KECK GEOLOGY CONSORTIUM

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

April 2009
Franklin & Marshall College, Lancaster PA.

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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

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Project Director: ***LISA A. GILBERT*****,** Williams College and Williams-Mystic
Project Faculty: ***NEIL R. BANERJEE***, University of Western Ontario

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KAREN TEKVERK: Haverford College
Research Advisor: Chris Oze, Bryn Mawr College

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

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MINERALOGY AND METASOMATISM OF THE ROUYN-NORANDA INTER-PILLOW HYALOCLASTITES IN THE ABITIBI GREENSTONE BELT

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Research Advisor: Chris Oze, Bryn Mawr College

INTRODUCTION

The Abitibi Greenstone Belt is an Archean sequence of metamorphosed volcanic, plutonic, and sedimentary rocks located in eastern Canada near the Québec-Ontario border (Hannington et al., 2002). This area exhibits kilometers-thick sequences of massive lavas, pillow lavas, broken-pillow breccias, and stratified hyalotuffs which have been subsequently altered to greenschist and sub-greenschist facies (Dimroth et al., 1978). Indications of microbial activity have been discovered in the well-preserved Archean pillow lavas of the Barberton Greenstone Belt in South Africa, which are similar in composition to the rocks of the Abitibi Greenstone Belt (Furnes et al., 2004). This suggests that the Abitibi Greenstone Belt may be a fruitful place to look for signs of early life. The Rouyn-Noranda area of the Abitibi Greenstone Belt has undergone significant alteration; however, its potential for harboring early life has not yet been analyzed (Hannington et al., 2002). Further study of the mineralogy and alteration of the Abitibi Greenstone Belt may reveal whether the area has the potential to show chemical or fossil signatures of early life. Alteration through water-rock interactions would indicate that the Abitibi Greenstone Belt could have harbored life.

The objective of this study is to assess the degree of water-rock interactions and P-T alteration in order to determine the degree and extent of hydrothermal alteration. To complete these objectives, mineral alteration studies will assess the origin of alteration, as well as the degree of fluid alteration and water-rock interactions. Remineralization at low pressures and temperatures (such as those found at mid-oceanic ridges) would suggest hydrothermal alteration of the rocks. As well, mass transfer of elements into and out of the samples post-deposition suggests hydrothermal alteration of the rocks. This alteration will be examined utilizing two methods. Mineral alteration studies will include detailed petrographic analysis of thin sections from cores of inter-pillow hyaloclastites in the Abitibi Greenstone Belt, as well as X-ray diffraction (XRD) analyses. Geochemical analysis through X-ray fluorescence (XRF) analyses will be used to assess the water-rock interactions and mass transfer of elements into and out of the samples.

BACKGROUND

Mineralogical composition of the Abitibi Greenstone Belt includes secondary alteration of original minerals into albite, chlorite, epidote, quartz, tremolite-actinolite, prehnite, pumpellyite, and calcite, in addition to the minerals typically present in a mid-ocean ridge basalt (MORB) (Hannington et al., 2002). This has been produced through varying degrees of mass transfer (i.e. metasomatism) and pressure-temperature (or tectonic) metamorphism. Hydrothermal and/or metasomatic alteration is capable of producing suites of albite, chlorite, epidote, quartz, and tremolite-actinolite, in addition to minerals present in less substantial quantities than these five (Hannington et al., 2002). Pressure-temperature alteration to suites of prehnite, pumpellyite, chlorite, epidote, calcite, and lesser minerals is also likely, as the Abitibi Greenstone Belt has been subjected to significant tectonism over the past 2.7 billion years (Dimroth et al., 1978; Dimroth et al., 1982; Dimroth et al., 1983; Mueller et al., 1996; Hannington et al., 2002). Most P-T alteration in this system would not have implications for the generation of early life. However, alteration at pressures and temperatures conducive to the growth of deep sea extremophiles would suggest that this area of the Abitibi Greenstone Belt could have once fostered early life.

METHODS

Twelve core samples of the glassy margins of pillows and interpillow hyaloclastites (IPH) were taken from the John Deere (JD) and Air Liquide (AL) outcrops of the Blake River Group (Gilbert and Banerjee, this volume), using either a one-inch or a two-inch drill bit. These samples are KT01, KT02, KT03, KT04, KT08, KT09, KT10, KT11, KT12, KT13, SG93-2, and L+L12. One thin section was made from each sample, except for sample KT12, which was subdivided into two sections (KT12B and KT12D), due to differences in different regions of the core. Whenever possible, thin sections were made from parts of the cores which exhibited obvious pillow rinds. Petrographic analyses were performed to garner information with regards to mineralogies, remineralizations, and mineral fabrics. Mineralogies were described as being significant, small, and rare in each thin section. Minerals categorized as "significant" comprise a significant percentage of the thin section (more than ten percent), while minerals categorized as "small" comprise a small percentage (less than ten percent) of the thin section. Minerals categorized as rare occur once or sporadically, but do not occur throughout the thin section.

In addition to petrographic analysis, X-ray flourescence (XRF) and X-ray diffraction (XRD) analyses were performed on a selected series of samples to determine the major and trace element chemistry and mineralogy of the rocks. Whole rock chemistry analysis was completed by XRF analysis by Washington State University GeoAnalytical Laboratory on five samples: KT01, KT02, KT03, KT12, and SG93-2. X-ray diffraction analysis was completed using a Rigaku Ultima IV XRD at Bryn Mawr College on eight samples: KT04, KT08, KT09, KT10, KT11, KT13, SG93-2, and L+L12. X-ray diffraction values were collected between 2θ values of 3.0 and 60.0, with a generator potential of 40kV, a generator current of 40mA (using CuKα radiation), and a scan speed of 0.01°/s. Both XRF and XRD analysis were performed on sample SG93-2.

RESULTS

Petrographic

Minerals observed in thin section include epidote, tremolite-actinolite, chlorite, quartz, calcite, pyrite, magnetite, other opaques, potassium feldspar, plagioclase, and possible muscovite and/or chloritoid (Table 1). Almost all of the samples contained epidote, and most contained tremolite-actinolite, chlorite, or both. These minerals made up much of the visible mass of each thin section. However, many samples also contained an abundance of quartz and/or calcite. In these samples, quartz was generally very small (less than 0.05mm) and occurring as either a replacement of some larger previous phenocryst or in veins. Calcite was generally larger than both the quartz and most of the surrounding crystals in the thin section (up to 0.2mm crystals), and occurred primarily in veins throughout the thin sections. In addition to quartz and calcite, many samples (KT11, KT13, SG93-2, and L+L 12) showed large (up to 3mm in longest direction) euhedral to subhedral grains of pyrite. These occurred predominantly near the pillow rinds, and sometimes with quartz. Magnetites and other opaques (see Kernan, this volume) also tended to occur within or near the pillow rinds, and often with calcite and/or quartz.

XRD and XRF

The most abundant minerals identified in XRD analyses were quartz, followed by calcite. Other possible minerals included amesite, actinolite, tremolite, cordierite, indialite, clinochlore, chlorite, albite, dickite, cubanite, epidote, brookite, and muscovite. The presence of quartz and calcite in many of the samples is confirmed by petrographic identification of the two minerals in most of the thin sections. Petrographic identification also confirms the presence of actinolite, tremolite, chlorite, albite, epidote, and muscovite in the samples. While amesite, cordierite, indialite, clinochlore, dickite, cubanite, and brookite were not seen in thin section, their presence is possible, particularly as minerals too small to see in thin section.

Sample	Site	Description	Epidote	Trem-Act	Chlorite	Quartz	Calcite	Pyrite	Magnetite	K-spar	Opaques
KT01	AL	IPH and rim	S	S	r	S	o	o	s	o	o
KT02	AL	IPH and rim	S	o	s	o	o	o	o	S	o
KT03	AL	IPH and rim	S	s	o	s	o	o	o	S	o
KT04	AL	IPH and rim	S	S	o	s	o	o	o	o	o
KT08	AL	IPH at triple jucture	s	o	s	s	r	o	o	s	r
KT09	AL	pillow rind breccia	S	o	S	s	o	o	o	o	s
KT10	JD	IPH	S	s	S	o	s	o	o	S	S
KT11	JD	IPH	S	o	o	o	S	S	o	S	o
KT12(B)	JD	IPH	S	S	S	s	s	o	o	o	s
KT12(D)	JD	IPH	S	S	S	s	s	o	o	o	s
KT13	JD	IPH	?	o	o	o	o	S	?	o	?
SG93-2	AL	rim	S	S	S	r	o	s	o	s	s
L+L12	AL	IPH	S	s	S	o	s	S	o	o	o

Table 1: Minerals seen in petrographic analysis, categorized as significant (S), small (s), and rare (r), as well as not visible (o). There were also lone occurrences of plagioclase in KT03 and muscovite in KT08.

X-ray fluorescence (XRF) data (Fig. 1) appear similar to a normal mid-ocean ridge basalt (N-MORB) (McKenzie and O'Nions, 1991). When these samples are plotted normalized to an N-MORB, there are some differences apparent – TiO_2, MgO, and Na_2O appear somewhat depleted as compared to an N-MORB, while Al_2O_3 and CaO appear enriched. The divergences of samples analyzed using XRF from an N-MORB are generally minor, with one obvious exception. Sample KT12 is depleted in K_2O by approximately one order of magnitude as compared to an N-MORB.

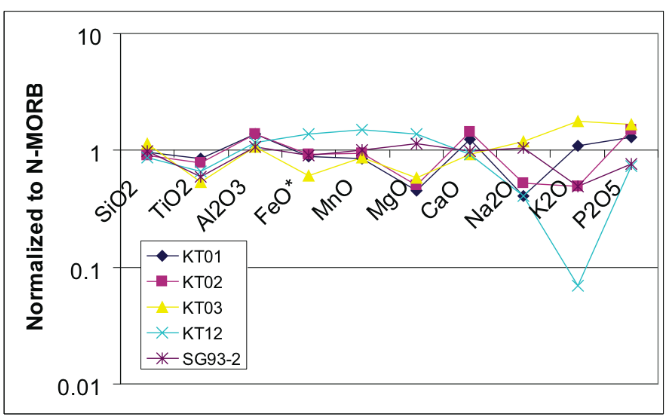

Figure 1: Major oxides of five samples (KT01, KT02, KT03, KT12, and SG93-2) normalized to an N-MORB (McKenzie and O'Nions, 1991). Samples show a depletion of TiO_2, MgO, and Na_2O and an enrichment of Al_2O_3 and CaO, suggesting mass transfer of elements within the samples.

DISCUSSION

Alteration by fluid flow often results in an increased mass transfer of elements in a rock, effecting a change in total rock chemistry through time, as new minerals are precipitated in the rock and preexisting minerals are weathered or removed. By analyzing a rock's mineralogical and chemical makeup as compared to its original, depositional makeup, we can determine the total extent of water-rock alteration and potentially the early alteration history of these rocks following basalt crystallization. As these greenstones were originally deposited as pillow basalts, although not a perfect analog, we use an N-MORB as an original compositional makeup, or starting point, for these rocks.

Hydrothermal and/or metasomatic alteration can produce suites of albite, chlorite, epidote, quartz, tremolite-actinolite, and lesser minerals in rocks from the Abitibi Greenstone Belt (Hannington et al., 2002). Both petrographic analysis and XRD analysis show all of these minerals. Tectonic alteration can produce suites of prehnite, pumpellyite, chlorite, epidote, calcite, and lesser minerals in rocks from the Abitibi Greenstone Belt (Hannington et al., 2002). Petrographic and XRD analysis do not exhibit all of these minerals. They do, however, show chlorite, epidote, and calcite in abundance. Because chlorite and epidote can be produced either metasomatically or at elevated pressures and temperatures, it is difficult to use these to determine the alteration history of these samples (Hannington et al., 2002). On the other hand, quartz and tremolite-actinolite are more indicative of lower grade hydrothermal and/or metasomatic alteration (Hannington et al., 2002). Because both are present in the samples, it can be inferred that they underwent both hydrothermal/metasomatic alteration as well as alteration associated with tectonic forces that ultimately resulted in its greenschist and sub-greenschist grade.

Much of the calcite seen in thin section occurs in veins throughout both the fine-grained greenstone portion of the thin section and the coarser-grained pillow rind area. These veins overprint the minerals around them, and have average grain sizes orders of magnitude larger than those found in the surrounding portions of the thin section. This is particularly true in the fine-grained greenstone portions of the thin sections. In addition, many thin sections exhibit occurrences of quartz as veins. Vein quartz typically shows a grain size a few to many times larger than that of the surrounding portions of the thin section, and occurs in meandering fractures through both the fine-grained greenstone and coarser-grained rind portions of the thin sections. Significant amounts of quartz occur in thin section outside of the veins, as well, particularly in the rind portions. Significant amounts of quartz may also be present in the finer-grained portions, but the grain size is too small to be certain. However, the frequent occurrence of quartz as either the first or one of the first hits in XRD analysis and the abundance of quartz in the portions of the thin sections where mineralogy can be determined through petrographic analysis suggests that much of the fine-grained material (likely ten percent or more) in each thin section is also quartz. The large size of these calcite and quartz grains and their overprinting of other minerals suggests that much of the formation of the calcite and quartz was also due, at least in part, to precipitation during hydrothermal and/or metasomatic alteration.

The euhedral to subhedral grains of pyrite, magnetite, and other opaques (see Kernan, this volume) also overprint other minerals seen in thin section, and show little alignment with the fabrics of the rest of the thin sections, although they do more frequently occur within and/or near the pillow rind. This suggests that their formation is due to a later remineralization of some of the surrounding minerals. The occurrence of these with calcite veins and quartz points to this remineralization as being at least partially metasomatic, rather than due entirely to pressure-temperature alteration.

In spite of metasomatic alteration in these rocks, the textures and fabrics of the samples are well-preserved. In addition, the chemistry of five samples from the Blake River Group (KT01, KT02, KT03, KT12, and SG93-2) is similar, although not without differences. Normalized to an N-MORB, XRF data on these five rocks shows a depletion of TiO_2, MgO, and Na_2O and an enrichment of Al_2O_3 and CaO, which suggests mass transfer has occurred within the samples. However, none of these depletions or enrichments fall far from the chemical composition of an N-MORB. All are within an order of magnitude of an N-MORB. Even the most severe divergence from an N-MORB in the normalized samples occurs in KT12, and is only about one order of magnitude off of an N-MORB. This preservation of texture and chemistry suggests that the Abitibi Greenstone Belt has remained relatively well-preserved, and would therefore provide a good place to search for signs of early life.

SUMMARY

The objective of this study is to determine the degree and extent of hydrothermal alteration in a suite of rocks from the Blake River Group of the Abitibi Greenstone Belt (Gilbert and Banerjee, this volume), using mineral alteration studies including petrographic analysis, X-ray diffraction, and X-ray fluorescence. The identification, distribution, and abundance of quartz, calcite, and remineralized opaques such as pyrite and magnetite in thin section suggests that these rocks have undergone metasomatic and/or hydrothermal alteration, potentially at grades lower than greenschist facies. The presence and major occurrence of these minerals is confirmed by XRD analysis, which reaffirms the conclusion that these rocks have undergone both metasomatic and/or hydrothermal alteration. This conclusion is also strengthened by differences between a standard N-MORB and the chemistry of the samples given by XRF analysis; however the broader similarities between these rocks and a standard N-MORB and the preservation of rock textures throughout remineralization suggests that these rocks are well-preserved. Because this area is well-preserved and has been metasomatically altered, potentially at P-T conditions that could potentially support early life, it may be an opportune place to search for chemical and/or fossil signatures of life such as those found in the Barberton Greenstone Belt in South Africa (Furnes et al., 2004).

REFERENCES

Dimroth, Erich, Imreh, Laszlo, Rocheleau, Michel, and Goulet, Normand, 1982, Evolution of the south-central part of the Archean Abitibi Belt, Quebec; Part I: Stratigraphy and paleogeographic model: Canadian Journal of Earth Sciences, v. 19, p. 1729-758.

Dimroth, Erich, Imreh, Laszlo, Goulet, Normand, and Rocheleau, Michel, 1983, Evolution of the south-central segment of the Archean Abitibi Belt, Quebec. Part II: Tectonic evolution and geochemical model: Canadian Journal of Earth Sciences, v. 20, p. 1355-373.

Dimroth, Erich, Imreh, Laszlo, Goulet, Normand, and Rocheleau, Michel, 1983, Evolution of the south-central segment of the Archean Abitibi Belt, Quebec. Part III: Plutonic and metamorphic evolution and geotectonic model: Canadian Journal of Earth Sciences, v. 20, p. 1374-388.

Dimroth, Erich, Cousineau, Pierre, Leduc, Maxime, and Sanschagrin, Yves, 1978, Structure and organization of Archean subaqueous basalt flows, Rouyn-Noranda area, Quebec, Canada: Canadian Journal of Earth Sciences, v. 15, p. 902-18.

Furnes, Harald, Banerjee, Neil R., Muehlenbachs, Karlis, Staudigel, Hubert, and de Wit, Maarten, 2004, Early Life Recorded in Archean Pillow Lavas: Science, v. 304, p. 578-581.

Hannington, Mark D., Santaguida, Frank, Kjarsgaard, Ingrid M., and Cathles, Larry M., 2003, Regional-scale hydrothermal alteration in the Central Blake River Group, western Abitibi subprovince, Canada: implications for VMS prospectivity: Mineralium Deposita, p. 393-422.

McKenzie, Dan, and O'Nions, R. K., 1991, Partial Melt Distribution from Inversion of Rare Earth Element Concentrations: Journal of Petrology, v. 32, p. 1021-1091.

Mueller, W. U., Daigneault, R., Mortenson, J. K., and Chown, E. H., 1996, Archean terrane docking: upper crust collision tectonics, Abitibi greenstone belt, Quebec, Canada: Tectonophysics, v. 265, p. 127-50.