KECK GEOLOGY CONSORTIUM

PROCEEDINGS OF THE TWENTY-SECOND ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

April 2009
Franklin & Marshall College, Lancaster PA.

Dr. Andrew P. de Wet, Editor
Keck Geology Consortium Director
Franklin & Marshall College

Dr. Stan Mertzman
Symposium Convenor
Franklin & Marshall College

Kelly Erb
Keck Consortium Administrative Assistant

Diane Kadyk
Academic Department Coordinator
Department of Earth & Environment
Franklin & Marshall College

Keck Geology Consortium
Franklin & Marshall College
PO Box 3003, Lancaster PA 17604-3003
717 291-4132 keckgeology.org

ISSN # 1528-7491

The Consortium Colleges National Science Foundation

KECK GEOLOGY CONSORTIUM
PROCEEDINGS OF THE TWENTY-SECOND ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

ISSN# 1528-7491

April 2009

Andrew P. de Wet
Editor & Keck Director
Franklin & Marshall College

Keck Geology Consortium
Franklin & Marshall College
PO Box 3003, Lanc. Pa, 17604

Stan Mertzman
Symposium Convenor
Franklin & Marshall C.

Keck Geology Consortium Member Institutions:
Amherst College, Beloit College, Carleton College, Colgate University, The College of Wooster, The Colorado College Franklin & Marshall College, Macalester College, Mt Holyoke College, Oberlin College, Pomona College, Smith College, Trinity University Union College, Washington & Lee University, Wesleyan University, Whitman College, Williams College

2008-2009 PROJECTS

THE BLACK LAKE SHEAR ZONE: A POSSIBLE TERRANE BOUNDARY IN THE ADIRONDACK LOWLANDS (GRENVILLE PROVINCE, NEW YORK)
Faculty: *WILLIAM H. PECK*, *BRUCE W. SELLECK* and *MARTIN S. WONG*: Colgate University
Students: *JOE CATALANO*: Union College; *ISIS FUKAI*: Oberlin College; *STEVEN HOCHMAN*: Pomona College; *JOSHUA T. MAURER*: Mt Union College; *ROBERT NOWAK*: The College of Wooster; *SEAN REGAN*: St. Lawrence University; *ASHLEY RUSSELL*: University of North Dakota; *ANDREW G. STOCKER*: Claremont McKenna College; *CELINA N. WILL*: Mount Holyoke College

PALEOECOLOGY & PALEOENVIRONMENT OF EARLY TERTIARY ALASKAN FORESTS, MATANUSKA VALLEY, AL.
Faculty: *DAVID SUNDERLIN*: Lafayette College, *CHRISTOPHER J. WILLIAMS*: Franklin & Marshall College
Students: *GARRISON LOOPE*: Oberlin College; *DOUGLAS MERKERT*: Union College; *JOHN LINDEN NEFF*: Amherst College; *NANCY PARKER*: Lafayette College; *KYLE TROSTLE*: Franklin & Marshall College; *BEVERLY WALKER*: Colgate University

SEAFLOOR VOLCANIC AND HYDROTHERMAL PROCESSES PRESERVED IN THE ABITIBI GREENSTONE BELT OF ONTARIO AND QUEBEC, CANADA
Faculty: *LISA A. GILBERT,* Williams College and Williams-Mystic and NEIL R. BANERJEE, U. of Western Ontario
Students: *LAUREN D. ANDERSON*: Lehigh University; *STEFANIE GUGOLZ*: Beloit College; *HENRY E. KERNAN*: Williams College; *ADRIENNE LOVE*: Trinity University; *LISA SMITH:* Amherst College; *KAREN TEKVERK*: Haverford College

INTERDISCIPLINARY STUDIES IN THE CRITICAL ZONE, BOULDER CREEK CATCHMENT, FRONT RANGE, CO
Faculty: *DAVID P. DETHIER*: Williams College and *MATTHIAS LEOPOLD*: Technical University of Munich
Students: *EVEY GANNAWAY*: The U. of the South; *KENNETH NELSON*: Macalester College; *MIGUEL RODRIGUEZ*: Colgate University

GEOARCHAEOLOGY OF THE PODERE FUNGHI, MUGELLO VALLEY ARCHAEOLOGICAL PROJECT, ITALY
Faculty: *ROB STERNBERG*: Franklin & Marshall College and *SARA BON-HARPER*: Monticello Department of Archaeology
Students: *AVERY R. COTA*: Minnesota State University Moorhead; *JANE DIDALEUSKY*: Smith College; *ROWAN HILL*: Colorado College; *ANNA PENDLEY*: Washington and Lee University; *MAIJA SIPOLA*: Carleton College; *STACEY SOSENKO*: Franklin and Marshall College

GEOLOGY OF THE HÖH SERH RANGE, MONGOLIAN ALTAI
Faculty: *NICHOLAS E. BADER and ROBERT J. CARSON*: Whitman College; *A. BAYASGALAN*: Mongolian University of Science and Technology; *KURT L. FRANKEL*: Georgia Institute of Technology; *KARL W. WEGMANN*: North Carolina State University
Students: *ELIZABETH BROWN*: Occidental College; *GIA MATZINGER, ANDREA SEYMOUR, RYAN J. LEARY*, *KELLY DUNDON* and *CHELSEA C. DURFEY*: Whitman College; *BRITTANY GAUDETTE*: Mount Holyoke College; *KATHRYN LADIG*: Gustavus Adolphus College; *GREG MORTKA*: Lehigh U.; *JODI SPRAJCAR*: The College of Wooster; *KRISTIN E. SWEENEY*: Carleton College.

BLOCK ISLAND, RI: A MICROCOSM FOR THE STUDY OF ANTHROPOGENIC & NATURAL ENVIRONMENTAL CHANGE
Faculty: *JOHAN C. VAREKAMP*: Wesleyan University and *ELLEN THOMAS*: Yale University & Wesleyan University
Students: *ALANA BARTOLAI*: Macalester College; *EMMA KRAVET and CONOR VEENEMAN*: Wesleyan University; *RACHEL NEURATH*: Smith College; *JESSICA SCHEICK*: Bryn Mawr College; *DAVID JAKIM*: SUNY.

Funding Provided by: Keck Geology Consortium Member Institutions and NSF (NSF-REU: 0648782)

Keck Geology Consortium: Projects 2008-2009
Short Contributions – CANADA

SEAFLOOR VOLCANIC AND HYDROTHERMAL PROCESSES PRESERVED IN THE ABITIBI GREENSTONE BELT OF ONTARIO AND QUEBEC, CANADA
Project Director: ***LISA A. GILBERT*****,** Williams College and Williams-Mystic
Project Faculty: ***NEIL R. BANERJEE***, University of Western Ontario

GEOCHEMICAL INVESTIGATION OF HYDROTHERMALLY ALTERED MAFIC VOLCANIC FLOWS FROM THE 2.7 GA ABITIBI GREENSTONE BELT, ONTARIO AND QUÉBEC, CANADA
LAUREN D. ANDERSON**:** Lehigh University
Research Advisor: Gray E. Bebout

INTERPILLOW HYALOCLASTITES, PILLOW RIM ALTERATION, AND FLUID FLOW IN MAFIC VOLCANICS OF THE BLAKE RIVER GROUP, ROUYN-NORANDA, QUÉBEC
STEFANIE GUGOLZ**: Beloit College**
Research Advisor: Jim Rougvie

FLUID INDUCED MINERALOGY IN A SERIES OF MAFIC EXTRUSIVES OF THE ABITIBI GREENSTONE BELT, ROUYN-NORANDA, QUEBEC
HENRY E. KERNAN: Williams College
Research Advisors: Reinhard A. Wobus and Lisa A. Gilbert

PALEO-PERMEABILITY OF ABITIBI GREENSTONE BELT HYALOCLASTITES: IMPLICATIONS FOR ARCHEAN LIFE
ADRIENNE LOVE**:** Trinity University
Research Advisors: Benjamin Surpless and Lara Heister

VARIATIONS IN VESICLE DENSITIES WITHIN PILLOW BASALTS OF THE ABITIBI REGION: ROUYN-NORANDA, QUEBEC
LISA M. SMITH**:** Amherst College
Research Advisors: Peter D. Crowley: Amherst College and Lisa A. Gilbert: Maritime Studies Program of Williams College and Mystic Seaport

MINERALOGY AND METASOMATISM OF THE ROUYN-NORANDA HYALOCLASTITES IN THE ABITIBI GREENSTONE BELT
KAREN TEKVERK: Haverford College
Research Advisor: Chris Oze, Bryn Mawr College

Funding provided by: Keck Geology Consortium Member Institutions and NSF (NSF-REU: 0648782)

Keck Geology Consortium
Franklin & Marshall College
PO Box 3003, Lancaster Pa, 17603
Keckgeology.org

SEAFLOOR VOLCANIC AND HYDROTHERMAL PROCESSES PRESERVED IN THE ABITIBI GREENSTONE BELT OF ONTARIO AND QUEBEC, CANADA

Project Director: Lisa A. Gilbert, Williams College and Williams-Mystic
Project Faculty: Neil R. Banerjee, University of Western Ontario

INTRODUCTION

More than 60% of the Earth's surface is composed of oceanic crust. The formation of new oceanic crust at ridge axes and the reincorporation of old crust into the mantle or its accretion onto continental margins at subduction zones are perhaps the most fundamental components of the plate tectonic cycle. These processes control the physiography of the Earth and the chemical and thermal evolution of the crust and mantle. Seafloor volcanoes, including seamounts and mid-ocean ridges, are dynamic environments where globally significant chemical, biological, and heat fluxes occur between the lithosphere and hydrosphere. The focus of this project was a study of water-rock-microbial alteration of the ancient seafloor preserved in the Abitibi Greenstone Belt (AGB).

Greenstone belts such as the AGB are useful for understanding ancient seafloor processes that we cannot access directly. When we study modern oceanic crust it is generally either just on the very surface of the seafloor, in a one-dimensional hole drilled into the crust, or by some remote method that prohibits detailed mapping. Greenstone belts are not perfect analogs of normal ocean crust and are likely preserved because they may be atypical (e.g. Karson, 2002). However, seafloor volcanic rocks are not all generated at normal mid-ocean ridge settings, and seamounts, back-arc spreading, and oceanic plateaus represent a significant portion of volcanic rocks found on the seafloor.

Investigations of seafloor hydrothermal systems are inherently interdisciplinary, reflecting the complex linkages between geological, biological, chemical, and physical processes. In particular, the role of microorganisms in the alteration of oceanic crust has only recently been demonstrated (see Furnes et al., 2008 for a review). The temperature and depth limits of oceanic basement microbiological activity have yet to be explored, but microbial activity occurring in the sub-seafloor biosphere may have a profound impact on processes and chemical fluxes during water-rock reactions and possibly hold the key to the development of life on the Earth and other planets.

GEOLOGICAL SETTING

The AGB (Fig. 1) is the largest and one of the most accessible, best-studied, and best-preserved Archean (2735-2670 Ma) greenstone belts in the world (Card, 1990; Daigneault et al., 2004). Like most greenstone belts worldwide, it comprises primarily ultramafic to mafic volcanic rocks, many of which exhibit pillowed morpholgies, breccias and hyaloclastites typical of seafloor volcanism, felsic volcanic rocks and turbiditic to conglomeratic clastic sedimentary rocks (e.g., Dimroth et al., 1978). The belt is cut by a number of major, late-stage transcurrent shear zones, which served as the locus for fluid flow and ore deposition (e.g. Ludden and Hubert, 1986). Despite some deformation and later weathering, the AGB in general, and in particular the many delicate volcanogenic features in the mafic volcanic units of the Blake River Group (BRG), are remarkably well preserved (Mueller, et al., 2004).

Because of its economic value (copper, zinc and gold deposits), the volcanology of the AGB has been broadly mapped (e.g., Wyman et al., 1999), which provides the necessary background for a detailed study of the interplay of seafloor fluid flow and physical volcanology through very detailed (me-

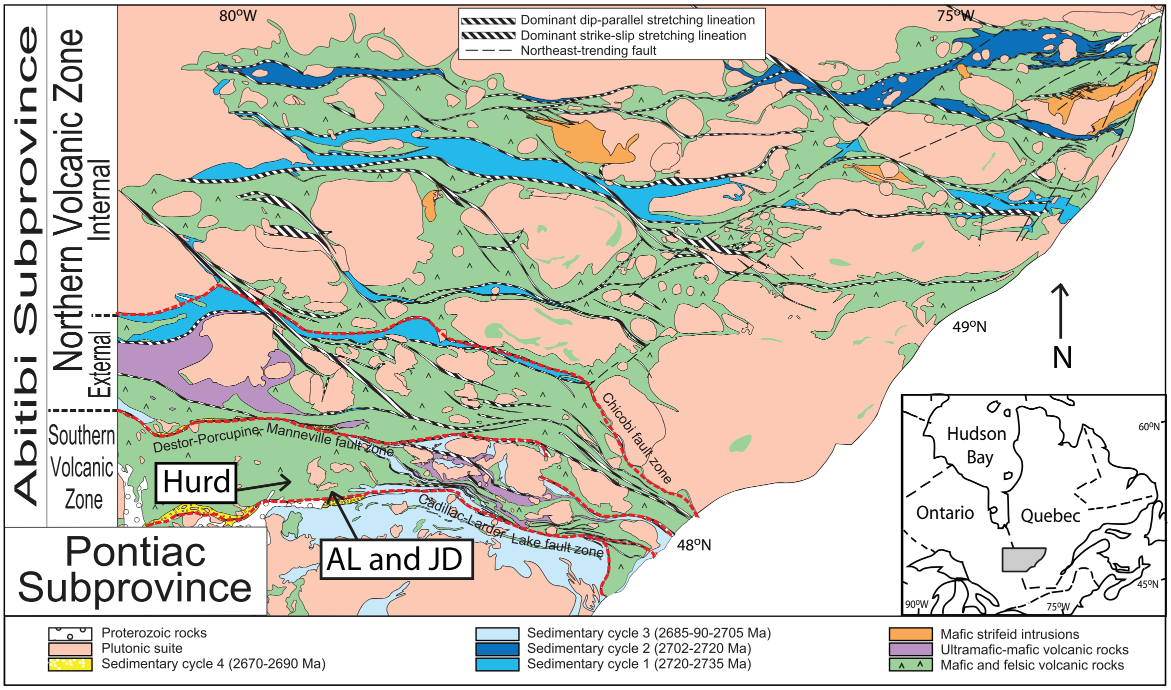

Figure 1. General geology of the Archean Abitibi Greenstone Belt (modified from Daigneault et al., 2004; Mueller et al., 2009). The Air Liquide (AL) and John Deere (JD) sites are within the town of Rouyn-Noranda, Quebec; the Hurd site is 90 km to the NNW in the rural Harker Township, Ontario.

ter-scale) mapping and sampling, contributing to a broader understanding of Archean seafloor physical, chemical, and biological processes. In particular, our chosen study sites afford us the relatively rare opportunity to study seafloor volcanic and hydrothermal processes in an area that is both easily accessible and has a significant thickness of exposed extrusive mafic rocks.

The study sites are located within the Blake River Group (BRG), a 3000 km^2 volcanic sequence in the Southern Volcanic Zone of the AGB (Fig. 1; Chown et al., 1992). The BRG (2706-2697 Ma) is a 4-7 km-thick sequence of primarily mafic volcanic rocks exposed across the Quebec-Ontario border, with over 100 km of exposed complex Archean ocean crust (Mueller et al., 2009; Pearson and Daigneault, 2009). The study sites are within a nested megacaldera complex comprised of three calderas (Mueller et al., 2009; Pearson and Daigneault, 2009). The Air Liquide (AL) and John Deere (JD) sites are predominantly pillowed and massive flows, although some hyaloclastite flows occur locally, and are located within 1 km of each other on the edge of Rouyn-Noranda. Units at AL dip vertically, north up, with excellent exposures. JD also dips nearly vertically, with up varying between southeast and northeast around an open z-shaped fold. The Hurd Property site (Hurd) is located 90 km northwest of Rouyn-Noranda in Harker Township, on the Ontario side of the BRG (Fig. 1). The 2701 Ma rocks at Hurd constitute a 62 m-thick sequence of submarine volcaniclastic deposits that dip vertically, with south southwest up, and are underlain by a sequence of thin lava flows and overlain by a poorly exposed massive basalt (Bridge et al., submitted; Scott et al., 2003; Ayers et al., 2002).

Field studies were conducted in the pillows, massive basalts, hyaloclastites, and breccias in and immediately surrounding the town of Rouyn-Noranda, Quebec as well as the Hurd Property in Harker Township, Ontario (Fig. 1). In Rouyn-Noranda, we studied two areas of mafic volcanics behind the Air

Liquide facility (AL) and the folded mafic volcanics across the street at JD behind a John Deere facility (Fig. 2). At AL mapped a 150 x 160 m area (Fig. 3). The series of flows, interspersed with pillows and hyaloclastites mapped at the AL site exemplifies the complexity of seafloor basalt morphologies, glassy lithologies, and styles of hydrothermal flow found even in a small area. We also studied the Hurd Property, a site of previously discovered microbial biosignatures (Bridge et al., submitted) to expand prior mapping, geochemical, and physical properties work there, and for a comparison to the Rouyn-Noranda areas.

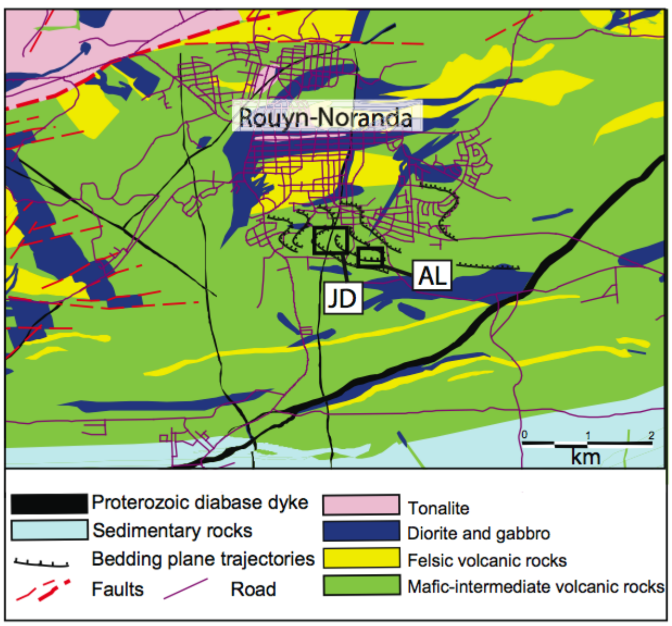

Figure 2. Rouyn-Noranda, Quebec geology (after Mueller et al., 2008), with locations of JD and AL sites.

FLUID FLOW WITHIN THE SEAFLOOR

Fluid flow within the modern seafloor transports tremendous heat and dissolved components between the basaltic crust and the ocean. Our understanding of the geometry, intensity, and duration of fluid flow both in the modern seafloor, and in the Archean is incomplete and limited by exposure and access. Porosity and permeability, two important controls on hydrothermal fluid flow, have been measured in hand samples from the seafloor, and more commonly using indirect methods; these parameters vary tremendously based on geologic setting, basement topography, sedimentation, and other factors (see Jacobson, 1992; Fisher, 1998 for reviews). Porosity of young seafloor rocks has been estimated to represent as much as one-third of the total volume of the shallowest volcanics (e.g., Gilbert et al., 2007), decreasing with age as hydrothermal circulation wanes and permeable zones seal (Jacobson, 1992). Outrcop mapping of porosity and permeability of pillows at the Troodos Ophiolite in Cyprus produced estimates similar to modern seafloor (Gillis and Sapp, 1997)

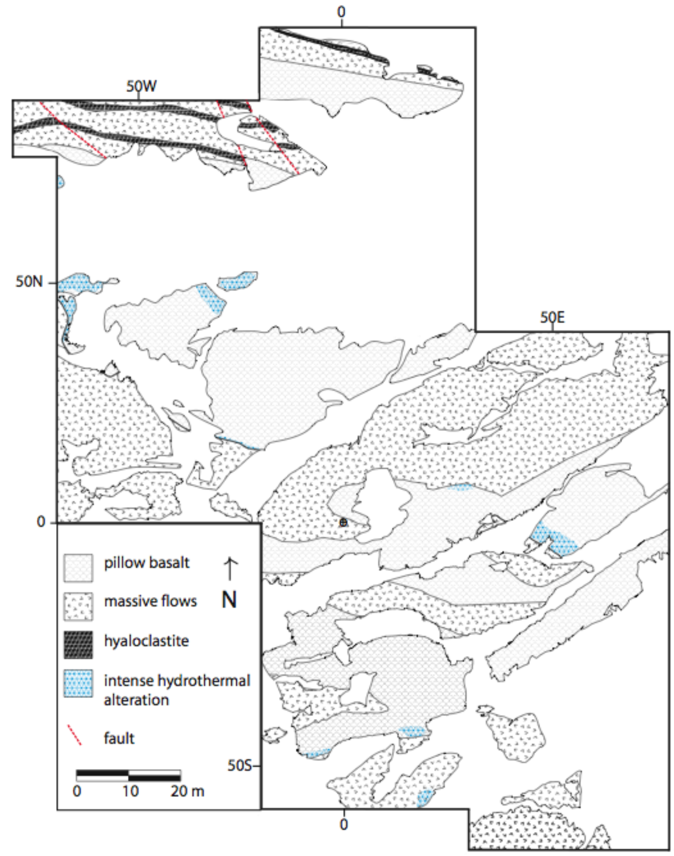

Figure 3. Detailed geologic map of the Air Liquide area, with the map center (0,0) at 49.221˚N, 079.001˚W. Mapping was done on a 5 m grid.

To compare zones of likely fluid flow, we selected sites with a variety of seafloor morphologies: pillows, flows, and hyaloclastites. We mapped and sampled in several dimensions for studies of physical properties (including density, velocity, permeability, and porosity), petrology, mineralogy, geochemistry, and in various combinations to help constrain original setting, understand fluid flow and porosity of the extrusive layer, and explore the variety of compositions and relationships between volcanic facies preserved. In the context of modern ocean crustal processes, using comparisons from other greenstone belts, ophiolites, and modern seafloor volcanic rocks, these results provide a better understanding of how hydrothermal fluid flow operates now and may have operated early in Earth's history.

Henry 'Ted' Kernan (Williams '09) focused on hydrothermal processes that lead to sulfide mineralization throughout the large, well-exposed AL outcrop (Fig. 3) at the edge of the town of Rouyn-Noranda. He broadly determined the distribution of sulfides present in different lithologies and examined petrography, major and trace element geochemistry, and physical properties to compile indicators of hydrothermal activity throughout each unit of the extrusive pile. Of particular interest are his findings of the relative enrichment of trace metals: the hyaloclastites are significantly enriched above pillow margins and cores, with the least enrichment within the interior of the low-porosity/high density massive basalt units. The highest sulfide concentrations in the area are coincident with changes in lithology, primarily at the transition between the tops of pillow units and overlying massive units, within the interpillow zones of the uppermost pillows. These contacts represent a change in eruptive style and with the onset of lower porosity massive flows likely a change in hydrothermal plumbing, making the connected fractures between the capped pillows a natural zone of permeability through which many syn- and, possibly, post-volcanic hydrothermal fluids have traveled.

To determine the relative timing and causes of alteration, Karen Tekverk (Haverford '09) examined the glassy margins of pillows and interpillow hyaloclastites (IPH), as well as calcite- and/or quartz-filled veins. Tekverk used whole rock geochemistry, XRF, and XRD to aid her petrographic study of metamorphic mineralogy, fabric orientation, and grain size indicators to assess the degree of fluid alteration and water-rock interactions. She compared the alteration histories to examine the relative influences of infiltration of metasomatic fluids during seafloor processes and later tectonic deformation. Such a comparison is important to our models of fluid migration from original conditions on the seafloor, through emplacement, to the present. Although there is evidence of some later alteration, mineralogy and fabric orientation in the pillow edges and IPH indicate fluid flow of hydrothermal origin, especially in the least deformed pillows. The JD area, which is within an open z-shaped fold (Fig. 2) showed more evidence of tectonic deformation.

To get a sense of originally open pore space within the interiors of the pillow basalts and massive units, Lisa M. Smith (Amherst '09) examined characteristics of the vesicles at both Rouyn-Noranda sites (AL and JD). Smith compared novel determinations of vesicle size and density made in the field with those using thin section microscopy, and found agreement between methods, with an overall vesicularity of 5% for non-glassy morphologies at both sites. She examined various eruptive morphologies to observe how differing styles of eruption influence vesiculation. In particular, she made detailed maps of vesicle distribution from pillow top to bottom and laterally across pillows, finding a near radial symmetry and a high density of vesicles in the center of the pillow. She also examined vesicle deformation as an indicator of pillow deformation, using three sites cross a syncline at JD (Fig. 2)– one on the western limb, one on the eastern limb, and one in the hinge of the fold. Although vesicles and drain-back features are often unconnected, they represent an original porosity of seafloor volcanics that is thought to influence the seismic character and physical/chemical evolution of the crust.

The glassy margins of pillow basalts, formed from the quenching of the outer skin of subaqueous lavas, provide a set of connected fractures through which hydrothermal fluid can flow. Stefanie Gugolz (Beloit '09) characterized hydrothermal alteration and fluid flow through the pillow and interpillow zones of Archean mafic volcanics of the BRG in Rouyn-Noranda (Fig. 2). By examining pillow size and shape, as well as interpillow hyaloclastite (IPH) area and alteration halos around glassy pillow rims, her work has the goal of understanding the influence of pillow morphology on fluid flow. Gugolz used a variety of petrolographic, geochemical, and physical properties to characterize inter-pillow zones of hydrothermal fluid flow. In the JD and AL study areas, hydrothermal fluid flow is focused along IPH zones, supported by field evidence for thinner alteration halos in areas with more IPH, whereas thicker alteration zones occur along the edges of horizontally elongate pillows with small IPH zones. These zones of high fluid flow within the upper ocean crust are important to locate likely evidence of sub-seafloor life such as microbial trace fossils, volcanic massive-sulfide deposits, and to better understand hydrothermal fluid flow.

VOLCANOES AND MICROBES

Limited Archean-age rocks have survived on Earth, but those that do contain valuable information pertaining to the evolution of Earth and life's early development. Past searches for traces of the earliest history of life on Earth have mostly been confined to sedimentary rocks but recently, traces of microbial life have been found in modern and ancient submarine volcanic rocks. Microbial alteration features are ubiquitous within the oceanic crust, having been discovered in basalts of all ages, wherever fresh glass is preserved. More recent work in ophiolites and greenstone belts has extended the evidence for microbial alteration of oceanic basalts back into the Archean, significantly beyond the record preserved in the modern oceans (e.g., Furnes et al., 2007; 2008). Ancient subaqueous volcanic rocks potentially preserve a new and largely unexplored record of early life. The investigation of these microbial trace fossils preserved in greenstone belts extends the evidence for microbial alteration of pillow basalts back to the Archean (e.g., Banerjee et al., 2007; 2006) and is of astrobiological relevance to the exploration for life on Mars and in our solar system for a number of reasons. First, it shows that robust biosignatures of a presently observable, global microbial process can be preserved for billions of years in the geological record. Second, it suggests that microbial life had already colonized volcanic rocks on Earth at a time when liquid water might have been present at or near the surface of Mars.

Compared to the other lithologies, hyaloclastites seem to represent the highest seafloor permeability, and thus are likely places to look for extensive microbial communities. Adrienne Love (Trinity '09) explored the link between the paleo-permeability of hyaloclastite flows and the development of microbial communities within the BRG, at both the Hurd and Rouyn-Noranda sites. Using a combination of detailed field sketches, image analysis, and thin section petrography, Love focused on understanding fluid flow paths and permeability in the mafic volcanic rocks in the context of the physical emplacement and subsequent alteration of hyaloclastites. Her maps of hyaloclastites include the proportion of basaltic clasts, and the size and shape of cm-scale and smaller glassy fragments, through which water would have likely flowed.

Lauren Anderson (Lehigh '09) focused on the preservation of geochemical and mineralogical biosignatures in the hyaloclastites and basalts of the Rouyn-Noranda and Hurd sites. In particular her study involves analysis of abundance and stable isotopic composition of nitrogen preserved in these ancient volcanic rocks and a comparison of major and trace element geochemistry. Nitrogen is a major component of Earth's modern atmosphere and is recognized as a key element to biologic evolution. Modern hydrothermally altered basalts are observed to have elevated N contents believed to represent significant a contribution of N from overlying sedimentary and organic sources (Li et al., 2007). The goal of her study is to determine whether similarly elevated nitrogen contents and diagnostic isotope ratios resulting from ancient organic input are preserved in mafic volcanics from the AGB, especially in the rocks such as the hyaloclastite samples from Hurd that preserve tubular-shaped microfossils.

ACKNOWLEDGEMENTS

We would like to thank Wulf Mueller from the Université du Québec à Chicoutimi for introducing us to the field site and the wonders of Archean geology in the Abitibi. Both he and Lyndsay Moore helped lead field trips and helped put our study into the larger regional framework. Thanks to Nathan Bridge '08 and Mike Laliberty '09 from the University of Western Ontario, Cheyenne Sica '10 from Queens University, for field support during the project, and to Kim Elson '10 from Carleton College, who helped organize field gear before the field component, assisted tirelessly in the field, and directed laboratory work at Williams-Mystic following the field program. Thanks also to Gray Bebout and Lara Heister for visiting the field and providing the students with their expertise, and to all the advisors for their contributions throughout the year. Additional financial assistance was provided by a grant from National Sciences and Engineering Research Council of Canada, the U.S. Department of Energy, and Williams-Mystic.

REFERENCES CITED

Ayer, J., Y. Amelin, F. Corfu, S. Kamo, J. Ketchum, K. Kwok and N. Trowell, 2002, Evolution of the southern Abitibi greenstone belt based on U–Pb geochronology: autochthonous volcanic construction followed by plutonism, regional deformation and sedimentation, Precambrian Res. 115, 63–95.

Banerjee, N.R., Furnes, H., Muehlenbachs, K., Staudigel, H., and de Wit, M., 2006, Preservation of ~3.4–3.5 microbial biomarkers in pillow lavas and hyaloclastites from the Barberton Greenstone Belt, South Africa, Earth and Planetary Science Letters, 241, 707-722.

Banerjee, N.R., A. Simonetti, H. Furnes, K. Muehlenbachs, H. Staudigel, L Heaman, and M.J. Van Kranendonk, 2007, Direct dating of Archean microbial ichnofossils, Geology, 35(6), 487–490.

Bridge, N. J., Banerjee, N. R., Mueller, W., Muehlenbachs, K., Chacko, T., submitted, A volcanic habitat for early life preserved in the Abitibi Greenstone belt, Canada, Submitted to Precambrian Research, 30 p.

Card, K.D., 1990, A review of the Superior province of the Canadian Shield, a product of Archean accretion: Precambrian Research, 48, 91-156.

Chown, E.H., R. Daigneault, W. Mueller, and J. Mortensen, 1992, Tectonic evolution of the Northern Volcanic Zone, Abitibi belt, Quebec, Can. J. Earth Sci, 29, 2211-2225.

Daigneault, R., W.U. Mueller, and E.H. Chown, 2004, Abitibi greenstone belt plate tectonics: the diachronous history of arc development, accretion, and collision. In The Precambrian Earth: tempos and events. Edited by P. Eriksson, W. Altermann, D. Nelson, W.U. Mueller, and O. Catuneaunu. Developments in Precambrian Geology, 12, 88-103.

Dimroth, E., P. Cousineau, M. Leduc, and Y. Sanschargrin, 1978, Structure and organization of Archean subaqueous basalt flows, Rouyn-Noranda area, Quebec, Can. J. Earth Sci., 15, 902-918.

Fisher, A.T., 1998, Permeability within basaltic crust, Rev. Geophys., 36(2), 143-182.

Furnes, H., Banerjee, N.R., Muehlenbachs, K., Staudigel, H., and de Wit, M., 2004, Early life recorded in Archean pillow lavas, Science, 304, 578-581.

Furnes, H., Banerjee, N.R., Staudigel, H., Muehlenbachs, K., McLoughlin, N., de Wit, M., and Van Kranendonk, M., 2007, Comparing petrographic signatures of bioalteration in recent to Mesoarchean pillow lavas: tracing subsurface life in oceanic igneous rocks. Precambrian Research 158, 156-176.

Furnes H., McLoughlin, N. Muehlenbachs, K., Banerjee, N.R., Staudigel, H., Dilek, Y., de Wit, M., Van Kranendonk, M., Schiffmann, P., 2008, Oceanic pillow lavas and hyaloclastites as habitats for microbial life through time – A review In: Links between Geological Processes, Microbial Activities, and Evolution of Life "

Ed. Y. Dilek, H. Furnes and K. Muehlenbachs, Springer Book Series, 1-68.

Gilbert, L.A., R.E. McDuff, and H.P. Johnson, 2007, Porosity of the upper edifice of Axial Seamount, Geology, 35(1), 49-52.

Jacobson, R.S., 1992, Impact of crustal evolution on changes of the seismic properties of the uppermost ocean crust, Rev. Geophys, 52, 72-87.

Karson, J.A., 2002, Geologic Structure of the uppermost oceanic crust created at fast- to intermediate-rate spreading centers, Ann. Rev. Earth Planet. Sci., 30, 347-384.

Li, L., G.E. Bebout, and B.D. Idleman, 2007, Nitrogen concentration and d15N of altered oceanic crust obtained on ODP Legs 129 and 185: Insights into alteration-related nitrogen enrichment and the nitrogen subduction budget. Geochimica et Cosmochimica Acta, 71, 2344-2360.

Ludden, J. and C. Hubert, 1986, Geologic evolution of the Late Archean Abitibi greenstone belt of Canada, Geology, 14, 707-711.

Mueller, W.U., R. Daigneault, J.K. Mortensen, and E.H. Chown, 1996, Archean terrane docking: upper crust collision tectonics, Abitibi greenstone belt, Quebec, Canada, Tectonophysics, 265, 127-150.

W. U. Mueller, R. Daigneault, V. Pearson, and D. Gaboury, 2008, Effusive and explosive subaqueous volcanism in the Abitibi greenstone belt, GAC-MAC Field Excursion Guide, 9.

Mueller, W.U., J. Stix, P.L. Corcoran, and R. Daigneault, 2009, Subaqueous calderas in the Archean Abitbi greenstone belt: An overview and new ideas, Ore Geology Reviews, 35(1), 4-46.

Mueller, W.U., J. Stix, J.D.L. White, and G. Hudak, 2004, Archean calderas. In The Precambrian Earth: tempos and events. Edited by P. Eriksson, W. Altermann, D. Nelson, W.U. Mueller, and O. Catuneaunu. Developments in Precambrian Geology, 12, 345-356.

Pearson, V. and R. Daigneault, 2009, An Archean megacaldera complex: the Blake River Group, Abitibi greenstone belt, Precambrian Research, 168, 66-82.

Scott, C., D. Richard, and A.D. Fowler, 2003, An Archean Submarine Pyroclastic Flow: The Hurd Deposit, Harker Township, Ontario, Canada. American Geophysical Union Special Volume on Explosive Volcanism, Geophysical Monograph 140, 317-327.

Scott, C.R., W.U. Mueller, and P. Pilote, 2002, Physical volcanology, stratigraphy, and lithogeochemistry of an Archean volcanic arc: evolution from plume-related volcanism to arc rifting of SE Abitibi Greenstone Belt, Val d'Or, Canada, Precambrian Research, 115, 223-260.

Wyman, D.A., R. Kerrich, and D.I. Groves, 1999, Lode Gold Deposits and Archean Mantle Plume–Island Arc Interaction, Abitibi Subprovince, Canada. The Journal of Geology, 107(6), 715-725.