmont: Role of Eclogite-High-P Granulite Facies Rocks in Central South Carolina, Geological Society of America, Abstracts with Programs, 33/6, A263.
- Dennis, A.J., and Shervais, J.W., 2001, Recognizing a terrane boundary internal to the Carolina composite terrane, southern Appalachian Piedmont: Eclogite-granulite facies metamorphism north of the Carolina slate belt-Charlotte belt boundary: Geological Association of Canada- Mineralogical Society of Canada Programs, v. 26, p. 27.
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- Shervais, J.W., Dennis, A.J., Secor, D.T., and McGee, J.J., 2000, Tectonic Setting of the Newberry Eclogite/Granulite And Its Implications For the Origin of the Carolina Composite Terrane. Geological Society of America, Abstracts with Programs, 32/2, A73.
- Dennis, A.J., Wright, J.E., Maher, H.D., Mauldin, J.C., and Shervais, J. (1997) Repeated Phanerozoic Reactivation of a Southern Appalachian Fault Zone Beneath the Up-Dip Coastal Plain of South Carolina. Geol. Society America, Abstracts w/Programs, 29/6, A223.
- Mauldin, J.C., Shervais, J., Dennis, A.J. (1997) Petrologic and Structural Constraints on the Classification of Crystalline Basement Beneath the Savannah River Site, S.C. Geol. Society America, Abstracts w/Programs, 29/6, A455.

Masters Theses

- Joshua Mauldin, Petrology and Geochemistry of Crystalline Basement from a Neoproterozoic Volcanic Arc, Savannah River Site, South Carolina, *M.Sc. Thesis*, 1997.
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Summary of Research Projects

High-Pressure Granulite and Eclogite Facies Metamorphism in the Carolina Arc Terrane: Implications for Pre-Alleghanian Collision Tectonics in the Southern Appalachians

The eastern margin of North America in the southern and central Appalachians comprises a tectonic collage of terranes that formed in locations exotic to Laurentia during the late Neoproterozoic through early Paleozoic, and were subsequently accreted to Laurentia during the mid- to late Paleozoic. These exotic terranes evolved independently of Laurentia for much of their existence, and preserve evidence of orogenic and magmatic events that are not observed in Laurentia. One of the most extensive of these exotic peri-Gondwana terranes is the Carolina terrane, which comprises a large portion of the southern Appalachian orogen east of the Blue Ridge province. The Carolina terrane is an exotic Avalonian terrane that formed adjacent to Gondwana in the late Neoproterozoic, and was not accreted to Laurentia until the mid- to late Paleozoic.

The central part of the Carolina terrane in western South Carolina comprises a 30 to 40-km wide zone of high grade gneisses that are distinct from greenschist facies metavolcanic rocks of the Carolina slate belt (to the SE) and amphibolite facies metavolcanic and metaplutonic rocks of the Charlotte belt (to the NW). This region, termed the Silverstreet domain, is characterized by penetratively deformed felsic gneisses, granitic gneisses, and amphibolites. Mineral assemblages and textures suggest that these rocks formed under high-pressure metamorphic conditions, ranging from eclogite through high-P granulite to upper amphibolite facies.

Mafic rocks occur as amphibolite dikes, as meter-scale blocks of coarse-grained garnet-clinopyroxene amphibolite in felsic gneiss, and as residual boulders in deeply weathered felsic gneiss. Inferred omphacite has been replaced by a vermicular symplectite of sodic plagioclase in diopside, consistent with decompression at moderate to high temperatures and a change from eclogite to granulite facies conditions. All samples have been partially or wholly retrograded to amphibolite assemblages. We infer the following P-T-t history: (1) eclogite facies P-T conditions at $T \approx 650\text{-}730^\circ\text{C}$, $P \geq 1.4$ GPa, (2) high-P granulite facies P-T conditions at $T \geq 700\text{-}800^\circ\text{C}$, $P \approx 1.2\text{-}1.5$ GPa, (3) retrograde amphibolite facies P-T conditions at $T \approx 720\text{-}660^\circ\text{C}$ and $P \approx 0.9\text{-}1.2$ GPa. This metamorphic evolution must predate intrusion of the 415 Ma Newberry granite and must post-date formation of the Charlotte belt and Slate belt arcs (≈ 620 Ma to 550 Ma).

Comparison with other medium temperature eclogites and high pressure granulites suggest that these assemblages are most likely to form during collisional orogenesis. Eclogite and high-P granulite facies metamorphism in the Silverstreet domain may coincide with a $\approx 570\text{-}535$ Ma event documented in the western Charlotte belt or to a late Ordovician-early Silurian event. The occurrence of these high-P assemblages within the Carolina terrane implies that, prior to this event, the western Carolina terrane (Charlotte belt) and the eastern Carolina terrane (Carolina Slate belt) formed separate terranes. The collisional event represented by these high-pressure assemblages implies amalgamation of these formerly separate terranes into a single composite terrane prior to its accretion to Laurentia.

Work is continuing on these rocks to determine their ages, using Sm-Nd isotope systematics and two-point garnet-whole rock isochrons, and to determine the ages of co-facial gneisses that host the boudins, using U-Pb zircon analyses. This work is being carried out by Dennis in conjunction with Professor Scott Samson of Syracuse University. Zircons separated from the co-facial gneisses will also be examined for inclusions of ultra-high pressure minerals such as coesite. The age constraints will allow us to correlate terrane amalgamation in the Carolina terrane to metamorphic and deformational events that have been documented there already.

Publications resulting from this project:

Shervais, J.W., Dennis, A.J., McGee, J.J., and Secor, D.T., 2003, Deep in the heart of Dixie: Pre-Alleghanian eclogite and HP granulite metamorphism in the Carolina terrane, South Carolina, USA. *Journal of Metamorphic Geology*, 21 (1): 65-80.

Dennis, A.J., **Shervais, J.W.**, and Secor, D.T., Jr., 2000, Newberry, South Carolina Eclogite: Structural setting and style of occurrence, in A. Wyeth (editor) *A Compendium of Field Trips of South Carolina Geology*, South Carolina Department of Natural Resources, Geological Survey, 29-38.

(Continued on following page)

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Abstracts resulting from this project:

- Dennis, A.J., Secor, D.T., and **Shervais, J.W.** (2001) Constraints on Assembly of the Carolina Composite Terrane In The Southern Appalachian Piedmont: Role of Eclogite-High-P Granulite Facies Rocks in Central South Carolina, Geological Society of America, Abstracts with Programs, 33/6, A263.
- Dennis, A.J., and **Shervais, J.W.** (2001) Recognizing a terrane boundary internal to the Carolina composite terrane, southern Appalachian Piedmont: Eclogite-granulite facies metamorphism north of the Carolina slate belt-Charlotte belt boundary: Geological Association of Canada- Mineralogical Society of Canada Programs, v. 26, p. 27.
- Dennis, A.J., **Shervais, J.W.**, McGee, J. and Secor, D.T., Jr. (2000) Recognizing a terrane boundary internal to the Carolina composite terrane, southern Appalachian Piedmont: Eclogite-granulite facies metamorphism north of the Carolina slate belt-Charlotte belt boundary: Geological Society of America Abstracts with Programs, v. 32/7, A234-A235.
- Dennis, A.J., **Shervais, J.W.**, and Secor, D.T. (2000) Faults bounding eclogite-bearing gneisses, Newberry, South Carolina: Geological Society of America Abstracts with Programs, v. 32/2, A-14.
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Data and Collections:

All of the samples collected in the course of this project are now stored and curated at the University of South Carolina in Aiken, South Carolina. This collection includes samples of the eclogites and amphibolites, along with samples of the co-facial gneisses. Many of these samples were collected by drilling with a 1" portable drill to allow sampling of polished stream outcrops where hammer samples would be impossible to collect, or of boudins that would be destroyed by hammer sampling.

We also mapped all or parts of five USGS 7.5' quadrangles as part of this study. Two quads were completely mapped (Blair and Whitmire south) and three quads were mapped north of the slate belt boundary fault (Chappells, Prosperity, Silverstreet); the southern parts of these quads had already been mapped. This maps will be compiled with existing adjacent maps for publication by the South Carolina Geological Survey.

Summary of Research Projects

The Kohistan Island Arc Terrane and Adjacent Rocks of the Subjacent Indian Plate, NW Pakistan: Formation and Evolution of a Complex Collisional Orogen

The Kohistan arc terrane of the western Trans-Himalaya exposes a remarkable cross-section through an island arc sequence which developed as a result of the northward subduction of neo-Tethyan oceanic crust beneath Asia during late Jurassic and early Cretaceous times. The arc terrane is bounded by two major faults: the Northern Suture or Main Karakoram Thrust in the north and the Indus-Tsangpo Suture or Main Mantle Thrust in the south. These faults separate arc rocks of the Kohistan terrane from continental rocks of Asia to the north and the Indo-Pakistan continent to the south. Both the Main Mantle Thrust and Main Karakoram Thrust are characterized by discontinuous outcrops of blueschist and ophiolite in serpentinite or shale-matrix melange .

Recent tectonic models for the development of the western Trans-Himalaya suggest that the Kohistan-Ladakh terrane, which began as an intra-oceanic island arc in the late Jurassic, became a continental Andean-type arc on the southern margin of the Asiatic plate after the closure of a small back arc basin along the Main Karakoram Thrust in the mid Cretaceous (≈ 100 Ma). Continued northward subduction of the Tethyan lithosphere led to development of a "successor arc" in the late Cretaceous to late Paleocene, built upon the accreted Mesozoic arc. Initial closure of the Neo-Tethys ocean occurred circa 50 to 55 Ma, followed by underthrusting of Indo-Pakistan beneath Asia along the Main Mantle Thrust.

The Dir-Utror volcanics represent a continental margin arc assembled along the southern border of Asia after collision of the Mesozoic Kohistan island arc and its subsequent amalgamation to the mainland. Detailed geologic mapping shows that in the region around Dir the Dir-Utror volcanic series is dominated by mafic to intermediate composition rocks derived from LREE-enriched mantle beneath the arc. The high proportion of high-MgO basalts (12% areally) is similar to that observed in the Aleutian arc. The scarcity of more evolved felsic volcanics (dacite, rhyolite) can be explained by the nature of the underlying crust, which consists of accreted intra-oceanic arc volcanic and plutonic rocks, and is mafic relative to normal continental margins.

Most felsic volcanics (rhyolites, dacites) have REE systematics that are consistent with the hypothesis that they formed by fractional crystallization of more mafic basaltic andesites. Magma-mixing of low-MgO basalt with rhyolite or dacite does not seem to be important in this volcanic series, although this process appears to be common in the southern Andes . Some andesites may have formed as crustal melts, based on their high LILE contents, high La/Lu, and deep negative Eu anomalies. The REE pattern for one of these andesites crosses the chondrite-normalized patterns of dacites and rhyolites, showing that these rocks cannot be related by fractional crystallization, assimilation, or magma-mixing. The REE systematics of these andesites are compatible with an origin by crustal anatexis, leaving a refractory residue mineralogically similar to high pressure mafic and ultramafic granulites of the Jijal complex.

The northern margin of the Indian plate in NW Pakistan was deformed and metamorphosed to amphibolite facies conditions during its collision with Asia and the Kohistan arc terrane. The locus of this collision is the lower Swat region, just south of the confluence of the Swat and Indus Rivers. Rocks assigned here to the Lower Swat terrane include basement gneiss (the Swat Gneisses), a detached "cover sequence" of metasediments (the Alpurai Group), and the Manglaur thrust zone, a schuppenzone composed of imbricated slices of Swat Gneisses and Alpurai Group metasediments that underlies the more coherent units. Many of the tectonic contacts within and between these units have been intruded by sills of syntectonic tourmaline granite. Counter-clockwise rotation of India after its collision with Asia resulted in west-vergent thrusting, duplex formation, and doming of the earlier thrust sheets.

Petrography, microprobe-generated X-ray maps of chemical zoning in garnets, and garnet zoning profiles all indicate a multi-stage garnet growth history in paragneisses of Lower Swat terrane. Thermobarometry calculations indicate that garnet cores formed at lower temperatures, followed by progressively higher temperatures and pressures for subsequent garnet generations. These P-T estimates show that paragneisses of the Lower Swat terrane developed during two stages of prograde metamorphic growth under amphibolite to upper amphibolite facies conditions. The second phase of garnet growth was followed by retrograde metamorphism to greenschist facies conditions.

Correlation of the structural-tectonic history with the P-T estimates and garnet growth history suggest that during the initial collision of India and Asia around 55-45 Ma, the Lower Swat terrane was subducted underneath the Kohistan island arc terrane to a depth of ≈ 30 -35 km, forming the first generation of garnets. Counterclockwise rotation of India at ≈ 45 Ma caused a temporary hiatus in subduction and resulted partial exhumation of the Lower Swat terrane, and partial resorption of the G1 garnets. Continued convergence with Asia, along with

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counterclockwise rotation of India, caused renewed subduction of India under the Kohistan arc terrane and resulted in widespread intrusion of tourmaline leucogranite along all active tectonic boundaries, and west-vergent thrusting and imbrication in the Indian plate margin. The second generation garnets are the result of this event. The extreme margins of G2 garnet and the widespread retrograde mineral assemblages result from rapid uplift and unroofing of the lower Swat terrane during extensional unroofing of the orogen along high-angle normal faults.

Doctoral Dissertations

Imtiaz Ahmad, Collision Tectonics in NW Himalaya: Structure, Stratigraphy, and P-T path of the India Plate, Lower Swat, North Pakistan, *Ph.D. Dissertation.*, 1999.

M.U.K. Khattak, Petrology And Stable Isotope Geochemistry of the Nanga Parbat-Haramosh Massif, Northern Pakistan, *Ph.D. Dissertation*, 1995.

M. Tahir Shah, Geochemistry, Mineralogy, and Petrology of the Sulfide Mineralization and Associated Rocks in the Area around Besham and Dir, Northern Pakistan, *Ph.D. Dissertation*, 1991.

Publications Resulting From This Project:

Shah, M.T. and **Shervais, J.W.**, (1999) The Dir-Utror metavolcanic sequence, Kohistan arc terrane, northern Pakistan. *Journal of Asian Earth Sciences*, 17/4, 459-475.

Shah, M.T. and **Shervais, J.W.** (1997) Oxygen isotope geochemistry of the Dir metavolcanic sequence and associated copper mineralization in Kohistan arc terrane, northern Pakistan. *The Nucleus*, 34, 49-55.

Khattak, M.U.K., Stakes, D.S., and **Shervais, J.W.** (1995) P-T-t paths of garnets from the Nanga Parbat-Haramosh massif, the Kohistan and the Ladakh island arc terranes, northern Pakistan. *Geol. Bull. Univ. Peshawar*, 28, 97-108.

Khattak, M.U.K., Stakes, D.S., **Shervais, J.W.**, Arif, M., and Shah, M.T. (1995) Stable isotope thermometry of the Nanga Parbat-Haramosh massif and the Kohistan-Ladakh island arc, northern Pakistan. *Geol. Bull. Univ. Peshawar*, 28, 109-126.

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Shah, M.T., Ikramuddin, M., and **Shervais, J.W.** (1994) Behaviour of Tl relative to K, Rb, Sr, and Ba in mineralized and unmineralized metavolcanics from the Dir area, northern Pakistan, *Mineralum Deposita*, 29, 422-426.

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Summary of Research Projects

Metasomatism and Magma Evolution in the Upper Mantle

Understanding the origin and evolution of continental lithosphere is a fundamental goal of solid earth geophysics, which seeks to characterize the material properties and physical state of the Earth. This goal is important because continental lithosphere records the bulk of Earth history and because a rigid lithosphere is central to plate tectonics. Although the lithosphere is defined by its physical properties, it must consist of real rocks with distinct petrologic origins and geochemical characteristics. Field-based petrologic and geochemical studies are paramount to our goal of understanding lithosphere evolution because they provide the ultimate “ground truth” for broader scale geophysical experiments that can only infer regional scale structures and average physical properties.

Most basalts erupted at the Earth's surface originate by partial melting of the Earth's upper mantle. The chemical and isotopic composition of magmas erupted in different tectonic settings reflect differences in mantle composition, in melting process, and in subsequent magma evolution. Understanding the roles of metasomatism (which modifies mantle composition) and magma evolution (which modifies the resulting melts) is crucial to our understanding of how the Earth evolves chemically and thermally through time.

The projects listed here approach the question of mantle composition and evolution from two different perspectives: first, by looking at rocks which compose the upper mantle, as exposed in alpine peridotite massifs, and second, by looking at the partial melts (volcanic rocks) which form from this mantle. These projects are related in many ways to our work in the Snake River Plain of southern Idaho.

Publications Resulting From This Project

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Master's Theses:

Richard A. Cooke, Compositional effects of Mantle Metasomatism in Alpine Peridotites, *M.Sc. Thesis*, 1992.

Ilona Lawless, Petrology, Chemistry, and Petrogenesis of alkaline volcanic and plutonic rocks from Tahiti, French Polynesia, *M.Sc. Thesis*, 1990.

Summary of Research Projects

Petrogenesis of the Lunar Highlands Crust

Deciphering the origin and evolution of the lunar highland crust is crucial to our understanding of the Moon's early magmatic history and, by inference, the early history of other terrestrial planets. My current work on lunar samples focuses on analyzing the major and trace element composition of primary cumulus phases in lunar highlands crust using the electron microprobe and Secondary Ion Mass Spectrometry (ion microprobe). These data can be inverted using equilibrium crystal/liquid partition coefficients to calculate possible parent magma compositions. These data offer new insights into the evolution of the moon's crust and into the general processes of cumulate rock formation.

The central focus of our work over the last four years has been the elucidation of processes and magma suites that formed the western highlands crust. Our work at the Apollo 14 site focused on the two largest groups of post-magma ocean igneous rocks, the Mg-suite and the alkali suite, using electron microprobe and ion microprobe studies of mineral chemistry, whole rock geochemistry, and new petrologic observations of existing samples. We have adopted the use of Moore County achondrite as a plagioclase standard for SIMS analysis (after Papike and others, 1996), which has allowed us to complete two major manuscripts on the REE geochemistry of the Mg-suite and alkali suite parent magmas (Shervais and McGee, 1998a, *Geochimica Cosmochimica Acta*, vol. 62, p. 3009-3023, and Shervais and McGee, 1999b, *American Mineralogist*, vol. 84, #5/6, p. 806-820). We have completed a major review of highland lithologies at the Apollo 14 site, including new whole rock major element geochemistry for nine highlands clasts, and integrating our new data on the Mg-suite and alkali suite parent magmas (Shervais and McGee, 1999a, *Journal of Geophysical Research*, vol. 104, #E3, p. 5891-5920). We have also published a shorter review of western highlands petrology as part of the Larry Taylor memorial (Shervais, 1999, *International Geology Review*, vol. 41, p. 141-153). These publications include our first attempts at constraining the Mg-suite and alkali suite parent magmas, and modeling their evolution. This work is still incomplete because it is not yet clear which forward modeling programs are most appropriate for lunar highlands compositions (McGee and Shervais, 1998a).

The Mg-suite is an enigma because rocks of this suite exhibit both refractory mineral chemistry (indicating a primitive parent magma) and high concentrations of KREEPy incompatible elements (indicating an evolved parent magma). Previous ion probe studies of this suite were confined to the relatively evolved norites (Papike et al, 1994, 1996). Our study is the first and only SIMS investigation to focus on primitive Mg-suite troctolites and anorthosites (Fo87-90, An94-96). Our data show that primitive cumulates of the Mg-suite crystallized from magmas with REE contents $\approx 1.5x$ to $2x$ high-K KREEP in concentration, and relative REE abundance patterns similar to KREEP. The data do not support models for crustal metasomatism to enrich the Mg-suite cumulates after formation, or models which call for a superKREEP parent to the troctolites and anorthosites (Shervais and McGee, 1998a).

We have also begun modeling Mg-suite formation and evolution. Our data, and previous work on this suite, suggest that Mg-suite parent magmas must have ultramagnesian komatiitic compositions that are relatively high in both Ca and Al (Hess, 1994; Shervais and McGee, 1999a). The most likely source of these magmas is partial melting of the primitive lunar interior, followed by buffering to high Mg contents in rising diapirs of early lunar magma ocean cumulates (Shervais and McGee, 1999a). We also suggest that the Mg suite may evolve along two distinct crystal lines of descent, depending on the depth of intrusion: deep crustal intrusions may form px-bearing troctolites and Mg anorthosites with high mg', while shallow intrusions form the series dunite-troctolite-gabbro-norite, with lower mg' troctolites (Shervais and McGee, 1998a, 1999a).

The alkali suite has more evolved mineral compositions than the Mg-suite, but similar whole rock incompatible element concentrations. Our SIMS data show that plagioclase-rich cumulates of the alkali suite crystallized from magmas with high REE concentrations ($\approx 0.7x$ to $\approx 2.2x$ high-K KREEP) that were fractionated relative to high-K KREEP (La/Lu $\approx 2x$ high-K KREEP), had small positive Eu anomalies relative to KREEP, and were enriched in plagiophile elements (Shervais and McGee, 1998b). The alkali suite parent magma may be related to the Mg-suite parent magma, but these magmas cannot be related by simple fractional crystallization as suggested by Snyder et al. (1995a). Our data suggest that the alkali suite parent magma may have originated as a KREEPy melt, but it was modified by anorthosite assimilation, fractionating the REE and enriching the resulting hybrid magma in Eu and other plagiophile elements (Shervais and McGee, 1998b, 1999a). This is the first published SIMS data for any alkali suite rocks (aside from various LPSC abstracts by the PI, and an abstract by Snyder et al, 1994).

We have developed a new model for the formation of alkali suite anorthosites and norites, based on our SIMS data and on fundamental petrologic observations, in which the assimilation of calcic anorthosite forces the crystallization of additional sodic plagioclase. In diopside-saturated ternary systems, assimilation of calcic plagioclase will force

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the hybrid melt into the plagioclase-only volume along isotherms that slope towards albite. Subsequent crystallization will result in plagioclase that is more sodic than crystals formed immediately prior to assimilation, and the volume of melt will decrease rapidly as the assimilated calcic plagioclase reacts with the liquid to form more sodic equilibrium feldspar (Shervais and McGee, 1998b,c, 1999a). Because of the low REE contents of ferroan anorthosite plagioclase, we conclude that the assimilant must have been older Mg-suite anorthosite or even troctolite, where the dense mafic phases would settle out of the system while plagioclase would float and digest slowly into the melt. We are currently preparing a manuscript for publication which develops this model more fully.

We have also found direct evidence for magma mixing in one alkali suite anorthosite (Shervais and McGee, 1998d). The mixing of primitive magma with a more evolved magma has distinct petrologic manifestations that are easily distinguished from those produced by the assimilation of crystalline rocks. In particular, the occurrence of reverse zoning in early-formed crystals is characteristic of magma mixing, but does not occur during assimilation because the assimilant cannot raise the temperature of the hybrid magma above its pre-assimilation value. There is some suggestion that the magma mixing we have observed involves mixing of an Mg-suite magma into an alkali suite magma. Alternately, an evolved alkali suite magma may have mixed with a primitive alkali suite parent magma – perhaps during convective overturn of a zoned magma chamber. Injection of hot primitive melt into the magma chamber may have induced this convective overturn, with mixing between the primitive magma and the evolved magma already resident in the chamber (Shervais and McGee, 1998d).

Publications Resulting From This Project (Since 1988)

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Summary of Research Projects

Extended Abstracts & Abstracts (1997 to 2004 only)

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- Shervais, J.W.**, 2000, Origin of the Lunar Highlands: Fundamental Petrologic Concepts. Geological Society of America, Abstracts with Programs, 32/2, A73.
- Shervais, J.W.** and McGee, J.J., 1999, Ancient Crust Formation at the Apollo 14 Site. in *Lunar and Planetary Science XXX*, Abstract #1750, Lunar and Planetary Institute, Houston (CD ROM).
- Shervais, J.W.** and McGee, J.J., 1998a, Alkali suite anorthosites and norites: Flotation cumulates from pristine KREEP with magma mixing and the assimilation of older anorthosite. in *Lunar and Planetary Science XXIX*, Abstract #1699, Lunar and Planetary Institute, Houston (CD ROM).
- Shervais, J.W.** and McGee, J.J., 1998b, Magma mixing in the petrogenesis alkali suite anorthosites: reverse zoning in plagioclase, 14305,303. in *Lunar and Planetary Science XXIX*, Abstract #1706, Lunar and Planetary Institute, Houston (CD ROM).
- Shervais, J.W.** and McGee, J.J., 1998c, Major element geochemistry of Apollo 14 highland clasts by fused bead electron microprobe analysis: 14305 and 14321. in *Lunar and Planetary Science XXIX*, Abstract #1709, Lunar and Planetary Institute, Houston (CD ROM).
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