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PROVENANCE AND TECTONIC SETTING OF THE PALEOPROTEROZOIC DENHAM FORMATION IN EAST-CENTRAL MINNESOTA

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INTRODUCTION

The Denham and Little Falls Formations in east-central Minnesota are a Paleoproterozoic sequence of metamorphosed sedimentary and igneous rocks (Fig. 1, Fig. 1, Craddock et al., this volume). The deposition age of these rocks is unknown but is younger than the 2,557±15 Ma McGrath gneiss that unconformably underlies the Denham Formation and older than the 2,009 Ma mafic dikes that crosscut these rocks (Holm et al., 2005). Furthermore, a meta-basalt in the Denham formation has a Sm-Nd age of 2,197 Ma (Beck, 1988). The rocks were metamorphosed during the Penokean Orogeny around 1.8 Ga (McKenzie, 2004).

Previous studies present various hypotheses for the tectonic setting for the deposition of the rocks in the Denham area. Thurston (2002) suggests that after the Kenoran Orogeny (~2.7 Ga) the Superior Province was part of the Kenorland supercontinent until lithospheric stretching at 2.48 Ga broke this supercontinent apart. During the aftermath of this breakup (between 2.45 and 2.11 Ga) there were many intracratonic and continental margin basins created across the Canadian Shield, so it is possible that the Denham sequence is related to these events (Aspler et al., 2001). The time frame given in this scenario correlates with the age range of the Denham and Little Falls Formations. Boerboom and Jirsa (2001) also wrote that the Denham rocks “represent a rift-margin assemblage” and describe a model of intracratonic rifting where a shallow sea was created into which the McGrath Gneiss eroded.

The purpose of this study is to determine the tectonic setting of the Denham area during the time period of the deposition. Age dating of detrital zircons extracted from the Denham Formation was used to identify the provenance of the sediments that make up the meta-sedimentary rocks. Whole rock geochemistry of major and trace elements was used to determine the tectonic setting responsible for the formation of the meta-basalt that occurs in the middle of the Denham sequence.

STRATIGRAPHY OF THE DENHAM AND LITTLE FALLS FORMATIONS

The sediment and basalt sequence that appears to have been present is analogous to that of other areas of rifting in more modern times (Fig. 1). The rocks have been metamorphosed but their protoliths can still be identified. At the base of the formation is a conglomeratic arkose ranging up to a siltstone. This is interpreted as having occurred along a shoreline and as the basin deepened the siltstone was deposited in shallow water or on a mudflat. Above that, there is a dolomitic arkose that was also deposited in a supratidal zone. The overlying basalt is a common component in rifting and was deposited underwater as evidenced by the

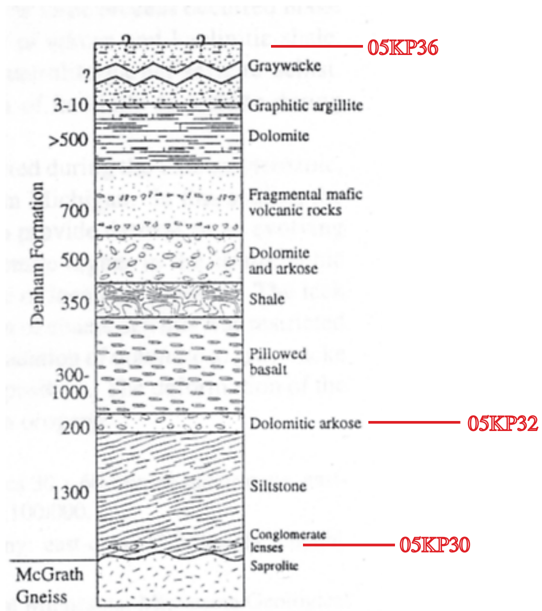

Figure 1: Stratigraphic column of Denham formation with sample locations indicated. Thicknesses in feet (Boerboom and Jirsa, 2001).

pillows. The overlying shale and dolomitic arkose are a repeat of the previous shoreline and shallow water sequence, followed by a deepening indicated by the dolomite that was deposited in a subtidal zone. Finally there is a schist for which the protolith is a turbidite deposited on a slope in deeper water (Prothero, 2004).

U-PB ZIRCON DATING

Samples from two different units of the Denham Formation, a conglomeratic arkose (05KP-30C) and a stratigraphically higher dolomitic arkose (05KP-32), and one sample from the overlying Little Falls Formation (05KP-36) (Fig. 1) were collected for detrital zircon separation. Standard separation procedures were used to extract the zircons from the rocks.

Laser Ablation-Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) was used for U-Pb dating of zircon following the procedures outlined in Chang et al. (2006). A total of 120 grains from sample 05KP-30, 106 grains from sample 05KP-32 and 1 grain from 05KP-36 were analyzed. A few grains in each sample were large enough or had distinct enough zoning to warrant multiple ablation spots and analyses on the same grain. Some of the analyses were rejected or labeled as suspect based upon analytical results. Any analysis for which ages determined by the three different isotope ratios are within 10% of Concordia are graphed on a Concordia diagram and a frequency histogram of ages.

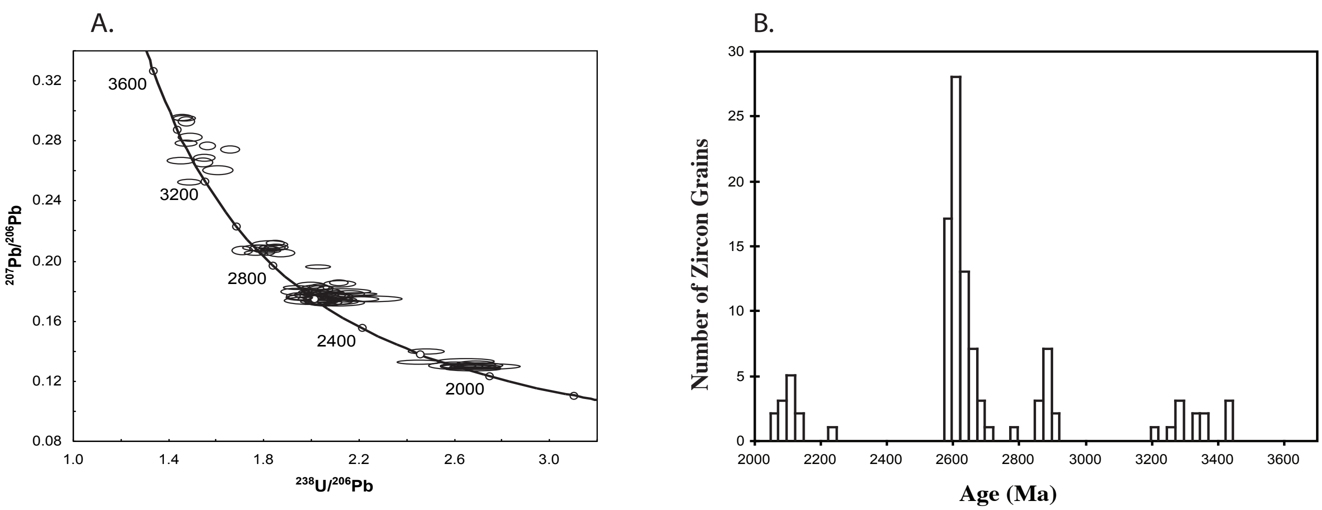

Figure 2: Inverse concordia diagram (A) and frequency histogram (B) for sample 05KP30 showing major input ages of around 2.1 Ga, 2.6 Ga, 2.7 Ga and 3.2-3.4 Ga. Both diagrams include only the ages that are more than 90% concordant. n=107.

An additional use of the zircon ages is to give a youngest possible age of deposition for the rock being studied. While the difference between the zircon's age and the date of deposition may be off by even billions of years in some cases, the rock unit will be no older than the youngest zircon in the sample (Andersen, 2005).

Sample 05KP-30 yielded 107 concordant analyses with distinct age populations at 2100 Ma, 2625 Ma, 2900 Ma, 3300 Ma, and 3450 Ma on the frequency distribution shown in Figure 2. The youngest zircon grain in this sample is 2,072±17 Ma, and the oldest grain is 3,447±17 Ma. Sample 05KP-32 yielded 54 concordant analyses with age populations at 2700 Ma and 3475 Ma on the frequency distribution shown in Figure 3. The youngest zircon grain in this sample is 2,173±11 Ma, and the oldest grain is 3,505±8 Ma. Sample 05KP-36 from the uppermost schist yielded only one zircon on which two analyses were done. Both analyses were more than 10% discordant yielding $^{207}Pb/^{206}Pb$ ages of 1,962.1±4.4 Ma and 1,929.5±4.9 Ma.

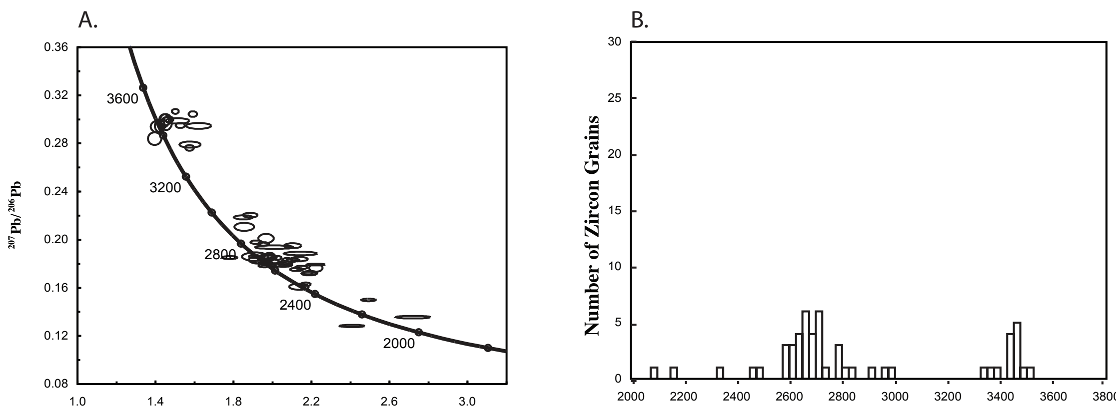

Figure 3: Inverse concordia diagram (A) and frequency histogram (B) for sample 05KP32 showing major input ages of around 2.7 Ga and 3.4 Ga. Both diagrams include only the ages that are more than 90% concordant. n=54.

META-BASALT GEOCHEMISTRY

A sample of amphibolite from the Denham Formation (05KP-33) was also collected for major and trace element geochemistry analysis. The protolith of the amphibolite is basalt, which can occur in many different depositional environments and tectonic settings. By comparing the results for the geochemistry of the Denham amphibolite to the values determined for other types of basalts, a conclusion can be made regarding the tectonic setting responsible for the Denham basalt. Whole rock geochemistry of the meta-basalt was determined using X-Ray Fluoroscence at Macalester College. Glass beads were used for major elements and pressed powders were used for trace elements.

The metabasalt in the Denham formation has a major element geochemistry of alkaline basalt with 53 wt% SiO_2 and 7 wt% Na_2O+K_2O with normative diopside, nepheline, olivine, plagioclase and orthoclase. Figure 4 is a triangle plot of trace elements Y, La, and Nb showing that, within measurement and graphical error, the trace element composition also indicates an alkaline composition.

DISCUSSION

The whole rock chemistry of the Denham meta-basalt supports the hypothesis of the Denham area having been a continental rift margin at the end of the Kenorland breakup. Alkaline basalt is seen in different tectonic settings and is a

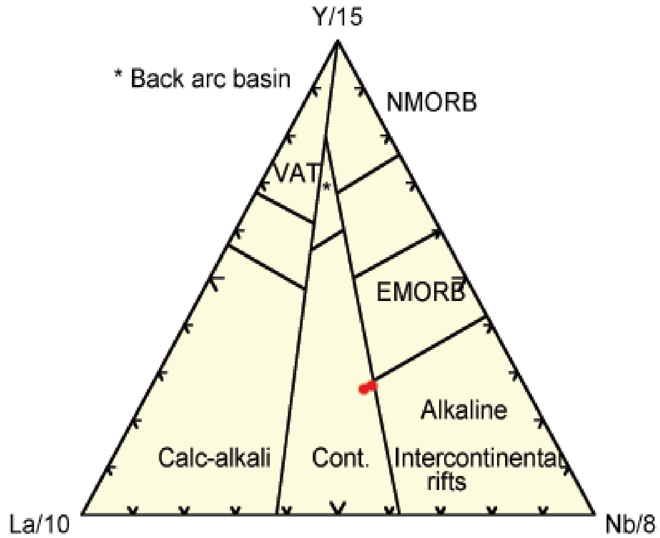

Figure 4: Plot of trace elements Y, La, and Nb in the Denham meta-basalt. The data fall on a line between EMORB, continental, and alkaline intercontinental rifts. Because of the uncertainty of exactly where the line gets drawn in these types of graphs and because of the other geochemical data, the basalt is interpreted as being alkaline.

common product of continental rifts, so the new evidence supports the proposed rift setting.

The first conclusion that can be reached from the LA-ICPMS work is the age of the Denham formation. It must be older than the cross-cutting dikes (2,009 Ma) and younger than the youngest zircon found (2,072.7±17.9 Ma in sample 05KP30). These ages place a tight constraint on the age of the Denham.

The possible source regions are located on a geologic map of Minnesota (Fig. 1, Craddock et al., this volume). One main region is the greenstone terrane of northern Minnesota and Canada, divided into the Wabigoon and Wawa subprovinces. These areas include ages of 3,000 Ma to 2,900 Ma, 2,830 Ma, and 2,720-2,730 Ma.

The other source region is the Minnesota River Valley, located in southwestern Minnesota. It includes granitic intrusions of several different ages. Schmitz et al. (2006) have dated zircons in different phases of the Morton Gneiss, one of these intrusions, between 3,145 Ma and 3,422 Ma. Bickford et al. (2006) dated the Morton Gneiss and the Montevideo Gneiss, another of these intrusions, at 3,500 Ma with a different zircon forming event between 3,440 Ma and 3,420 Ma. They also dated the growth of rims at 3,385 Ma and 3,140 Ma (Bickford et al., 2006). This area also includes an intrusion called the Sacred Heart Granite, dated at 2,604 Ma (Bickford et al., 2006) and 2,580 Ma (Schmitz et al., 2006).

The Morton and Montevideo Gneisses are most likely the sources for the zircons dated between 3,225 Ma and 3,450 Ma in sample 05KP30 and between 3,250Ma and 3,525Ma in sample 05KP32.

There are zircons from both sample 05KP30 and 05KP32 that are between the ages of 3,000 Ma and 2,900 Ma that may have originated from the Wabigoon Greenstone Subprovince. It is possible that the large groupings of zircons between the ages of 2,600 and 2,750 Ma are from both the Sacred Heart Granite and the greenstone subprovinces.

Hemming et al. (1995) suggest that ages around 2,100 Ma and 2,200 Ma in younger rocks can possibly be attributed to proterozoic rocks that we have no current record of. This may also be the case for these ages in the Denham formation.

There are few zircons with ages near the 2,557 Ma age of the McGrath gneiss. This is a very surprising result that this closest obvious source of zircons for the Denham rocks does not have definitive representation in the zircon age distribution. Instead of the hypothesis that the McGrath Gneiss eroded into an opening basin there must have been some other scenario where the McGrath did not provide sediment to the Denham formation and surrounding rocks contributed instead.

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