Provenance analysis of the Marquette Range Supergroup sedimentary rocks from northwestern Wisconsin and western Michigan using U-Pb isotope geochemistry on detrital zircons by LA-ICP-MS

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TABLE OF CONTENTS

Abstract

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ABSTRACT

Recent advancements in high-resolution U-Pb dating of heavy mineral fractions in sedimentary rocks have been increasingly useful in provenance studies. New LA-ICP-MS (laser ablation inductively coupled plasma mass spectrometry) data have been obtained from detrital zircon populations within the Palms and Tyler Formations, sedimentary units of the Marquette Range Supergroup in northwestern Wisconsin and western Michigan. The zircons from the Palms Formation are dominated by Neoarchean $^{207}Pb/^{206}Pb$ ages between 2664 and 2830 Ma with the strongest concentration of ages at ca. 2706 Ma. A Mesoarchean $^{207}Pb/^{206}Pb$ age of ca. 3523 Ma is also present. These data correspond with known ages of Archean rocks in the Lake Superior region. Thus, the Puritan quartz monzonite (2735 ± 16 Ma) and related volcanic rocks and the gneisses of the Watersmeet Dome region (3410-3600 Ma) and intruding dikes (ca. 2600 Ma) probably represent the major sediment source of the Palms Formation. The Tyler Formation records a strong Paleoproterozoic $^{207}Pb/^{206}Pb$ age between 1818 and 1938 Ma, with the youngest ages at 1818 ± 15 Ma. A Neoarchean component is present with $^{207}Pb/^{206}Pb$ ages between 2525 and 2815 with an average age of ca. 2665 Ma, along with additional ages of 2949, 2023, 2402, and 3168. The Paleoproterozoic ages in the Tyler Formation are typical of ages in igeneous intrusive rocks (1860 to 1835 Ma) that were emplaced in the Wisconsin magmatic terranes during the Penokean orogeny. The Neoarchean age of 2665 Ma, along with the lesser input of 2949 and 3168 Ma grains, represent ages typical of the high-grade gneiss and granite rocks of the Marshfield terrane.

Keywords: Marquette Range Supergroup, Paleoproterozoic, Archean, LA-ICP-MS, U-Pb, zircon, provenance

INTRODUCTION

Precambrian rocks of the Lake Superior region have long been of interest, largely due to the presence of extremely old (3.6 Ga) rocks thought to represent remnants of Earth's earliest crust and because of the occurrences of major economic deposits of iron-formations. However, even with a long history of petrologic, structural, geochronological, and geochemical study of the Precambrian terranes of the Lake Superior region, much of the tectonic history of this area remains to be understood. Sedimentary successions can provide important records of tectonic processes and orogenic cycles, but studies of sedimentary units in the Lake Superior region are complicated by incomplete preservation of Precambrian strata and a widespread blanket of Pleistocene glacial deposits that covers most of the region. A variety of recent advancements in the development of high-resolution U-Pb dating techniques of detrital zircon have allowed detailed studies of Precambrian sedimentary rocks (e.g. Van Wyck and Norman, 2004; Pufahl and Fralick, 2004; Medaris et al., 2005). Provenance studies utilizing these new dating methods can provide valuable insights into the depositional environments of these rocks which in turn help describe the tectonic evolution of the Lake Superior region.

In this study, I use U-Pb isotope geochemistry from detrital zircons contained in the sedimentary record of the Palms and Tyler Formations of northwestern Wisconsin and western Michigan to determine the provenance of these sedimentary deposits. This project is part of a larger, collaborative geochronological study undertaken by the Keck Geologic Consortium Minnesota Research Group, under the direction of Professors Craddock, Davidson, and Wirth of Carleton College and Macalester College. In this paper, I 1) present new U-Pb age dates from detrital zircons contained in the sedimentary Palms and Tyler Formations of Wisconsin and Michigan, 2) correlate these ages with intrusive or thermotectonic events, and 3) attempt to constrain the provenance of these formations.

Detrital Zircon Geochronology

The analysis of heavy detrital mineral fractions in clastic sedimentary rocks is useful for interpreting the sediment source and depositional environment of ancient sediments (Fedo et al., 2002). Detrital zircon ($ZrSiO_4$) plays a particularly prominent role in heavy-mineral fraction sediment provenance studies. A common accessory mineral in most rocks, zircon occurs in nearly all sedimentary deposits and is often studied because of its resistance to chemical weathering and physical breakdown during transport (Pollock et al., 2002). Zircon is useful in geochronological studies due to its extremely high U/Pb ratio at the time of formation and its ability to retain the daughter products of U and Th during radioactive decay (Fig. 1). The fact that U-Pb dating involves two different U isotopes decaying at different rates to two different Pb isotopes provides the possibility to detect potential isotopic disturbances (Bourdon et al., 2003). In an undisturbed system, both the ^{238}U-^{206}Pb and ^{235}U-^{207}Pb decay should have consistent ratios yielding the same ages and plot on a concordia diagram. Isotopic disturbances, generally caused by Pb loss, result in discordant ages.

Myriad studies utilizing detrital zircon in the past 20 years have been increasingly successful in both discovering the maximum age of stratigraphic successions and time gaps in the geologic record, in determining provenance characteristics such as age and composition, and in testing regional paleogeographic reconstructions via

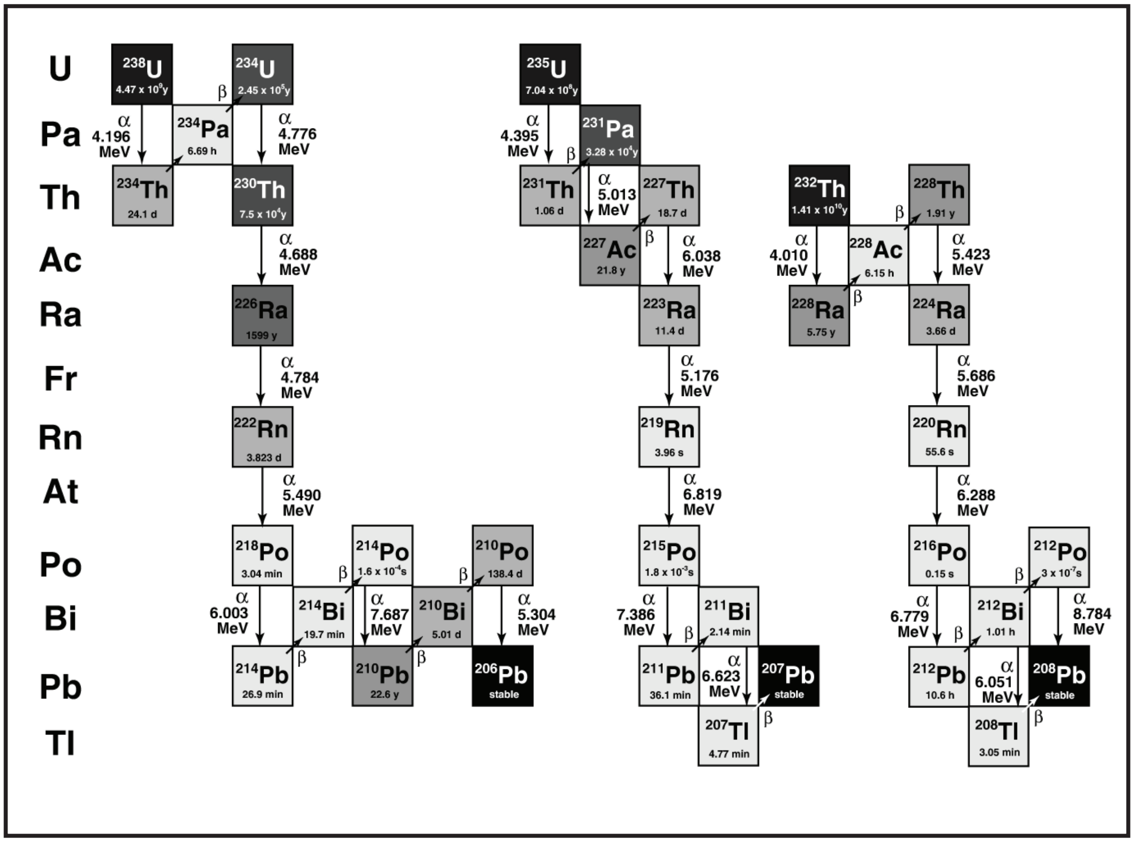

Figure 1. Schematic drawing of the ^{238}U, ^{235}U and ^{232}Th decay chains, from Bourdon et al., 2003. The grayscale reflects half-life, with darker greys for longer half-lives. In an undisturbed system, both the ^{238}U-^{206}Pb- and ^{235}U-^{207}Pb-decay should have consistent ratios, yielding the same ages and plotting directly on a concordia diagram.

provenance analysis (e.g. Fedo et al., 2002 and references therein). This success can be contributed to the development of single grain and in situ dating methods, such as SHRIMP (sensitive high resolution ion microprobe) and LA-ICP-MS (Laser ablation inductively coupled plasma mass spectrometry) dating. Compared to SHRIMP dating, LA-ICP-MS is less precise but faster and much more cost-effective. Thus, LA-ICPMS dating is especially useful for provenance studies which require the measurement of up to 100 grains per sample in order to include all major sedimentary source components (Bernet and Speigel, 2004). The main problems of LA-ICP-MS dating are an instrumental mass bias and a laser-induced elemental fractionation of U and Pb due to volatility differences (Chang et al., in press). These errors can be corrected externally by repeated measurements of a standard during sample collection.

Sediment provenance analysis is an extremely important application of detrital geochronology because sediment source areas show distinct patterns of U-Pb crystallization, especially in orogenic settings. Cooling ages derived from bedrock samples often cluster in certain age groups rather than a continuum of ages across an orogen (Bernet and Speigel, 2004). Thus, the single ages derived from detrital zircon analyses can be compared with the age patterns of potential source areas, leading to better understanding of the tectonic history of the studied region.

TECTONIC SETTING

When using detrital zircon fractions for sediment provenance studies, it is necessary to compare geochronological data with other detrital data or known provenances to interpret the origins of the zircon; this requires an understanding of the tectonic history and geologic setting of potential source regions. The generalized tectonic framework of the Lake Superior Region is presented in Figure 2. Archean-aged gneiss and granite rocks (ca. 3500 Ma-3100 Ma) are exposed in the Minnesota River Valley (southern MN), the Watersmeet Dome region (northern MI) and within the Marquette Range region (WI/MI). While the best studied of these Mesoarchean rocks are those of the Minnesota River Valley on the southern margin of the Superior craton, the granite and gneiss rocks in Wisconsin and Michigan are approximately the same age and appear to have had similar subsequent histories (Bickford et al., 2006; Sims, 1980 and 1991; Schneider et al., 2002). The presence of these ancient terranes on both the northern and southern margins of the Superior craton suggest they are remnants of earlier, perhaps more extensive, continental crust that was involved in the formation of the Superior craton in the interval 3000-2700 Ma (Bickford et al., 2006). Indeed, the Mesoarchean granite-gneiss units are juxtaposed with predominately juvenile Neoarchean (ca. 2.7 Ga) granite-greenstone terranes. Morey and Sims (1976), Sims et al. (1989), and Sims (1991) recognized the boundary between the granite-greenstone terrane and the older gneiss-granite rocks on the basis of contrasts in their respective aeromagnetic and gravity anomalies and defined it as the Great Lakes Tectonic Zone (GLTZ). The GLTZ has been interpreted as a north-dipping (30-40^o) paleosuture (thrust zone) that resulted from a continent-continent collision in late Archean time (Ojakangas et al., 2001). The Archean craton began to undergo extension at ca. 2700 Ma (Ojakangas et al. 2001). An ocean basin, south of present-day Lake Superior, opened as a result of extension; this extension resulted in localized rifts in the form of graben/half graben basins. Sediment and volcanic rocks removed by erosion from the craton margin accumulated and were preserved in these basins. These sedimentary deposits now exist as the Chocolay Group

in Wisconsin and Michigan (LaBerge and Mudrey, 1979). The rift stage was terminated by actual crustal separation and sea-floor spreading and was followed by a phase of convergent tectonics that produced a volcanic island arc (LaBerge and Ojakangas, 1992). The island arc, preserved as the Wisconsin magmatic terranes, moved northward and collided with the southern margin of the Superior craton between 1895 and 1835 Ma in an event known as the Penokean Orogeny (Sims et al., 1989). In Wisconsin and Michigan, the Penokean can be divided into three different segments; from north to south, they are deformed and metamorphosed Paleoproterozoic sediment overlying Archean basement of the Superior craton, a central volcanic arc segment, and southern Archean crustal block (Van Wyck and Norman, 2004). In addition, LaBerge and Mudrey (1979) suggest that the accretion of the volcanic arc to the craton resulted in a fold-and-thrust belt with a foreland basin to the north, where sediments of the Marquette Range and Animikie Groups, composed of basal quartzites, iron-formations, and slate-greywacke sequences, were deposited. Following the termination of the Penokean orogeny, a period of widespread magmatic activity dominated by rhyolites and alkali granites occurred (Van Wyck and Norman, 2004; Medaris et al., 2005). Around 1.1 Ga, a rift system, known as the Midcontinent Rift System, developed in central North America. The rift extends from what is now eastern Lake Superior to present-day Kansas (Craddock, 1979; Ojakangas and Matsch, 1982). The rift system brought the Keweenawan Supergroup Volcanic rocks to the Lake Superior region; these volcanics unconformably overlie the sedimentary deposits of the Marquette Range Supergroup and the Animikie Group.

GEOLOGIC SETTING

This study primarily focuses on the metasedimentary units of the Marquette Range Supergroup (MRS) of the Gogebic and Marquette Ranges (Fig. 3). The MRS is a Paleoproterozoic continental margin assemblage that lies unconformably upon the southern margin of the Archean Superior craton in northern Wisconsin and Michigan. The MRS includes, from oldest to youngest, the Chocolay Group, a shelf marine facies, the Menominee Group, turbidites passing up into banded iron formation and the Baraga Group, a sequence of shales and turbidites (Ojakangas et al., 2001). The sedimentary rocks in this area generally increase in thickness from north to south. In the Gogebic Range (northwestern Wisconsin) the succession is about 2 km thick and increases to as much as 9 km thick in the Marquette Range along the Michigan-Wisconsin border (Morey 1993, 1996).

Chocolay Group

Archean granitic and mafic volcanic rocks are unconformably overlain by the lowest units of the Chocolay Group of the MRS, Sunday Quartzite and Bad River Dolomite (Fig. 4). The basal unit of the MRS, Sunday Quartzite, is a prominently cross-bedded reddish quartzite containing conglomerate layers of quartz and granite cobbles in the lower part of the formation (LaBerge and Ojakangas, 1992). The majority of the formation is a gray quartzite, punctuated with current ripple marks and cross-bedding. The Sunday Quartzite grades upward into the Bad River Dolomite; the transition between the two is characterized by interbedded dolomite and quartzite (LaBerge and Mudrey, 1979). The dolomite is usually grey to buff colored and contains irregular, patchy beds of chert and stromatolitic layers (LaBerge and Mudrey, 1979). Quartzose beds are common in the upper part of the formation. In most locations, the Bad River Dolomite

has been metamorphosed to a tremolitic siliceous marble. Following the deposition of the Chocolay Group rocks, a period of erosion occurred which removed the Sunday Quartzite and Bad River Dolomite from all but the western end of the Gogebic range and the eastern end of the Marquette Range.

Palms Formation

The Palms Formation comprises the basal detrital unit of the Menominee Group of the MRS; it correlates lithologically with the Pokegama formation of Minnesota, the basal detrital unit of the Animikie Group (Fig. 4) (LaBerge and Ojakangas, 1992). Approximately 140 meters thick in Wisconsin, the formation thickens to about 230 meters east of Wakefield, Michigan (LaBerge and Murdrey, 1979). The Palms Formation is composed of three mapable units: (1) a basal conglomerate unconformably overlying Lower Precambrian greenstone and granite (in the central part of the range) or Bad River Dolomite and Sunday Quartzite (on the east and west ends of the range); (2) a thin- to medium-bedded buff-pink quartzite with thin interbeds of argillite or greywacke; and (3) a buff to pink, medium- to thick-bedded quartzite (LaBerge and Mudrey 1979). The dominant framework of the quartzite member is composed of well-rounded quartz and feldspar grains with a minor component of chert grains (LaBerge and Ojakangas, 1992). At the top of the Palms Formation, thin beds of granular iron-formation are interbedded with quartzite with the abundance and thickness of beds of iron-formation increasing upward with a corresponding decrease in detrital beds. This transition marks the conformable contact between the Palms Formation and the overlying Ironwood Iron-Formation and signals a major change from detrital to chemical sedimentation (Ojakangas et al., 2001).

Ironwood Iron Formation

The Ironwood Iron Formation consists of silica and iron-bearing minerals which have been divided into two facies types, slaty and cherty. The slate is a chemical mudstone consisting of fine layers of Fe-oxide and chert. The chert is a grainstone composed of rounded, sand-sized intraclasts of chert, Fe-oxide, Fe-carbonate, and/or Fe-silicate (Pufahl and Fralick, 2004). The iron-formation contains little detrital material, even though it is 600 to 900 meters thick in places (Aldrich 1929, LaBerge and Mudrey, 1979). While the iron-formation has a simple composition of chert and iron materials, it is extremely varied in appearance and has thus been divided into five members based on the dominant texture and bedding characteristics (LaBerge and Ojakangas, 1992). Throughout the Lake Superior Region, iron-formations are overlain both conformably and unconformably by thick slate-greywacke sequences and intercalated with volcanic rocks (Fig. 4). This signals a change back to detrital sedimentation along with volcanic activity (LaBerge and Mudrey, 1979).

Tyler Formation

In the Gogebic Range, the Tyler formation conformably overlies the Ironwood Iron-Formation (Fig. 4) (LaBerge and Mudrey, 1979). The Tyler is lithologically comparable to the Copps Formation at the eastern end of the range, the Michigamme Formation to the east, and the Rove, Thomson, Rabbit Lake, and Virginia Formations of Minnesota and Ontario (Ojakangas et al., 2001). The formation is composed of a thick sequence (approximately 2500 m) of interbedded greywacke/siltstone and argillite/slate. The typical Tyler greywacke framework contains quartz (73%), rock fragments (17%) and feldspar (10%), suggesting a granitic quartz-diorite provenance (Alwin, 1979).

Although the majority of the beds are structureless, some of the greywacke and siltstones show signs of turbidity current deposition, such as graded bedding, rip-up clasts, and Bouma sequences. Paleocurrent indicators, marked by sole marks and small-scale cross-bedding, show movement toward west-northwest and have little stratigraphic variation, suggesting a single source area for all of the Tyler Formation (LaBerge and Mudrey, 1979).

ANALYTICAL METHODS

Detrital zircon samples were processed at Macalester College using conventional mineral separation techniques (crushing, disc mill, Wilfley table, magnetic free-fall) followed by heavy liquid separation in methylene iodide (specific gravity 3.32) and further magnetic separations with a Barrier Frantz isodynamic separator. From the separated portion, approximately 100 grains per sedimentary unit were selected randomly in an attempt to include the complete range of colors and morphological types in order to analyze zircons that would reflect all of the possible source terranes. The selected zircons were mounted, along with the laboratory standards Peixe and FC-1 (564 ± 4 Ma and 1100 Ma, respectively; Chang et al., in press), with epoxy in 1-inch diameter grain mounts and polished to expose flat surfaces at the cores of the grains for analysis. Cathodoluminescence (CL) images of the zircons were collected at the University of Idaho and backscattered electron (BSE) images were collected at Carleton College, both with a JEOL 5600 scanning electron microscope (SEM), in order to identify growth rims and inclusions within the zircons and to provide a base map for recording laser spot locations. An attempt was made to sample both cores and rims of the zircons, especially when obvious growth rims were apparent. However, due to the small size of the grains in this study, analyses were generally limited to the core of the zircon.

Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS) analyses were performed in the GeoAnalytical Lab at Washington State University under the direction of Jeff Vervoort, Cameron Davidson, Karl Wirth and John Craddock, along with KECK 2005 student participants. Laboratory procedures for collection of the U-Pb data are described by Change et al. (in press). All work was performed using a ThermoFinnigan Element2 single collector double focusing magnetic sector ICP-MS coupled with a New Wave UP-213 laser ablation system operating with a wavelength of 213 nm. Zircons were ablated using a laser frequency of 10 Hz and a laser density of approximately 10J/cm^2. The laser beam was focused on the sample surface and ablation pit sizes ranged from 30 to 40 µm in diameter.

The ablated material was carried to the ICP-MS by He and Ar gas. Each analysis consisted of a 6 second warm-up, an 8 second delay to enable the sample to reach the plasma, and 35 seconds (300 sweeps) of rapid scanning in the e-scan (electric scan) mode. Data were acquired in pulse counting detector mode with 3 points measured per peak to obtain the masses of ^{202}Hg, ^{204}(Pb + Hg), ^{206}Pb, ^{207}Pb, ^{208}Pb, and ^{235}U, while analog mode was used to obtain the masses of ^{232}Th and ^{238}U. Quadrupole settling time was 1 ms for all masses and the sample time was 4 ms. The Element2 was tuned before each session using the NIST 612 glass standard and the zircon standard Peixe was analyzed until fractionation was stable and the variance in measured ^{206}Pb/^{238}U and ^{207}Pb/^{206}Pb ratios were at or near 1% (1 sigma standard deviation). A gas blank was collected in counting mode before each analysis with the plasma on but laser not firing. All operating parameters, including ICP-MS and laser settings, were held constant for standards and unknowns to minimize any potential bias between samples and standards.

Data reduction was performed following the method described by Chang et al. (in press). The raw data were corrected for fractionation and downloaded to a computer for off-line processing using an Excel program supplemented with Visual Basic macros. Final ages, concordia diagrams and probability density distribution-histogram plots were produced using the Isoplot/Ex macro (Ludwig, 2003).

RESULTS

I obtained LA-ICP-MS age data for zircons from the Palms and Tyler formations in northwestern Wisconsin and western Michigan. Sample locations are shown on Figure 3 and analytical data are summarized in Table 1. Complete analytical data are given in Appendices 1 and 2.

Palms Formation

I collected approximately 10-kg of medium-grained quartzite of the Palms Formation (KP05-42) from an outcrop near Radio Tower Hill in Wakefield, MI, off of Highway 2 (Fig. 3). The rock at this locality consists of interbedded argillite, siltstone, and sandstone transitioning to massive feldspathic quartzite (Fig. 5A). Most beds are continuous across the outcrop with lenticular beds of cross-bedded sandstone. Measurements of cross-bedding show a strong paleocurrent trend to the west with a weaker trend to the east. At this location, the Palms formation dips steeply 80º to the north.

Zircons separated from the Palms Formation are strikingly similar, consisting of small and primarily subhedral grains (Figs. 6 and 7). LA-ICP-MS analysis yielded the

data summarized in Table 1 and plotted in Figures 8 and 9. The 111 concordant grains analyzed from the sample are split into three groups that are well separated in frequency and age. The histogram in Figure 9 shows one major cluster of analyses (108 out of 111) of Neoarchean ^{207}Pb/^{206}Pb ages between 2664 and 2830 Ma. These zircons varied from 1 to almost 10 percent discordant and show a concentration of ages at ca. 2706 Ma. Although represented by only 2 grains, a Mesoarchean ^{207}Pb/^{206}Pb age of ca. 3523 Ma is present. One grain yielded a three percent discordant ^{207}Pb/^{206}Pb age of 2594 ±12 Ma, the youngest age represented in this data set.

Tyler Formation

I collected approximately 10-kg of medium- to coarse-grained sample of the Tyler Formation (KP05-40) from a road cut at the junction of U.S. Highways 51 and 2, north of Hurley, WI (Fig. 3). The sample is a greywacke-slate sequence; the greywacke beds contain Bouma sequences, rip-up clasts, and small-scale cross-bedding (Fig. 5B). The beds at this locality strike east-northwest and dip 60º-75 º northwest.

The Tyler Formation contains abundant prismatic zircons of a broad size and shape range (Figs. 6 and 7). LA-ICPMS analytical data (Table 1, Figs. 10 and 11) yielded 100 grains of less than ten percent discordance and suggest that the ages of the sample contain several populations of detrital zircons. Most of the zircons (76 out of 100 concordant grains) have Paleoproterozoic ^{207}Pb/^{206}Pb ages between 1818 and 1938 Ma with the youngest ages at 1818 ± 15 Ma. The well-defined peaks of the histogram in Figure 11 show the strongest concentration at ca. 1850 Ma. A second cluster of ages is represented by 18 grains with ^{207}Pb/^{206}Pb ages between 2525 and 2815 Ma with an average Neoarchean age of 2665 Ma. The analyses in this range tend to fall either on concordia or slightly below. The data show additional $^{207}Pb/^{206}Pb$ ages of 2949 (2 analyses), and 2023, 2402, and 3168 Ma, each represented by one analysis that falls slightly below concordia.

DISCUSSION

Provenance Interpretation

Palms Formation

U-Pb data from detrital zircons of the Palms Formation indicate that the age spectra within these rocks are dominated by Neoarchean zircons with a minor Mesoarchean input. The majority of analyzed grains within the Palms Formation have an age of ca. 2706 Ma. The youngest zircon yields an age of 2594 ± 12 Ma which indicates a maximum age of deposition to be between Neoarchean and Paleoproterozoic. These detrital zircon ages for the most part match what is known about the age of Archean basement rocks in the Superior Province (Fig. 12). Specifically, the cluster of $^{207}Pb/^{206}Pb$ ages between 2664 and 2830 Ma present in the Palms Formation have been similarly recorded in studies by Sims et al. (1980), revealing an age of 2735 ±16 Ma for the Puritan quartz monzonite, a pluton that intrudes the Ramsay Formation (mafic and felsic metavolcanic rocks), outcropping just south of the site of sample KP05-42. Thus, the Archean Puritan quartz monzonite and related intrusions probably represent a major component in the sediment source to the Palms Formation.

The Palms also contains a Mesoarchean age signature represented by two analyses of 3523 Ma. These ages correspond with geochronological data from tonalitic gneiss protoliths exposed in the Watersmeet Dome in northern Michigan which indicate that this rock is between 3410 Ma and 3600 Ma (Bickford et al., 2006). Leucogranite

dikes intruding the Watersmeet Dome gneiss reveal ages of ca. 2600 Ma (Van Wyck and Norman, 2004), which can explain the presence of the 2594 ± 12 Ma analysis.

Tyler Formation

The detrital zircon data contained in the Tyler Formation is dominated by Paleoproterozoic grains of ca. 1850 Ma. This age is typical of igneous intrusive rocks that were emplaced in the Wisconsin magmatic terranes during the Penokean orogeny (Van Wyck and Johnson, 1997). In Wisconsin, the orogen has been divided into two terranes, a northern Pembine-Wausau terrane and a southern Marshfield terrane, both of which contain numerous Penokean synorgenic plutons (Fig. 9). Of these, the Marshfield terrane contains calc-alkaline plutons of granitic composition with age components ranging from 1860 to 1835 Ma (Sims et al., 1989, 1993). Therefore, these Penokean volcanics in the Wisconsin magmatic terranes represent the major component in the sediment source to the Tyler Formation. The maximum age of deposition for the Tyler Formation is the age of the youngest recorded zircons: Paleoproterozoic grains of 1818 ± 12 Ma. This age could potentially push the boundary of rocks considered to be Penokean in age, usually thought to end ca. 1835 Ma (Bickford et al., 2006).

The Tyler Formation also records a Neoarchean U-Pb age range of 2525 and 2815 Ma with an average age of 2665 Ma, along with lesser input of 2949 and 3168 Ma grains. The source of these grains is most likely the high-grade gneiss and granite rocks of the Marshfield terrane, which Van Wyck and Norman (2004) showed to contain zircons of 2550, 2680, and 3000 to 3200 Ma (Fig. 12).

Samples in the Tyler Formation show contributions of ages from 2023 and 2402 Ma sources. These ages are significant yet problematic because there is no evidence for local derivation of these grains, since gneisses of these ages are unknown in the Wisconsin/Michigan region (Van Wyck and Norman, 2004). There are two interpretations for the provenance of these detrital data: either crustal rocks of this age do occur locally and are buried or have yet to be identified through high-resolution dating techniques, or these grains were introduced to the Tyler Formation from terranes outside the Lake Superior region. In a study of LA-ICP-MS geochronology detrital zircon ages of early Proterozoic quartzites in Wisconsin, Van Wyck and Norman (2004) posit the possibility that the source of 1.9-2.3 Ga zircons contained within their sampled Baraboo quartzite could be explained by recent geophysical studies that indicate the southern limit of the Marshfield terrane is marked by an east-west lineament called the Trempealeau discontinuity (Cannon et al., 1999). The Trempealeau discontinuity could possibly separate the Marshfield terrane from distinct Pre-Penokean crust south of the discontinuity, which may well be the source of the 2023 and 2402 Ma grains within the Tyler.

Tectonic Implications

The tectonic setting of the Lake Superior region during the Paleoproterozoic remains controversial. Primarily based on sedimentological and stratigraphic data, Hoffman (1987) and Barovich et al. (1989) proposed that the Paleoproterozoic sequences were deposited in a migrating foreland basin that formed in response to crustal loading during the Penokean Orogeny. The foreland basin model was modified by Morey and Southwick (1995) and developed further by Ojakangas et al. (2001); these studies ascribed the deposition of the Marquette Range and Animikie Groups to continental rifting during early, pre-collisional phases of the Penokean orogenic cycle. Conversely, Schneider et al. (2002), Pufahl and Fralick et al. (2004) and others suggest that the MRS sequences were deposited on an intermittently active, southward-sloping continental margin, with subsidence being driven by back-arc extension, as put forth by Hemming et al. (1995).

Recent geochronological studies using U-Pb dating of detrital zircons support the back-arc model of deposition (Van Wyck and Johnson, 1997; Schneider et al., 2002; Pufahl and Fralick, 2004, Van Wyck). Similarly, this study finds that the strong presence of Penokean grains within the Tyler Formation suggest that its deposition was contemporaneous with the arc-related volcanic rocks now preserved as the Wisconsin magmatic terranes. This can best be explained by the back-arc model which, based on SHRIMP U-Pb data from units within the MRS, was outlined by Schneider et al. (2002). This model, built around several geological constraints, envisions oblique Penokean subduction driven by back-arc extension. An important constraint in the derivation of this model involved the correlation of lithostratigraphic units, specifically iron-formations, throughout the region. Surely, further studies comparing the LA-ICP-MS U-Pb age results for the Palms and Tyler Formations of this study with their correlative units in Minnesota will help to further develop the tectonic framework of the back-arc model of deposition for the Paleoproterozoic sedimentary units of the Lake Superior region.

CONCLUSION

LA-ICP-MS ^{207}Pb/^{206}Pb ages of detrital zircons from the Palms Formation indicate that this sedimentary unit was derived from the Neoarchean basement rocks consisting of the Puritan quartz monzonite and its correlative rocks with a Mesoarchean input from the high-grade gneiss rocks of the Watersmeet Dome region. Detrital zircons within the Tyler Formation contain a major population of Penokean grains of ca. 1850 Ma, suggesting a provenance of Penokean synorgenic plutons emplaced in the Marshfield magmatic terranes of Wisconsin. The Neoarchean U-Pb age of 2665 Ma, along with lesser input of 2949 and 3168 Ma grains, are from the high-grade gneiss and granite rocks of the Marshfield terrane.

This study proves the effectiveness of using LA-ICP-MS for detrital zircon geochronology. Although less precise that SHRIMP analysis, this method provides an efficient and cost effective technique, offering the potential to analyze the large number of zircon grains necessary for an effective provenance study. Continuing U-Pb dating of detrital zircons contained within the stratigraphic record of the Lake Superior region will strengthen the stratigraphic and temporal relationships of Precambrian sedimentary units for the entire Lake Superior region as well as contribute to new interpretations of Precambrian tectonic history.

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