U-Pb Detrital Zircon and Geochemical Provenance Study of Precambrian Low-Grade Metasedimentary Rocks from Eastern Kansas and Western Missouri

by

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ABSTRACT

U-Pb analyses of single detrital zircons and bulk geochemical analyses were conducted to test the idea that pre-Late Cambrian, low-grade metasedimentary rocks from the basement of eastern Kansas and western Missouri were derived, in part, from clastic sedimentary rocks of the 1.1-1.2 Ga Midcontinent Rift. The 1.1-1.2 Ga arkosic rift sediments were proposed to have been eroded off of the Nemaha Uplift, and transported and deposited in structurally controlled basins in eastern Kansas and western Missouri.

Geochemical provenance and tectonic setting analyses of the metasedimentary rocks indicate derivation from average upper continental crust source rocks from an intracratonic setting. Enrichment in Cr, Ti, Co and Ni concentrations relative to clastic rocks of the Midcontinent Rift suggests a minor (<5%) mafic source input not seen in the rift derived clastic rocks.

U-Pb detrital zircon data extracted from the pre-Late Cambrian low-grade clastic metasedimentary rocks place a maximum age of deposition for one well at 1.0 Ga and for another well at 620 Ma. A minimum age limit is provided by the Late Cambrian-Early Ordovician Reagan and Lamotte sandstones that unconformably overlie the clastic rocks.

Additional provenance ages from the low-grade metasedimentary rocks range from 1.60-1.83 Ga. Provenance ages derived from the clastic rocks of the Midcontinent Rift System range in age from 1.1-1.2; 1.3-1.5; and 1.7-1.8 Ga. No zircons of the age range 1.1-1.2 and 1.3-1.5 Ga were found in the clastic metasedimentary rocks studied here, and only a few zircons fell in the age range 1.7-1.8 Ga. The majority of the zircons fell in the age range 1.6-1.7 Ga, a range not represented in the clastic rocks of the Midcontinent Rift system. Provenance ages derived from the low-grade metasedimentary rocks are not consistent with those derived from clastic rocks of the Midcontinent Rift System, and in fact, argues against the idea that the metasedimentary rocks were derived from clastic rocks of the Midcontinent Rift System.

Data indicate that these rocks are Neoproterozoic-Early Cambrian in age. The 1.0 Ga zircons may have been derived from the Grenville Orogen, and reached the basin by way of a pan-continental river system draining the Grenville Orogen (Rainbird, 1997). A source for the 620 Ma zircons is unknown at this time; however, data may point to igneous activity associated with the breakup of Rodinia. The absence of 1.3-1.5 Ga zircons, the age range of surrounding basement rocks, suggest that the surrounding basement rocks may have been covered by a blanket of sedimentary rocks prior to deposition of the low-grade metasedimentary rocks, and that the rocks probably received detritus from more distant regions. Continued isotopic, geochemical and petrographic studies are needed to address these ideas.

INTRODUCTION

The Midcontinent is a region of well-documented igneous and high-grade metamorphic provinces that range in age from the 1.8-1.6 Ga Central Plains Orogen (CPO), to the 1.1 Ga Midcontinent Rift System (MCR). Within the Precambrian basement of Kansas and Missouri, isolated packages of low-grade, clastic metasedimentary rocks have been penetrated by deep drilling. For example, one well in Vernon County, Missouri penetrated up to 300 meters of alternating units of feldspathic quartzite and metasiltstone (Skillman, 1948, Adams, 1956, Denison, 1966). These clastic rocks appear to occur in fault-bounded basins, as determined from potential field maps and subsurface mapping (Kisvarsanyi, 1974, 1984). Little is known, however, regarding the age and provenance of these rocks.

Some researchers (e.g. Skillman, 1948) have pointed out that these clastic sequences are pre-Late Cambrian, for they are unconformably overlain by basal sandstones of the Sauk transgression. Due to the often observed presence of rhyolite clasts in drill cuttings and in thin section, Denison (1966) and Sims et al. (1987) conjectured that the rocks were deposited concurrently with or subsequent to the formation of the 1.34-1.40 Ga Southern Granite-Rhyolite province (Van Schmus et al., 1993). Berendsen and Blair (1995) hypothesized that these low-grade metasedimentary rocks were derived from clastic sedimentary rocks of the 1.1 Ga Keweenawan rift. They proposed that the flanking rift basins were uplifted and eroded along the Nemaha tectonic zone sometime after the tectonic inversion stage of the Midcontinent Rift System (MCR). They also suggested that clastic sediments from the eastern Keweenawan rift basin were transported to and deposited in structurally controlled basins in eastern Kansas and western Missouri.

The main thrust of this study was to test the supposition that the low-grade metasedimentrary rocks were, at least in part, derived from the MCR clastic sedimentary rocks that are believed to have been eroded off of the Nemaha Uplift. The first part of this hypothesis tested was that these clastic rocks were deposited in the interim between MCR activity at 1.1 Ga and the Cambro-Ordovician Sauk Transgression (ca. 500 ma). Secondly, this study tested for a geochemical correlation between these clastic rocks and those of the MCR flanking basins.

I used U-Pb geochronology of single detrital zircon grains to constrain the age of deposition and for information regarding provenance. I also incorporated REE, trace and Sm-Nd isotopic geochemical techniques to gain further insight as to provenance and tectonic setting. I particularly focused on those elements that discriminate mafic versus felsic source rocks, primarily elements such as Cr, Ni, Co, V, Mg, Th, U, La and Sc. This study does not attempt to provide a complete provenance picture. Geochemical provenance data, while insightful, cannot stand alone. Detailed petrographic data are also required to construct a complete picture of tectonic setting and provenance, and are suggested for further study.

Geochronologic data suggest that the clastic rocks are indeed Neoproterozoic. Examination of Th/Sc, Cr/V, Cr/Th, Y/Ni ratios and La-Th-Cr and La-Th-Co ternary plots indicate a predominate upper-crustal felsic source; for the Cedar County, MO well, data also suggest the presence of a minor (<5%) mafic component. A comparison of my results with the geochemical signatures of Keweenawan clastic rocks yielded no conclusive evidence of a connection between them, and, in fact, argue against a connection. One sample yielded a suite of 1.0 Ga zircons, which strongly suggests a Grenvillian age source, possibly from the east. The same sample also has anomalously high concentrations of Cr, V, Ni, and Co relative to the clastic rocks of the Midcontinent Rift. It is possible that these rocks may be remnants of a Grenville Orogen foreland basin. Further study of these rocks and other similar rocks in the Midcontinent region, most notably the Tillman Metasedimentary group of Oklahoma, may yield more conclusive evidence for interpretation as a Grenvillian foreland basin, and may also provide important information with regard to latest Neoproterozoic to Early Cambrian plate reconstructions.

REGIONAL GEOLOGY

The regional setting of the Midcontinent is one of a series of late Paleo-Mesoproterozoic terranes accreted to an Archean shield. Figure 1 (Sims et al., 1987) is a generalized Precambrian basement map of the northern Midcontinent, including Kansas and part of Missouri. The Precambrian basement of Kansas and Missouri consists of three dominant provinces: the 1.6-1.8 Ga high-grade metamorphic and granitoid terranes of the Central Plains Orogen (CPO) (Sims and Peterman, 1986); the 1.34-1.40 Ga Southern Granite-Rhyolite province, the 1.47 Ga Eastern Granite-Rhyolite province, and the 1.1 Ga Midcontinent Rift system (MCR) (Bickford et al., 1981, Van Schmus and Bickford, 1981, Van Schmus et al., 1993).

The Central Plains Orogen represents an accreted arc and continental margin complex which consists of amphibolite grade metamorphic rocks (Van Schmus et al., 1993). The high grade metamorphic rocks were intruded by mesozonal granitoid rocks that ranged in composition from quartz diorite to granite and younger (1.34-1.50 Ga) epizonal granitic rocks (Lidiak, 1972, Kisvarsanyi, 1974, Bickford et al., 1981, Van Schmus et al., 1993). Bickford et al., (1986) and Sims and Peterman (1986) give an age range of 1.80-1.63 Ga for the formation of the CPO.

The Southern Granite-Rhyolite province (SGR) consists of epizonal granites and associated volcanics that range in age from 1.40 to 1.34 Ga (Bickford et al. 1986, Van Schmus et al., 1993). Sm-Nd crustal residence ages indicate that the rocks of the SGR were derived from distinctly older rocks (Nelson and DePaolo, 1985). The Nd isotopic signature is comparable to the Nd signature of rocks of the CPO. Van Schmus et al (1993) suggested that the SGR was derived from partial melting of the older, crustal rocks of the CPO and thus form a veneer over CPO rocks deeper in the subsurface. To the east granites and rhyolites also occur, but are slightly older, averaging in age around 1.48 Ga, and whose Nd isotopic signature suggests formation from more juvenile crust as opposed to rocks of the SGR. These rocks make up the 1.48 Ga Eastern Granite Rhyolite

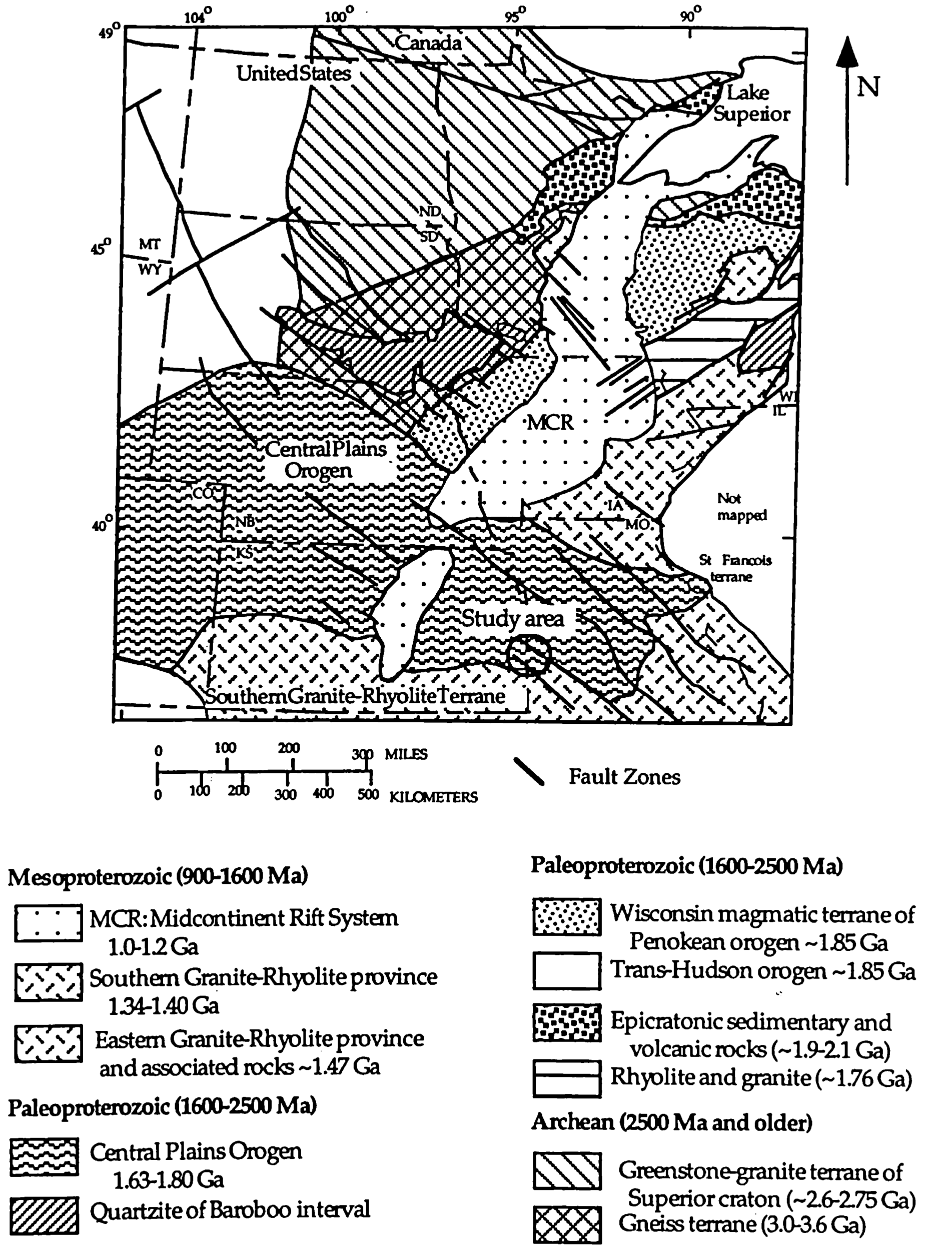


Figure 1. Precambrian geology of the Midcontinent region. CPO consists of high-grade metamorphic and granitoid rocks (ca. 1.8 to 1.63 Ga); SGR consists of epizonal granites and volcanics (ca. 1.4 to 1.34 Ga); MCR mafic volcanic, plutonic and associated arkosic sedimentary rocks (ca. 1.1 to 1.2 Ga) (adapted from Sims et al., 1987, geochronologic data from Van Schmus et al., 1993).

province (EGR) and are exposed at the surface in the St. Francis mountains (Van Schmus et al., 1993).

The third dominant province is the 1.2 -1.1 Ga Midcontinent Rift System which extends south from Keweenawan rocks of the Lake Superior region into northern Kansas (Van Schmus and Hinze, 1985, Van Schmus et al., 1993). The MCR represents the western arm of a triple junction, nucleating in the Lake Superior region. Rifting propagated southwestward, probably along pre-existing NNE-trending zones of weakness, and terminated in central Kansas (Klasner et al., 1982). The structure of the rift consisted of a central graben with arkosic clastic sedimentary rocks filling the central basin as well as being deposited in flanking basins (Fig. 2).

Cullers and Berendsen (1995) successfully correlated the clastic rocks from the rift basins along the length of the Rift, from Lake Superior to Kansas. Their studies indicate that the clastic rocks were predominately derived from the surrounding basement, and show very little influx from a mafic source. Only the finer-grained mudrocks indicate a mafic influx (Cullers and Berendsen, 1995). U/Pb analyses of detrital zircons from clastic rocks of the MCR support the conclusion that the clastic rocks were primarily derived from proximal basement rocks (Martin et al., 1993). Their analyses indicate that the arkoses have provenance ages that range in age from 1.7-1.8 Ga, 1.4-1.5 Ga and 1.1-1.2 Ga.

Around 1.1-1.0 Ga, tectonic inversion from an extensional regime to a compressional regime resulted in rift termination and a change in rift structure from a central graben to a central horst (Cullers and Berendsen, 1993).

The Kansas MCR segment is unique in that its eastern flanking basin is truncated by the NNE trending Nemaha tectonic zone (Fig. 2). Uplift along the Nemaha tectonic zone is generally attributed to Carboniferous tectonic activity associated with the Ouachita Uplift (Berendsen and Blair, 1995). Some researchers (Berendsen and Blair, 1995), however, have suggested that the Nemaha tectonic zone was a pre-existing structure that was reactivated in Paleozoic time. They suggested that the 400-mile-long, NNE-trending Nemaha tectonic zone was an

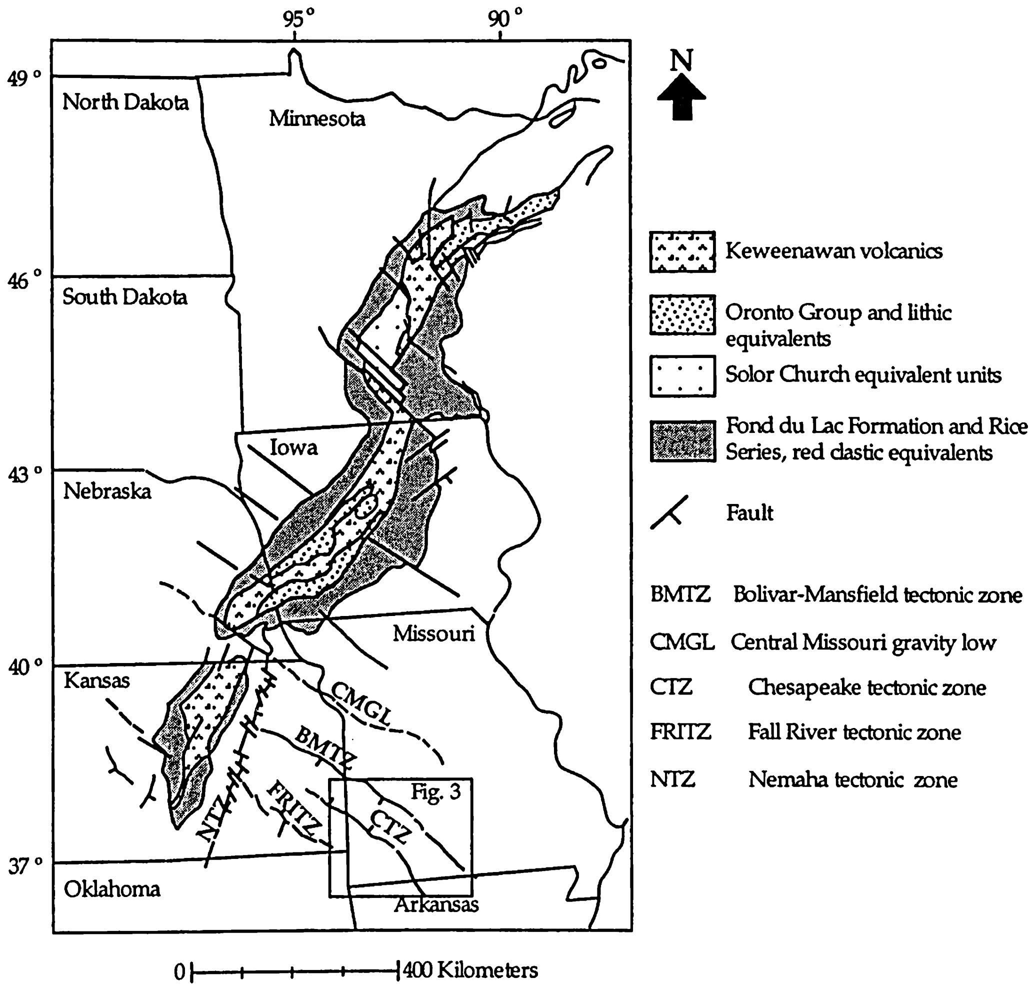


Figure 2. The Midcontinent Rift System (1.2 to 1.1 Ga). A dominant NNE trending feature, that may have propagated along existing NNE trending structures. The rift is accommodated by NW trending fault systems. During the tectonic inversion stage of the rift, uplift may have occured along the NNE trending Nemaha tectonic zone (NTZ), which may have uplifted the flanking basin, thus exposing those sediments to erosion and possible deposition in nearby fault bounded basins. (adapted from Cullers and Berendsen, 1995)

intregral part of the Midcontinent rift system. In their model, the Nemaha tectonic zone included part of a flanking rift basin to the east of the central rift valley, which was filled with a considerable thickness of clastic sedimentary rocks. During late stage compression of the rift, deformation along the Nemaha tectonic zone uplifted part of the basin, and the clastic sedimentary rocks were eroded and redeposited in structurally controlled basins in eastern Kansas and western Missouri (Berendsen and Blair, 1995).

Tectonic inversion of the rift has often been attributed to the compressional tectonics resulting from the Grenville orogen (Reed et al., 1993). The Grenville orogen, the youngest Precambrian orogen indigenous to Laurentia, developed along Laurentia's southeastern and northeastern margins between 1.3 and 1.0 Ga (Hoffman, 1989). Grenville orogen rocks outcrop in the Georgian Bay - Labrador region and Grenvillian inliers occur along the length of the Appalachians, west Texas, and in southern Mexico (Hoffman, 1989). There is little rock record of a foreland basin for the Grenville Orogen, however, particularly in the Canadian shield. Rainbird et al. (1997) suggest that rocks of the Grenville orogen foreland basin may be preserved in the subsurface of the Midcontinent region.

Rocks similar to those of the Grenville orogen occur in northwest Scotland, eastern Greenland and southern Scandinavia. Neoproterozoic plate reconstructions commonly join these lithotectonic blocks to the northeastern margin of Laurentia (Reed et al., 1993). For the southeastern margin, as recorded from Texas outcrops, the data suggest collision of arc rocks, reworked older crust, and a continental block of unknown age (Reed et al., 1993). Grenville basement rocks and similar Cambrian stratigraphic successions and faunas link the Argentine Precordillera to the Ouachita embayment of the southern margin of Laurentia (Thomas and Astini, 1996). Thomas and Astini (1996) propose that the Argentine Precordillera is a continental fragment rifted from the Ouachita embayment during Cambrian time (ca. 515 Ma) and accreted to the western margin of Gondwana (South America) sometime during Ordovician time (ca. 455 Ma). Beyond these data, little is known about the continental blocks that were once attached to the southern and southeastern margins of Neoproterozoic Laurentia.

Timing of the breakup of Laurentia is well established at around 625 ± 10 Ma (Bond et al., 1984) by tectonostratigraphic analysis, subsidence models and paleontology (Green, 1992). Rifting apparently occured in phases or pulses, with rifting beginning at around 760 Ma in the Maritime Provinces (Strong et al., 1978), to as late as Early to Middle Cambrian in the Ouachita rift in Oklahoma and Late Cambrian with the opening of the Ouachita embayment (Thomas and Astini, 1996). Within the subsurface of southeastern Missouri, the NE trending failed Reelfoot Rift is also believed to be a product of Neoproterozoic to early Cambrian rifting which ultimately led to the opening of the proto-Atlantic or Iapetus Ocean and continental breakup (Braile, et al., 1986, Hoffman, 1989).

At some time during the Neoproterozoic, prior to the Late Cambrian-Ordovician Sauk transgression (ca. ~503 Ma), the Midcontinent region apparently experienced an extended period of exposure and erosion. This is evidenced by the fact that the Late Cambrian to Early Ordovician basal sandstones, (e.g. the Lamotte and Reagan sandstones) and in some cases Ordovician dolomites (e.g. Bonneterre dolomite) unconformably overlie predominantly crystalline basement rocks. The hiatus between Precambrian and Early Paleozoic rocks is, relatively speaking, small along the paleo-margins of Laurentia. However, for the Midcontinent region this hiatus is quite large (Bally, 1989).

Structurally, eastern Kansas and western Missouri are dominated by NW and NNE-trending structures. Kisvarsanyi (1974) described dominant NW-trending structures of the basement that can be observed as lineaments on geophysical maps and as folds and faults in overlying Paleozoic sedimentary rocks. These features are believed to represent transcurrent faults or tectonic zones which characterize the structure of the Midcontinent basement (Sims, et al., 1987). The majority of the tectonic events recorded in the Midcontinent are believed to represent reactivation along pre-existing structural features (Berendsen and Blair, 1995). The MCR, the Nemaha tectonic zone and the Reelfoot Rift are dominant NNE-trending features. NW-trending fault zones cross-cut these NNE-trending features and may be coupled with deformation along NNE-features. In southern Missouri and central Kansas, some of the NW-trending tectonic zones are believed to have acted as transform fault zones during rifting along the Reelfoot Rift (Horrall et al., 1993) and along the Midcontinent Rift (Berendsen and Blair, 1995).

Low-grade metasedimentary rocks in eastern Kansas and western Missouri have been described from drill hole cuttings and cores. They consist of clastic rocks which include feldspathic quartzite, argillite, and metaconglomerate (Skillman, 1948). In some places the metasedimentary rocks lie on epizonal volcanic rocks of the Spavinaw province (Denison, 1966; synonymous with the SGR province). The metasedimentary rocks appear to be confined to grabens formed between NW trending tectonic zones such as the Bolivar-Mansfield and Chesapeake Tectonic zones (Fig. 3; Berendsen and Blair, 1995).

This study focuses on those wells that penetrate the apparent graben formed between the Bolivar-Mansfield and Chesapeake Tectonic Zones (Fig. 3). Two wells from Vernon County MO, V-2 and V-3, penetrate up to 1,245 feet (300 meters) of alternating units of quartzite and shale. Two wells in Bourbon County Kansas encountered what has been described as metagreywacke (Denison, 1966). One the wells, KSBB3, penetrated up to 450 feet (137 meters) of metagreywacke. The USGS well, MOCE1 in Cedar county MO, produced an 85 foot (26 meter) core of meta-arkose.

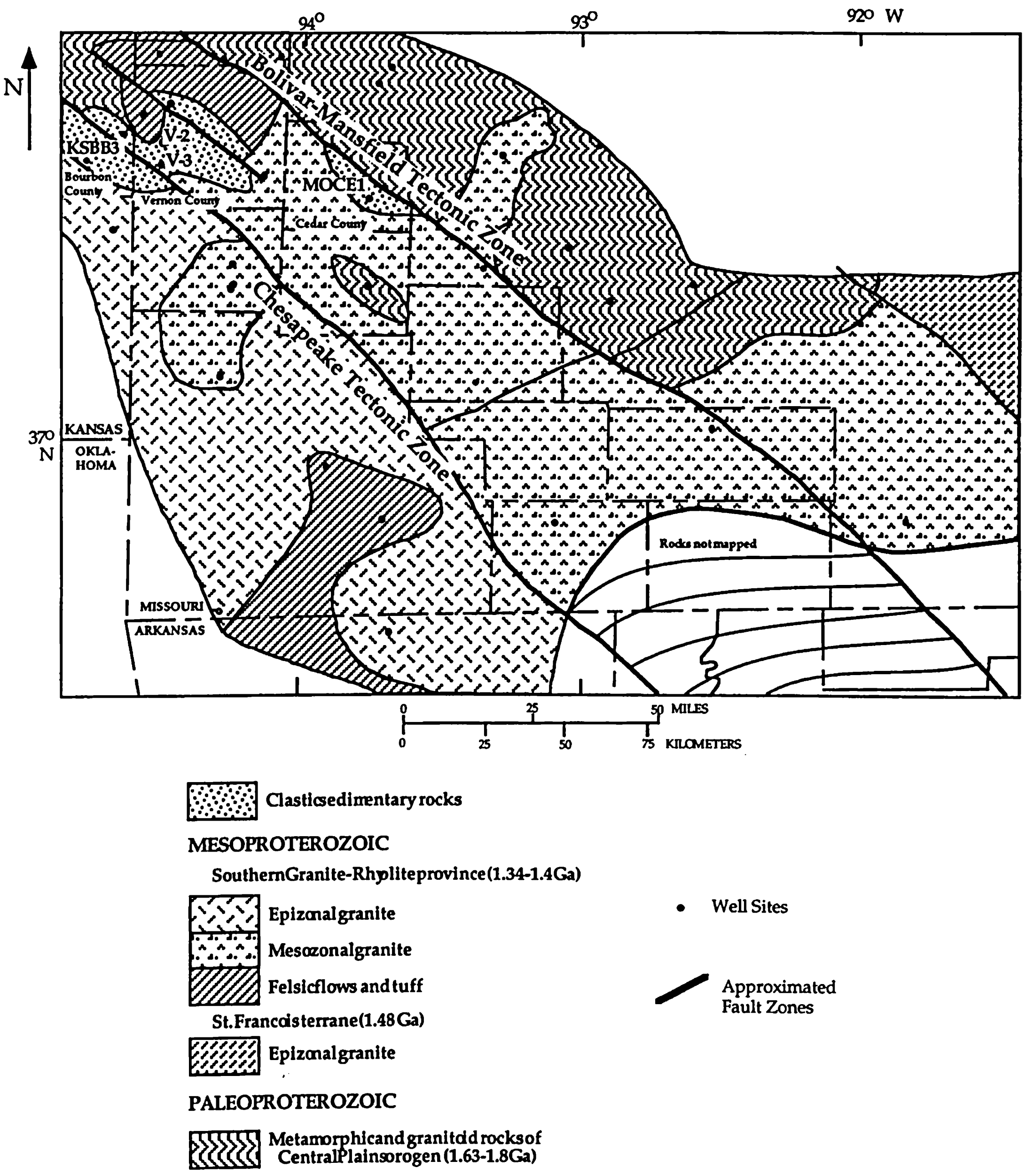


Figure 3. Geologic map of the Precambrian basement rocks of the study area in southwestern Missouri and eastern Kansas. Depth of sedimentary package is unknown at this time. KSBB3: Bourbon County, KS well; MOCE1: Cedar County,MO well; V-2 and V-3:Vernon County wells. Location of figure shown on figure 2 (adapted from Sims, 1987 & Kisvarsanyi, 1984).

PREVIOUS WORK ON CLASTIC METASEDIMENTARY ROCKS

Little is known about the source of the low-grade, clastic metasedimentary rocks or the timing of their deposition. Sims, et al., (1987) suggested that they are merely localized sediments trapped in Meso-Neoproterozoic grabens formed by differential vertical displacement along the NW and NE trending tectonic zones. Kisvarsanyi (1974), and Berendsen and Blair (1995) suggest that they may have been derived from clastic sedimentary rocks of the 1.1 Ga Keweenawan rift that were eroded off of the Nemaha uplift. Sims et al. (1987) also suggested that they may represent deposition contemporaneous with late stages of magmatism in the Southern Granite-Rhyolite province. If so, Sims et al. (1987) suggest that the metasedimentary rocks could potentially host economic ore resources due to the geologic similarities of the Precambrian Midcontinent region with the geologic setting in South Australia, where the Olympic Dam deposit is situated. The Olympic Dam is a world class ore deposit of gold, uranium, and copper that appears to be a type of strata-bound sediment-hosted ore deposit (Roberts and Hudson, 1983). The ore deposit is hosted by predominantly sedimentary breccias that occur in the down faulted blocks of a NW trending graben juxtaposed against granitic basement rocks (Roberts and Hudson, 1983).

Vernon County, Missouri: V-2 and V-3

Skillman (1948) described the rocks from two Vernon County, MO wells, V-2 and V-3 (Fig. 4 and Table 1). She distinguished eight major units of quartzite, siltstone and shale, for which she assigned each a letter designation (Fig. 5). Skillman (1948) referred to these sediments as pre-Upper Cambrian sediments, for the only time constraint she observed was the pronounced erosional contact with the overlying Late Cambrian Lamotte sandstone. In her study, she noted the typical presence of magnetite, muscovite, epidote and albite. Her use of the term quartzite implied only breakage across quartz grains and not a high-grade

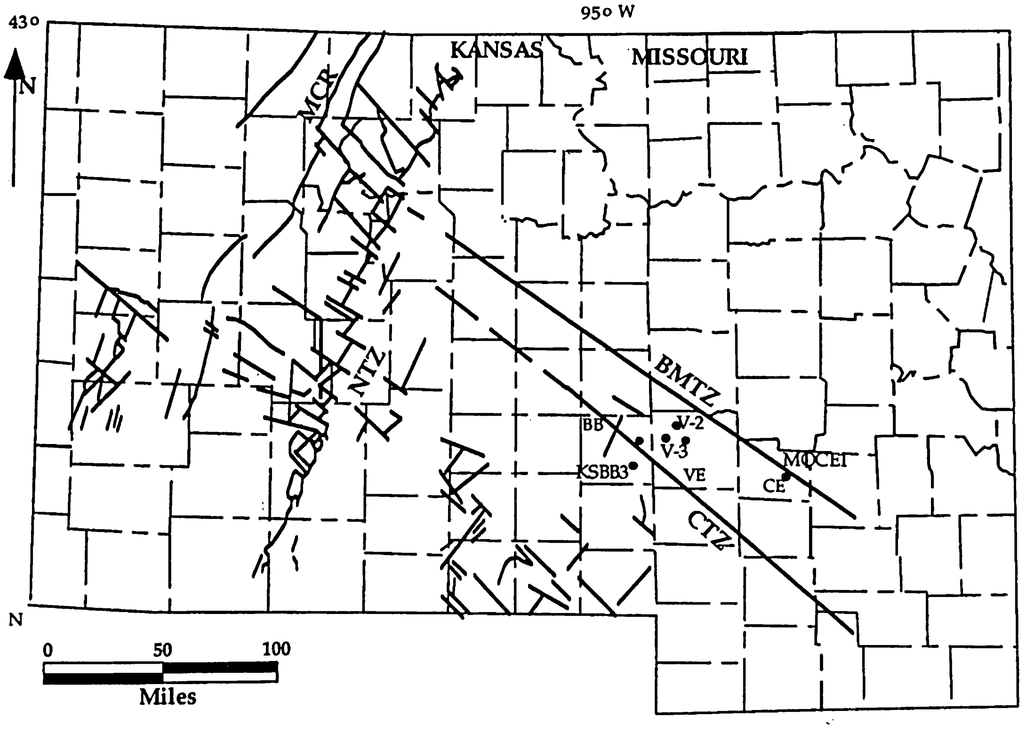


Figure 4. Location of wells used in this study. Predominant structural features are included. NTZ=Nemaha Tectonic Zone (part of the Nemaha Tectonic Zone), MCR=Midcontinent Rift System, BMTZ=Bolivar Mansfield Tectonic Zone, CTZ=Chesapeake Tectonic Zone; VE=Vernon County, MO, BB=Bourbon County KS, CE=Cedar County MO (adapted from Cullers and Berendsen, 1995)

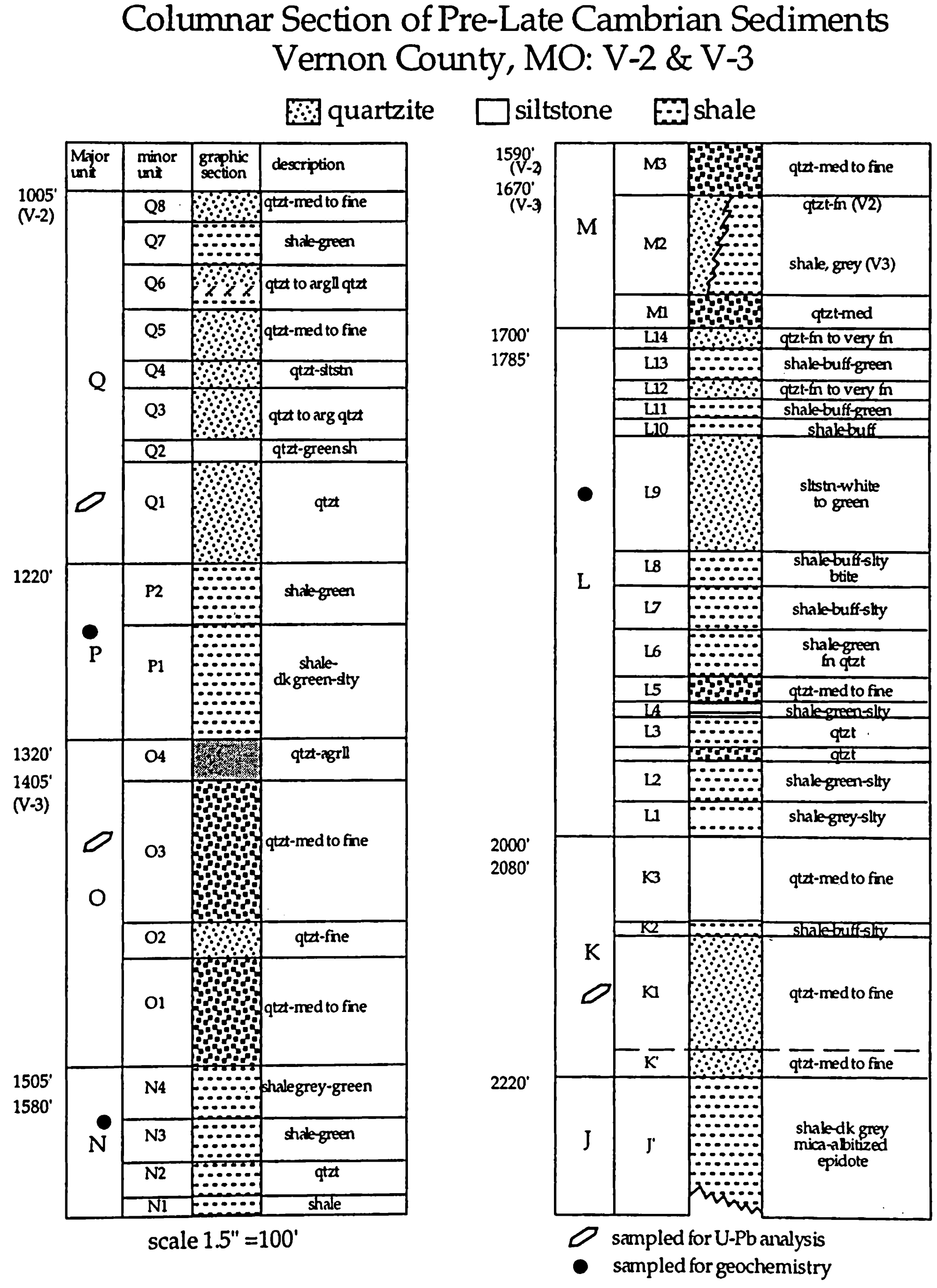


Figure 5. Columnar section of cuttings from the Vernon County, MO wells V-2 and V-3. Depths are given in feet, V-2 followed by V-3 (Modified from Skillman, 1948).

Table 1. Precambrian metasedimentary well information (Cole and Watney,1985).

County	ID Number	Operator	Lease/Well #	Location	Elevation	Depth PC	Total Depth	Rock Type	Research Role
Bourbon, KS	KSBB3	Oklahoma Natural	Stevenson	SW SW NE 16 26S 24E	933'	2157'	2273'	metasediment	U-Pb: 1949 -2155' Bulk Chem: 1943-53'; 2002-2035'; 2098-2127'; 2167'-2185'; 2233-2264'
Cedar, MO	MOCE-1 USGS:NS-2A	USGS	NS-2A	NW SW NE 22 34N 26W	890'	1605'	1685'	metarkose	U-Pb: 1635-1636' Bulk Chem: 1635-1636'
Vernon, MO	V-2	Nevada G & O Co	1 Henshaw	NW SE NE 31 37N 32W	803'	1005'	2018'	metaseds	U-Pb: Q Qtzt
Vernon, MO	V-3	Waymire	1 Stubblefield	NW SE SW 31 37N 32W	800'	1405'	2331'	metaseds	U-Pb: O & K Qtz; Bulk Chem: P, N &L Shs
Other wells that penetrate low-grade metasedimentary rocks:									Remarks
Bourbon, KS	KSBB1	Perry	1 Burney	22 25S 25E	826'	1680'	1995'	metasediment	Denison (1966) Vernon Metamorphic group
Butler KS	KSBU/022	Raymond	2 Classen	SE NE NW 18 24S 4E		3526'	3570'	Biotite Schist	Denison (1966) Vernon Metamorphic group
Butler KS	KSBU/002	Cities Service	36 Lathrop	SE SW NW 17 23S 4E		3131'	3213'	Qtz-mica schist	Denison (1966) Vernon Metamorphic group
Butler KS	KSBU/005	Phillips	23 Scully	SW SE NE 17 23S 4E		3572'	3582'	Qtz-mica schist	Denison (1966) Vernon Metamorphic group
Johnson, KS	MGS 4191	Kasper	1 James	NW NE NW 8 13S 25E	859'	2272'	2276.5'	Qtzite	Adams (1959)
Greenwood, KS	KSGW/001	Phillips	S-6 DeMalonie and Sowder	SW NW NW 12 22S 10E	1229'	3285'	3475'	metasediment/ Metagreywacke	Denison (1966) Vernon Metamorphic group
Greenwood, KS	KSGW/005	Orlando	1 Breitkreutz	SW NE SW 4 24S 10E	1365'	3484'	4774'	mica schist	Denison (1966) Vernon Metamorphic group
Miami, KS	MGS 2303	McDonald	1 Lee	16 16S 23E	975'	2290'	2707'	metasediment	Adams (1959)
Morris, KS	KSMO1	Leslie	1A McConnell	14-16S-9E		3145'		Mica quarzite	K/Ar 1.26 Ga/Rb/Sr 1.40Ga (Denison 1966)
Sedgewick, KS	KSSG/008	Continental	1 Casey	15 25S 1E	1435'	4205'	4224'	biotite phyllite	Denison (1966) Vernon Metamorphic group
Sedgewick, KS	KSSG/004	Bu Vi Bar	1 Hudson	E2 NE SW 12 26S 1W	1344'	4235'	4243'	qtzite or schist	

Table 1 continued.

County	ID Number	Operator	Lease/Well #	Location	Elevation	Depth PC	Total Depth	Rock Type	Research Role
Sedgewick, KS	KSSG/005	Marland Gypsy	1 Wright	NW NE SE 12 26S 1W	1343'	4190'	4310'	s. stn	
Sedgewick, KS	KSSG/006	Lauck	1 McLean	SW SW SE 1 27S 1W	1316'	4369'	4703'	Qtzite	
Sedgewick, KS	KSSG/003	Wentz	1 Bright	SE SW NE 12 26S 1W	1334'	4165'	4192'	mica schist	
Barry, MO	MGS 2082	Barry Cnty O & G Co	1 Jenkins	NW NW SE 23 24N 26W	1065'	1704'	1932'	metasediment	Adams (1959)
Jackson, MO	MGS 2096	Toll Estate	1 Greenwood	SE NW SE 27 47N 31W	967'	2214'	2216'	Qtzite	Adams (1959)
Vernon, MO	V-8/ 28279			6(aa) 36N 32W	795'	1300'	1520'	Qtzite	

metamorphic event. There is little supporting evidence for a dynamic event.

The quartzites are generally 60 to 95 percent quartz, with some plagioclase, microcline, orthoclase, chert and shale, and rare accessory zircon and tourmaline (Skillman, 1948). The quartzites are usually pinkish white in color, but where chlorite and epidote are present there is a greenish cast.

The shales and siltstones in V-2 and V-3 have comparable mineralogies to the quartzites, but with a greater concentration of sericite and muscovite (Skillman, 1948). Skillman (1948) did not observe much in the way of texture beyond a slight parallelism, but noted that the shales approach argillite in degree of recrystallization. In addition to epidote, albite and chlorite, Skillman (1948) also observed sericite, apatite, garnet, rutile and tourmaline, suggesting a probable low temperature hydrothermal alteration.

Skillman (1948) successively correlated the two wells, and noted that there is an apparent dip of approximately 40° to the southwest (corrected for post-Mississippian folding). She also noted that the Late Cambrian sediments pinch out against the pre-Late Cambrian surface to the northeast (Fig. 6). The actual structural relationship between these wells and the other wells studied cannot be determined without more drilling data or, perhaps, seismic data.

Adams (1959) also described the low-grade metasedimentary rocks from the two Vernon County wells. In addition Adams (1959) described 5 other wells that penetrate metasedimentary rocks (Table 1). I was unable to locate adequate samples from these wells for further analysis. Adams (1959) suggested that all the metasedimentary rocks are correlative, and may represent the same package of clastic rocks. His observations include the presence of a suite of secondary minerals consisting of albite, muscovite, sericite, biotite, chlorite, epidote, clinozoisite, sphene, magnetite, ilmenite, quartz, and hematite that suggest low temperature hydrothermal or metasomatic alteration (Adams, 1959). He also observed quartz grains enlarged and cemented by secondary quartz overgrowths and

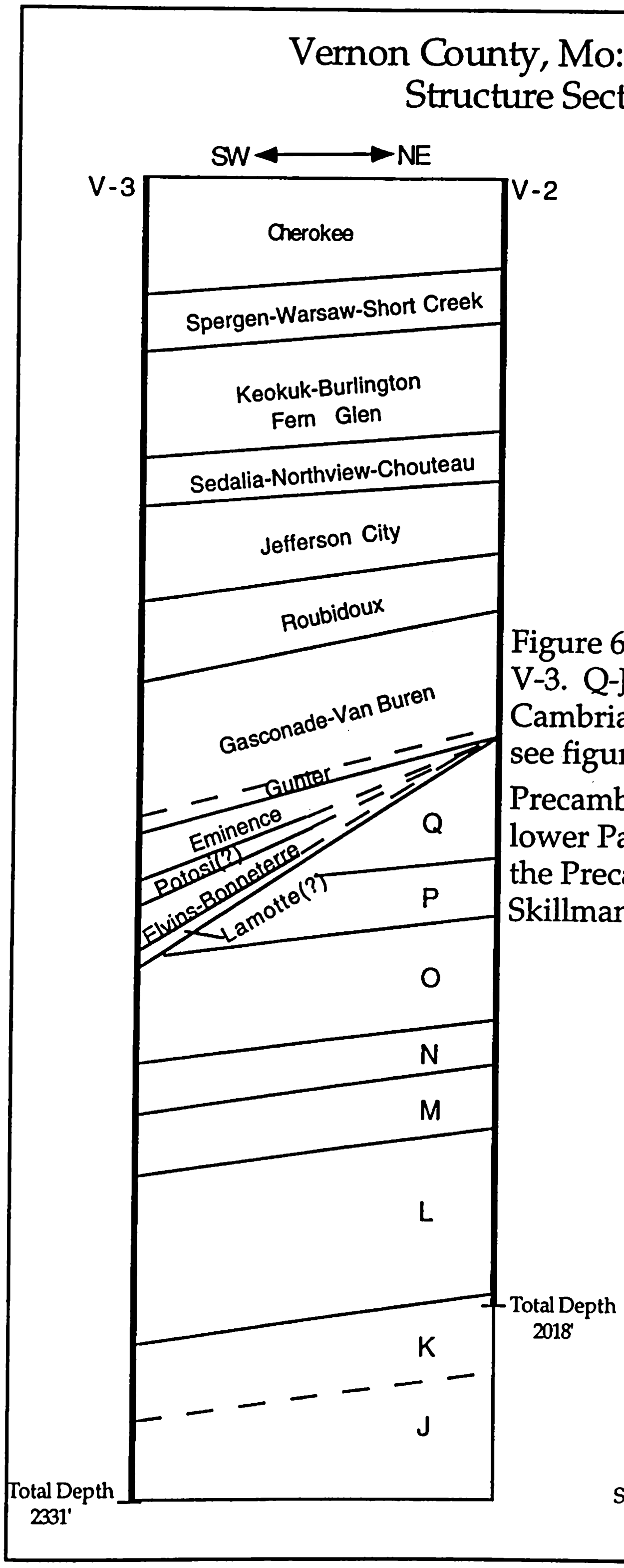


Figure 6. Correlation of wells V-2 and V-3. Q-J represent the pre-Late Cambrian metasedimentary rock units, see figure 5 for descriptions. The Precambrian units dip ~ 40° sw and the lower Paleozoic units pinch out against the Precambrian surface. (Modified from Skillman, 1948)

sandstones whose quartz grains form a sutured and interlocking fabric which shows a slight subparallel elongation. Metamorphism was apparently mild, and essentially hydrothermal in nature rather than deformational (Adams, 1959). Due to the similar mineralogies of the low-grade metasedimentary rocks and nearby high-grade gneisses, Adams (1959) suggested that the rocks represent the lowest grade of regional metamorphism, and occur on the flank of a metamorphic belt. At the time of his study age and well data for basement rocks was minimal. The high-grade gneiss and schists of which he spoke are rocks of the 1.6-1.8 Ga CPO (Van Schmus et al., 1993), and given the presence of rhyolite clasts, the metamorphic relationship that Adams (1959) proposed is untenable in light of present data.

Denison (1966) coined the term "Vernon Metamorphic Group" to include the clastic, low-grade metasedimentary rocks from all wells used in the present study and from other wells in the basement of eastern Kansas. He based this designation on his study of drill cuttings from V-2 and V-3. He too, described alternating units of feldspathic quartzite, metagreywacke and metasiltstone. In variance from Skillman's (1948) description, Denison noted the presence of rhyolite fragments, and he interpreted the interval from 2210 ft (674 m) to total depth (2331 ft, 710 m) to be syenite. Skillman (1948) called this the J shale, which she described as albitized and mineralized. Denison's (1966) observation of rhyolite fragments in the cuttings suggests deposition subsequent to the SGR, sometime after 1.3-1.4 Ga.

Bourbon County, KS: KSBB3

Included in Denison's (1966) Vernon Metamorphic Group are two Bourbon Kansas wells, KSBB1 and KSBB3, which he described as primarily containing metasiltstone and metagreywacke, respectively. His observations included the presence of epidote and, in some cases, preferentially oriented sericitic micas with most mica oriented parallel to bedding. He also noted the presence of chlorite and small green tourmaline grains.

Denison (1966) described Precambrian metasedimentary rocks from several other wells that he placed in his Vernon Metamorphic Group. The lithologies in these other wells range from feldspathic quartzite to biotite schist. Through the course of this project, I did seek samples from these wells, however, little or no samples were available.

Denison (1966) also refered to muscovite quartzite from the well KSMO7, Morris County KS, which he termed the Lyon County Quartzite. A whole rock K/Ar age yielded 1.26 Ga and a whole rock Rb/Sr age yielded 1.4 Ga. The lower K/Ar age is probably a result of argon loss during alteration. These data indicate that rocks of the Lyon County Quartzite are at least older than the SGR and record the thermal activity related to formation of the SGR (Denison, 1966). As described in other areas of Kansas, rocks from this particular suite of quartzites are very mature, consisting predominately of quartz and muscovite. They consistently form topographic highs in the basement and are most likely related to the quartzites that make up the well-established buried Precambrian hills of Barton County, KS (Walters, 1945). The quartzites of the current study have a distinctly different lithology, and do not consistently form topographic basement highs.

Cedar County, MO: MOCE1

The U.S. Geological Survey drilled and recovered 80 feet (24 m) of Precambrian metasedimentary rock from Cedar County, MO. The low-grade metasedimentary rock, in the form of core, has been described as meta-arkose and conglomerate with possible quartzite or meta-rhyolite (Kisvarsanyi, 1983). Van Schmus et al. (1993), published a U-Pb date of 1611 Ma for the Cedar County MO, meta-arkose; however, this represents an average of zircons from all contributing source rocks.

RESEARCH PLAN AND METHODOLOGY

Overview

The first problem was to address the depositional age of the rocks in the study area. To constrain the age of deposition, single detrital zircon crystals from differing morphologic populations were used for U-Pb isotopic analysis. By analyzing single zircon crystals, I could determine the age of the various source rocks and speculate about their provenance. The youngest zircons for a sample provide an upper (older) limit for the age of deposition. The younger limit is constrained by overlying rocks, which for this region are the Late Cambrian Reagan and Lamotte sandstones.

It has been demonstrated by many researchers that major and trace elements in conjunction with Nd-isotopic studies of sedimentary rocks are quite useful in determining source terrane types (McLennan, et al., 1993). The goal of the geochemical analysis is to analyze for the most diagnostic trace elements and REE that have proven to be effective provenance indicators (Taylor and McLennan, 1985, McLennan, et al., 1993) and which can distinguish a mafic component to these rocks.

The trace elements that were analyzed include the REE; La; Sc; V; Cr; Co; Ni; Rb; Sr; Cs; Nb; Zr; Hf; Ta; Th; U; Ti and Y. Potential source rocks for these sedimentary rocks include granitic, hi-grade metamorphic and possibly mafic rocks (Midcontinent Rift). Therefore, by looking at ratios of elements known to concentrate in felsic or granitic rocks (La, Th) relative to those that concentrate in mafic source rocks (Co, Cr, Ti, Sc) a mafic component, if any, may present itself. Ni and V are also potential indicators of a mafic source. Nd-whole rock isotopic data (obtained through mass spectrometry) versus Th/Sc are useful parameters in distinguishing source-terrane types. Nd isotopic composition is controlled by the average province age, where epsilon Nd represents the deviation of the $^{143}Nd/^{144}Nd$ ratio from average chondritic meteorites (McLennan and Hemming, 1992). Therefore a higher ε_{Nd} reflects a younger source (Taylor and McLennan, 1985). Th/Sc ratio is a sensitive index of bulk composition, where Th behaves incompatibly in most igneous processes and is therefore more concentrated in highly fractionated or felsic rocks.

Sc, however, behaves compatibly and is more concentrated in mafic rocks (Taylor and McLennan, 1985). Th/U versus Th (ppm) is a good indicator of upper crustal source versus depleted mantle source, where average upper crust has a Th/U ratio of 3.8, and generally higher (> 10 ppm) Th concentrations. A more depleted source would have lower Th/U and Th values (Taylor and McLennan, 1985). Chondrite normalized REE patterns are useful for determining the degree of intracrustal differentiation of the source rocks as well as source rocks that may be enriched in HREE or LREE (Nance and Taylor, 1976, McLennan, 1989a).

Sample Selection and Preparation

The nature of the rock samples available presented several problems for sample selection and interpretation. First, samples were in the form of cuttings, except for the Cedar County, MO core (MOCE1). Secondly, many of the wells that supposedly penetrated low-grade metasedimentary rocks, had very little sample available or the samples were often of poor quality, i.e. weathered or oxidized. This study was therefore limited to the few wells described above.

The problems of dealing with cuttings are three fold: first, stratigraphic resolution is poor; secondly, small cutting size increases difficulty in determining lithology, and removes the ability to examine rock fabric and sedimentary structures; and thirdly, contamination from overlying units is a constant concern. In addition, there is also the problem of sampling bias from the drilling process. The majority of the cuttings used in this study were disaggregated sand sized cuttings. It is possible that what was bagged at the surface is not representative of the original rock. Heavy minerals, in particular, could easily have dropped out prior to collection, and by the same token, softer, lighter mineral species could have been floured by drilling and separated from the rest of the sample.

With the aforementioned concerns in mind, I targeted the Q, O and K quartzites of V-2 and V-3 (Vernon County MO) for detrital zircon study, because heavy minerals tend to concentrate in sandstones. I also sampled a section from one half foot (15 cm) of 2.5 inch (6.4 cm) diameter core from the meta-arkose of MOCE1, from a depth of 1635 feet (498 m). From KSBB3, I compiled approximately 200 feet (61 m) of metagreywacke cuttings (Table 1).

Several studies (Banerjee and Bhattacharya, 1994, Bhatia and Crook, 1986, Floyd et al., 1990, McLennan et al., 1993) have shown that the chemical composition of fine-grained sedimentary rocks best represent the overall chemistry of all the source rocks. Therefore, for trace and REE analysis, I targeted the fine grained intervals: the P, N and L shales of V-3 (Fig. 5), and metagreywacke cuttings from the Bourbon County well, KSBB3, were collected from the interval between 1949 to 2155 ft (594-657 m). From MOCE1, I sampled the same interval used in detrital zircon work. Well information can be found on Table 1. I targeted those fine grained units that were thick enough so that I could be confident as to the lithology, and could, therefore, remove obvious contamination from fall.

All drill cuttings were examined under a binocular microscope to remove obvious contamination from overlying Paleozoic rocks. Drill bit shards were removed with a few sweeps of a hand-held magnet. The magnetic fraction was further examined to minimize magnetite removal.

In addition to the problems of working with cuttings is the almost complete lack of lateral well control. Correlation between these wells is impossible, excepting V-2 and V-3. While the lithologies are roughly similar in nature, correlation between the Vernon wells and the Bourbon and Cedar County wells is not feasible. Given their relative proximity, and their location between the Bolivar Mansfield and Chesapeake Tectonic Zones, I make the assumption that they are from the same basin and are representative of the depositional history of that basin.

Isotopic Analysis

Core samples were crushed to thumbnail-sized chips in a Braun chipmunk jaw crusher. Cuttings and core chips were then crushed to 2-3 millimeter sized grains in a Gy-Roll crusher. A pass through a Bico disc mill reduced samples to mm sized particles. Due to the small sample sizes, the samples were washed with water to remove the flour produced by milling. Samples were rinsed with acetone and dried to prevent oxidation. Several sweeps with a hand-held magnet removed magnetite and iron filings. The sample was sieved to less than 100 mesh, and then passed through bromoform (S.G. 2.85) to concentrate the heavy minerals. After the heavy fraction was washed with acetone and dried, it was then passed through a Frantz isodynamic magnetic separator. The non-magnetic fraction at 1.5 amps and a side tilt of 10^o was then passed through methylene iodide (S.G. 3.32). The heavy fraction from the methylene iodide separation was washed in 7 N HNO_3 for 30 minutes to dissolve any pyrite and remove any iron oxide from the zircon surfaces.

Samples were then passed through the magnetic separator with sequentially decreased side tilt angles, separating the zircons into fractions with decreasing magnetic susceptibility. At this point, I picked zircons by hand from the least magnetic fractions, separating them into populations based on morphology. For all samples at least four distinct morphologies were identified: 1) frosted, rounded grains, 2) clear elongated (3:1; length to width) prisms, 3) pink elongated prisms, and 4) clear stubby (2:1) prisms. Pink stubby crystals occurred in minor amounts and were also analyzed. Zircons free of obvious inclusions and cracks were preferentially chosen. However, zircon quantity was greatly limited by the small amount of sample material. Thus I was often limited to mostly small, not perfectly clear zircons. I separated and analyzed zircons based on morphology with the idea that a particular morphology may originate from a single source region.

All fractions were air abraded with pyrite for a minimum of 2 hours to remove possible overgrowths from the zircon grains (Krogh, 1982). A 7 N HNO_3 bath dissolved the pyrite. Single zircons from each population were picked out, weighed, and digested in Teflon microbombs in a HF/HNO_3 solution, and spiked with a $^{205}Pb/^{235}U$ mixed spike. Samples were digested for three days at 220-250^{o}C. Samples were converted to chlorides in 6 N HCL, followed by a pass through Dowex AG-1 ion exchange columns to isolate Pb and U (procedure modified from Krogh, 1973; Parrish, 1987).

Analyses were run on the VG Sector mass spectrometer at the Isotope Geochemistry Lab, University of Kansas. Pb was loaded onto rhenium filaments with silica gel and phosphoric acid, and U was loaded on the same filament. Pb was corrected for mass discrimination as determined by analysis of NBS SRM-982, equal-atom Pb, and analysis of NBS SRM-983, radiogenic Pb. Uranium fractionation was monitored by analyses of NBS SRM U-500. Uncertainties in U/Pb ratios due to uncertainties in fractionation and mass spectrometry for most analyses ranged up to ± 2%, due to the weak signal from many of the single grains. Data were reduced using PBDAT (Ludwig, 1993b), with a total Pb blank of 5 picograms and U blank of 1 picograms. Common Pb was corrected with Stacey-Kramers (1975) model Pb values. Data from each unit (or well) were plotted and regressed using the ISOPLOT program (Ludwig, 1993a) with 2-sigma uncertainties. U-Pb isotopic data are presented in Table 2, including uncertainties in radiogenic Pb ratios.

For Sm-Nd isotopic analyses, approximately 300 mg of rock powder were dissolved and REE were extracted using the methods of Patchet and Ruiz (1987). The isotopic ratios were measured on a VG Sector 5-collector mass spectrometer at the University of Kansas Isotope Geochemistry Lab. Nd was loaded on Re filaments with 1 µl of AGW-50 resin beads and phosphoric acid. Sm was loaded on Ta filament with Milli-Q H_2O. Generally 100 ratios are collected with a 1V ^{144}Nd beam or 150 ratios with a 500mV beam.

Geochemical Analyses

For geochemical and Sm-Nd isotopic analysis, cuttings were powdered using a Spex ceramic (alumina) ball mill for trace element and isotopic study and in a tungsten/carbide ball mill for major element study.

Major element data were determined by atomic absorption in the lab at the Kansas Geological Survey where precision of analyses is within 0.2%. For a detailed description of atomic absorption methods, refer to the text of Van Loon (1980).

Trace element data were obtained using a Fisons/VG PlasmaQuad 2+ ICP-MS at the University of Kansas. Three rock standards, SDC-1 (mica schist), SCO-1 (Cody shale) and JA-1 (andesite) were chosen based on the similarities of rock matrix to that of the study samples. The standards were used as external standards for calibration of elemental concentrations.

Due to the relative newness of the equipment to the KU labs, techniques for complete dissolution of whole rocks for ICP-MS analysis had not been confidently established. The first attempt at rock dissolution followed, with minor alterations, the general dissolution methods of Patchet and Ruiz (1987) which is used by the KU Isotope Geochemistry Lab for whole rock isotope analysis. The first procedure was as follows: approximately 300 mg of sample were predissolved in 1 ml 7 N HNO_3 and 3 ml HF, and then digested in 0.5 ml 7 N HNO_3 and 4 ml HF in a conventional oven at 180°C for 7 days. The samples were dried down on a hot plate set at 225°C, and then were brought up in 2% HNO_3 in 250 mg deionized H_2O. The samples were not converted to chlorides due to possible chloride interferences upon analysis. The solutions were placed in an ultrasonic bath for several hours to break up any remaining solids, particularly fluorides. Upon visual examination, the samples appeared to be completely dissolved, and the count data for elements such as Zr and Hf, which are generally found in the more refractory minerals, were sufficiently high enough to suggest successful dissolution. However, the count data for other elements, notably Th, U, Rb, Sr, and several of the REE decreased during the run, which suggests that these elements were being fixed by fluorides precipitating out of solution. This theory was supported by visual examination of solids in the solution after the run.

The dissolution procedure was then altered to counter the production of fluorides. This was done by reducing sample size, and increasing the HNO_3 volume to counteract fluoride formation. A one to one ratio of HF to HNO_3 was chosen to assure complete dissolution of the more refractory minerals, such as zircon, and to minimize fluoride formation. A chloride conversion step was also included, followed by a HNO_3 step to drive off the chlorides. The procedure is as follows:

Approximately 100 mg of sample was placed in a precleaned Teflon Parr bomb and predissolved in 1 ml 7 N HNO_3 and 3 ml HF on a hot plate set at 225°C until dry. The samples were then digested in 4 ml HF and 4 ml 7 N HNO_3 for 7 days in a conventional oven at 180°C. After cooling, samples were dried down on a hot plate at 225°C and then they were converted to chlorides in 6 ml of 6 N HCL for 24 hours at 180°C. Samples were dried down, and 6 ml of 7 N HNO_3 was added. The samples were again dried down on the hot plate at 225°C. After drying, the samples were brought up in 2% HNO_3 in 150 ml deionized H_2O, and placed in an ultra sonic bath for an hour. These solutions were introduced into the ICP-MS, along with the three rock standards and a procedure blank. The raw data were then corrected for blank and instrument drift with periodic analysis of a tuning solution. Data were further weight corrected, and then elemental concentrations were then calibrated by the known concentration of the three rock standards. Precisions of analyses for most elements were within ±5%.

RESULTS

Based on the subsurface geology as derived from well control, potential field maps, and Precambrian subsurface structure maps, I assume that these sedimentary rocks are all from the same basin and are at least depositionally related, if not directly correlative. However I will treat the sedimentary sections for each well, except the two correlated Vernon County wells (V-2 &V-3, Skillman, 1948), as separate entities. I assume only that each section represents discrete intervals in the depositional history of this basin.

U-Pb data for the detrital zircons are provided in Table 2, which also includes zircon morphology. Tables 3 and 4 provide all Sm-Nd isotopic data, and major and trace elements including REE, respectively. Included in Table 4 are data from previous studies of Midcontinent Rift clastic sedimentary rocks.

Geochronology

Vernon County, Missouri: V-2 and V-3

As previously described, I sampled three quartzite units (in order of decreasing depth: Q, O, K, Fig. 5) for which I could be confident as to the lithology and for which I had adequate samples. Figures 7, 8, 9 are concordia plots for each unit respectively.

The majority of the zircons are discordant. Given the assumptions that the detrital zircons represent a source terrain of said age, and that the low-grade metasedimentary rock sampled did not encounter a regional thermal event of sufficient intensity to affect the core and inner zones of the zircon; I interpret the varying degrees of discordance observed as normal diffusive lead loss (Faure, 1986). The scatter of data is interpreted as an indication of mixed sources. Data that fall on an apparent linear trend or cord I interpret to represent zircons from the same age terrain.

Figure 7 illustrates zircons from the Q quartzite plotted on concordia. Four grains plot on a cord, C, with an upper intercept of 1647±8

Table 2: Analytical results of U-Pb analyses of single detrital zircons

Fraction[1]	Sample[2]			Observed[3]	Radiogenic Ratios[4]			Ages[5]		
	Mass	[U]	[Pb]	$\frac{Pb^{206}}{Pb^{204}}$	$\frac{Pb^{207*}}{U^{235}}$	$\frac{Pb^{206*}}{U^{238}}$	$\frac{Pb^{207*}}{Pb^{206*}}$	$\frac{Pb^{207*}}{U^{235}}$	$\frac{Pb^{206*}}{U^{238}}$	$\frac{Pb^{207*}}{Pb^{206*}}$
	μg	*ppm*	*ppm*							
A. KSBB3: Bourbon County, KS										
#1 NM(0, 23)	1	260	65	441	2.9444	0.2098	0.10179	1390(20)	1230(20)	1657(6)
#3 M(1, 56)	2	627	104	529	1.1888	0.1444	0.05970	795(6)	870(5)	590(10)
#3 M(1, 58)	6	829	88	1442	0.8575	0.1029	0.06043	629(4)	631(3)	619(4)
#3 M(1, 62)	3	376	33	534	0.6942	0.0826	0.06092	535(6)	512(5)	636(10)
#6 M(0, 33)	2	28	7	96	3.4591	0.2049	0.12246	1500(100)	1200(70)	1990(50)
#8 M(0, 34)	1	351	76	447	2.9179	0.1972	0.10730	1390(20)	1160(20)	1754(7)
#8 M(0, 40)	1	237	58	316	2.7480	0.1944	0.10252	1150(20)	1340(20)	1670(10)
#11 M(0, 39)	2	570	66	365	0.8393	0.1006	0.06053	619(6)	618(5)	623(8)
B. MOCE-1: USGS NS-2A, Cedar Co., Mo										
#1 NM(0, 80)	3	294	100	365	3.5330	0.2590	0.09886	1530(20)	1480(10)	1603(5)
#1 M(0, 80)	2	109	29	230	3.6805	0.2720	0.09813	1570(20)	1550(20)	1589(7)
#1 M(0, V5)	1	122	39	596	3.7517	0.2689	0.10118	1580(20)	1540(10)	1646(7)
#3 M(0, V7)	1	54	17	154	3.4673	0.2554	0.09845	1520(80)	1470(80)	1600(20)
#3 M(0, 82)	3	57	14	121	1.6845	0.1678	0.07281	1000(30)	1003(20)	1009(23)
#3 NM(0, 81)	3	70	12	199	1.5202	0.1552	0.07104	940(20)	930(20)	960(10)
#3 M(0, V6)	2	118	19	629	1.6882	0.1652	0.07410	1004(8)	986(7)	1044(9)
#4 NM(0, 82)	1	97	32	297	4.5045	0.3042	0.10740	1730(40)	1710(40)	1756(7)
#4 M(0, V8)	1	255	64	580	2.8175	0.2081	0.09819	1360(30)	1220(20)	1590(10)
#4 M(0, 88)	1	286	99	376	4.0274	0.2825	0.10338	1639(20)	1604(20)	1686(10)
C. V-2 & V-3: Vernon County, MO										
1. V-2,Q Quartzite										
#1 NM(0, 13)	1	355	114	563	3.8522	0.2752	0.10152	1604(20)	1567(20)	1652(6)
#1 NM(0, 14)	3	532	125	1440	3.3146	0.2227	0.10793	1485(9)	1296(8)	1765(2)
#1 NM(0, 56)	3	58	14	244	3.2226	0.2367	0.09876	1460(40)	1370(20)	1600(30)
#1 NM(0, 40)	4	78	22	990	3.6008	0.2581	0.10119	1550(20)	1480(20)	1646(4)
#2 NM(0, 39)	2	497	152	672	3.7509	0.2695	0.10095	1582(10)	1538(9)	1642(4)
#2 NM(0, 33)	5	60	19	2350	4.8105	0.3119	0.11186	1787(9)	1750(9)	1830(2)
#2 NM(0, 34)	4	317	95	562	3.2546	0.2336	0.10105	1470(9)	1353(7)	1644(3)

Table 2, continued

Fraction[1]	Sample[2]			Observed[3]	Radiogenic Ratios[4]			Ages[5]		
	Mass	[U]	[Pb]	$\frac{Pb^{206}}{Pb^{204}}$	$\frac{Pb^{207*}}{U^{235}}$	$\frac{Pb^{206*}}{U^{238}}$	$\frac{Pb^{207*}}{Pb^{206*}}$	$\frac{Pb^{207*}}{U^{235}}$	$\frac{Pb^{206*}}{U^{238}}$	$\frac{Pb^{207*}}{Pb^{206*}}$
	μg	*ppm*	*ppm*							
1. V-2,Q Quartzite (continued)										
#1 NM(0, 33)	1	834	272	727	3.7363	0.2675	0.10131	1579(9)	1528(9)	1648(3)
#2 NM(0, 40)	3	404	122	1530	4.2886	0.2890	0.10761	1690(10)	1637(10)	1759(2)
2. V-3,O Quartzite										
#1 NM(0, 27)	2	103	32	411	3.7919	0.2699	0.10190	1590(20)	1540(20)	1659(9)
#1 NM(0, 17)	3	114	72	48	3.1407	0.2240	0.10170	1440(40)	1300(10)	1660(50)
#1 NM(0, 20)	2	118	36	640	3.7100	0.2666	0.10093	1570(20)	1520(20)	1641(4)
#1 NM(0, 30)	2	89	30	1680	4.8773	0.3163	0.11184	1800(10)	1770(10)	1830(3)
#2 NM(0, 14)	3	77	22	585	3.4522	0.2491	0.10050	1520(20)	1430(20)	1633(6)
#2 NM(0, 13)	13	15	4	610	3.6489	0.2591	0.10213	1560(30)	1490(20)	1633(9)
#2 NM(0, 16)	2	294	85	982	4.0420	0.2702	0.10850	1640(10)	1540(10)	1774(4)
#2 NM(0, 03)	2	62	20	941	3.7255	0.2714	0.09957	1580(30)	1550(30)	1616(4)
3. V-3,K Quartzite										
#1 NM(0, 45)	8	342	107	1400	3.7155	0.2663	0.10119	1570(10)	1520(10)	1646(4)
#1 NM(0, 54)	4	388	107	1384	3.9341	0.2710	0.10528	1620(10)	1550(10)	1719(4)
#1 NM(0, 79)	2	55	4	150	0.6777	0.0849	0.05791	530(20)	525(9)	530(90)
#2 NM(0, 45)	2	64	20	373	3.8632	0.2784	0.10064	1610(40)	1580(30)	1636(8)
#2 NM(0, 58)	3	36	12	740	3.7759	0.2742	0.09986	1590(10)	1562(9)	1620(10)
#2 NM(0, 62)	2	65	18	695	3.4320	0.2473	0.10064	1512(10)	1425(9)	1636(5)
#2 NM(0, 41)	2	265	96	275	3.7263	0.2675	0.10103	1580(10)	1530(10)	1643(7)
#1 NM(0, 23)	6	154	15	244	0.6548	0.0820	0.05789	511(7)	508(6)	530(20)
#1 NM(0, 14)	5	89	13	97	0.7107	0.0853	0.06043	545(20)	528(9)	619(50)
#1 NM(0, 03)	6	113	34	767	3.5720	0.2566	0.10100	1543(10)	1472(10)	1642(4)

1. Fractions: # = Zircon Morphologies: #1: clear, prismatic, elongated grains: #2: white, frosted, rounded grains: #3: clear to pink, stubby, prismatic grains: #4: clear, rounded, somewhat frosted grains: #6: large, euhedral, brownish zircon: #8: small, rounded, lusterous, pink ziron: #11: medium, pink, prismatic ziron: NM = nonmagnetic; M = magnetic: (0, 54) first number = degree of tilt on magetic seperator, second number is microcapsule #.
2. Total U and Pb concentrations corrected for blank.
3. Not corrected for blank or non-radiogenic Pb.
4. Radiogenic Pb corrected for blank and initial Pb; U corrected for blank.
5. Ages given in Ma using decay constants recommeded by Steiger and Jager (1977).

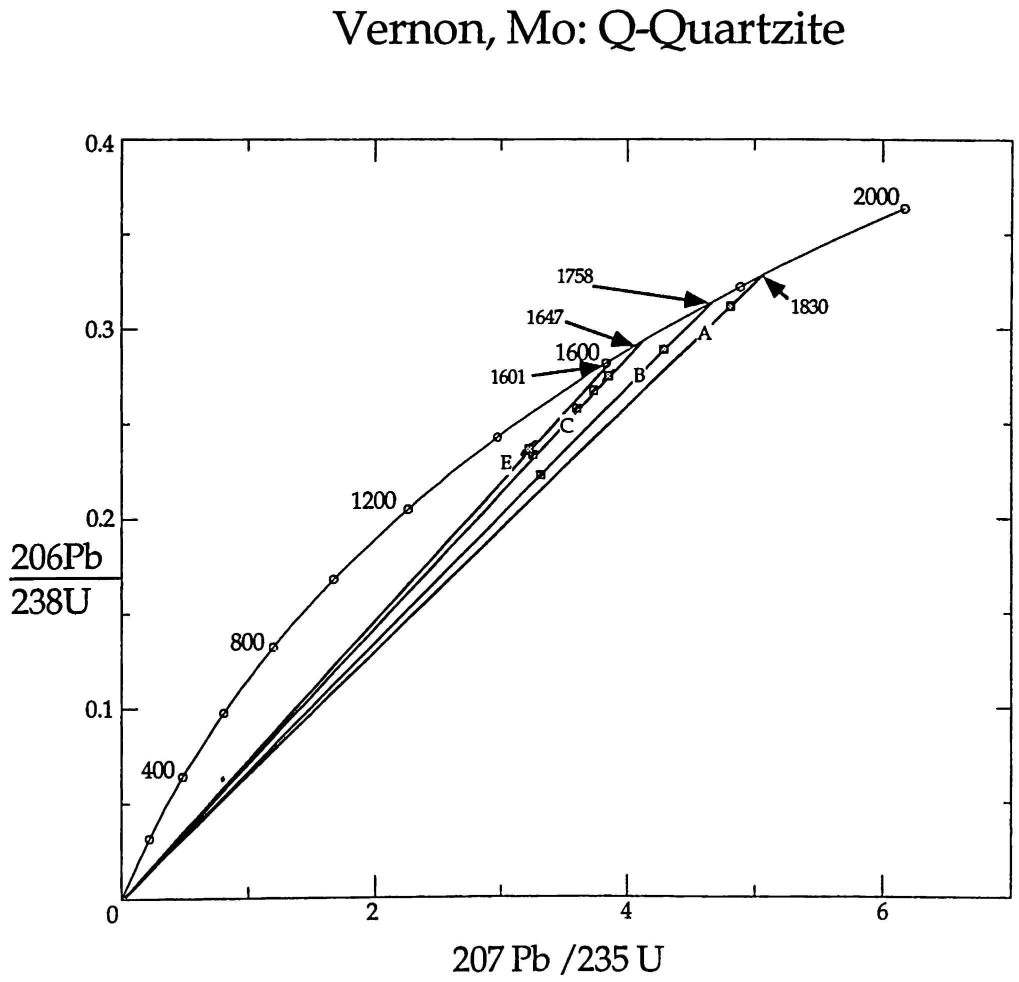


Figure 7. Concordia diagram of single detrital zircons recovered from the Q quartzite of V-2 Vernon County, MO. All cords (A-C, E) are forced through zero, and yield 206Pb/207Pb ages of 1830±2; 1758±3; 1647±8 and 1601±14, respectively. Error elipses represent 2-sigma errors.

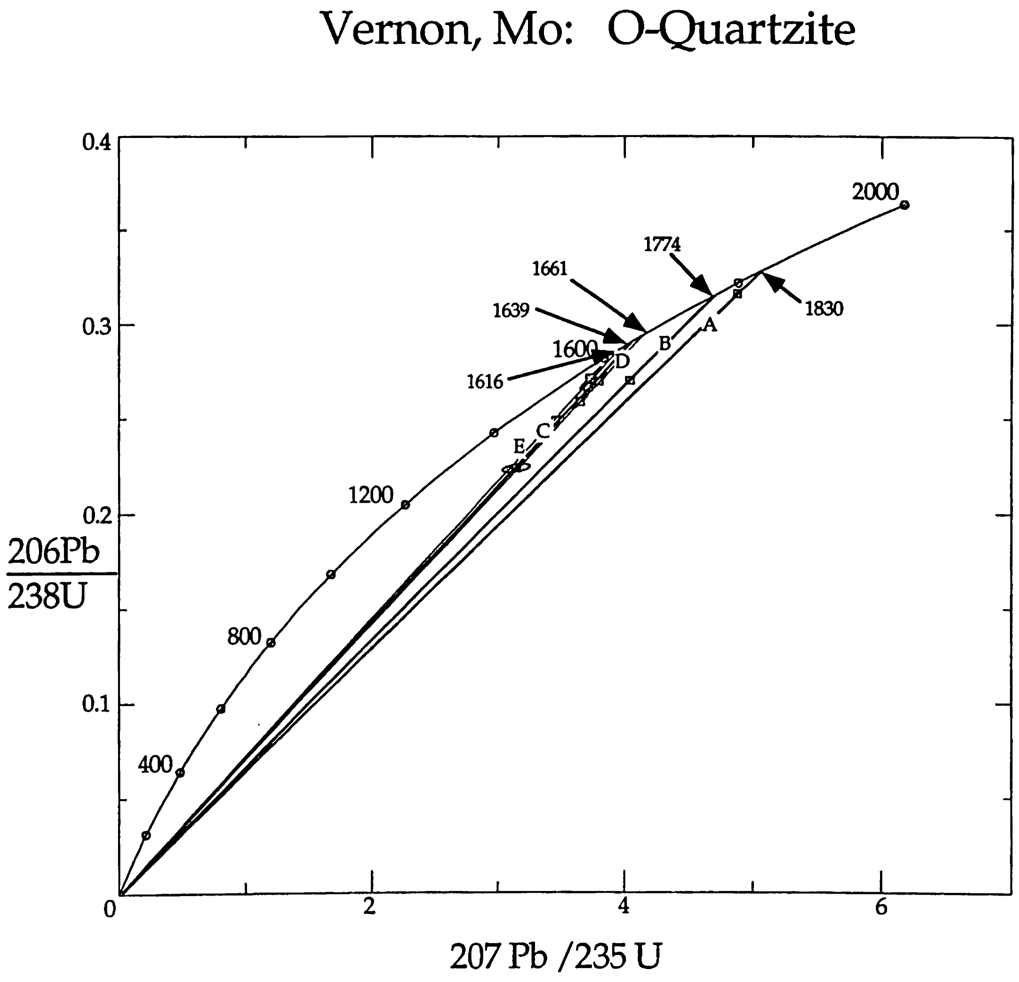
Ma. Two other grains fall on another cord, B, with an upper intercept of 1758±3 Ma. The remaining two grains are individually forced through zero and give upper intercepts ($^{207}Pb/^{206}Pb$ ages) of 1830±2 and 1601±14 Ma. For this sandstone unit, all zircons are derived from sources that range in age from 1.60 to 1.83 Ga.

Figures 8 and 9 are concordia plots of units O and K respectively. The O quartzite yields a suite of zircons derived from source rocks that are greater than 1.6 Ga.

The K quartzite (Fig. 9) yields similar trends as seen on the previous plots, where most grains yield ages greater 1.6 Ga. However, the K quartzite has three grains that plot nearly on concordia at around 525 Ma. This suite of zircons is not represented in any of the other samples, and is most likely infall from overlying units (see discussion section). In addition to the 525 Ma suite there are two reversely discordant grains from the K quartzite. The cause of the discordance is unclear at this time.

If all zircons from V-2 and V-3 are considered together, five distinct groupings, or cords (A-E) occur as seen in Figures 10-14. The majority of zircons from all three units yield ages that range from 1.60-1.76 Ga. Two grains from units O and Q plot on a cord with an upper intercept of 1830±2 Ma. The source for the latter is engimatic at this time. The CPO province has no known age greater than 1.8 Ga.

Another enigmatic result is the lack of zircons from the 1.37-1.47 Ga SGR and EGR provinces. Several researchers, me included, observed rhyolite fragments and clasts in the cuttings and in thin section; therefore it is surprising that they are not represented in the zircons studied. This could be a sampling bias, however, I did attempt to sample a diverse range of zircon morphologies. Sampling bias is unlikely, given the large dataset. It is unlikely that if 1.37-1.47 Ga zircons were present in the sample that they were simply not sampled. As it presently stands, the three quartzites studied from the two Vernon County wells appear to be predominantly derived from rocks that range in age of 1.60-1.83 Ga, and apparently did not receive detritus from 1.37-1.47 Ga source rocks.



Vernon, Mo: O-Quartzite

Figure 8. Concordia diagram of single detrital zircons recovered from the O quartzite of V-3, Vernon County, MO. All cords (A-E) are forced through zero, and yield 206Pb/207Pb ages of 1830±3; 1774±4; 1639±14; 1661±6; and 1616±5, respectively.

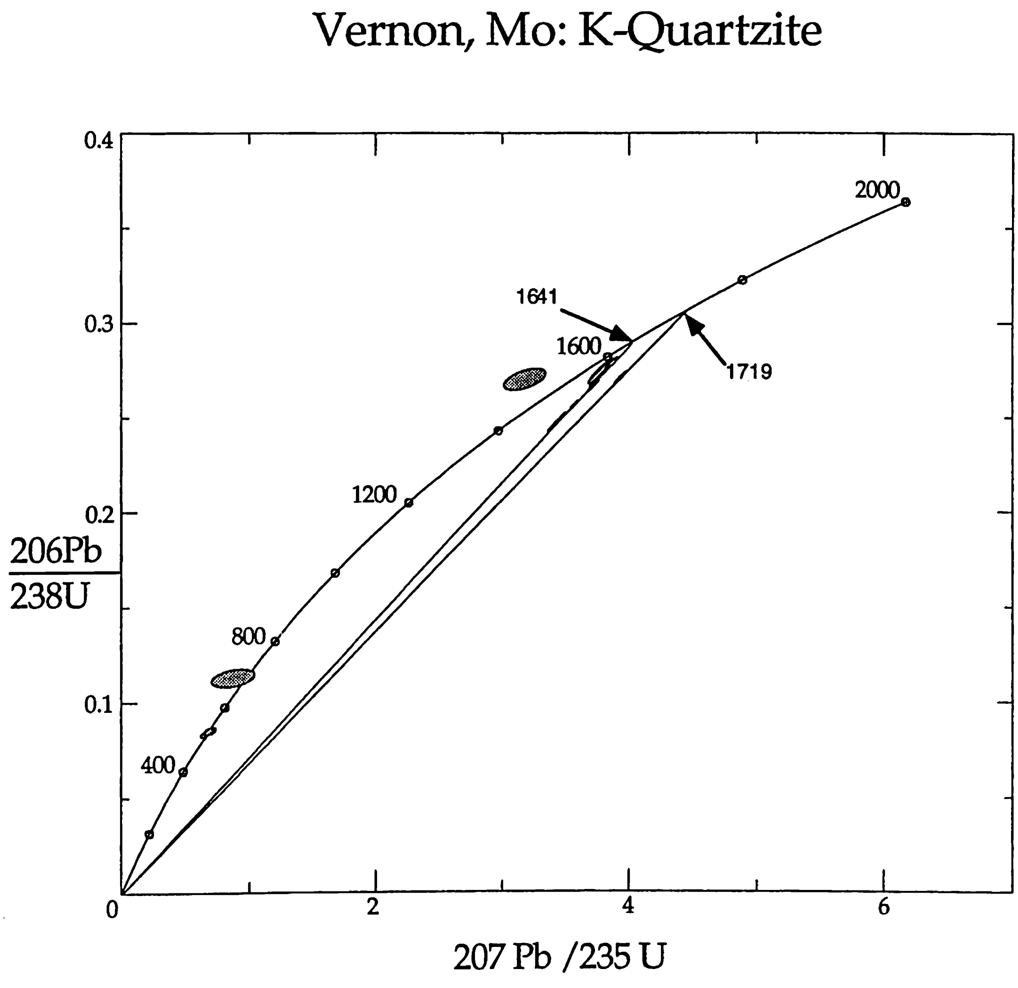


Figure 9. Concordia diagram for single detrital zircons recovered from the K-quartzite of V-3, Vernon County, MO. Most grains fall on two cords yielding 206Pb/207Pb ages of 1641±7 and 1719±4 Ga, respectively. Two grains fall on concordia at ~525 Ma and are interpreted as contamination from overlying Paleozoic units.

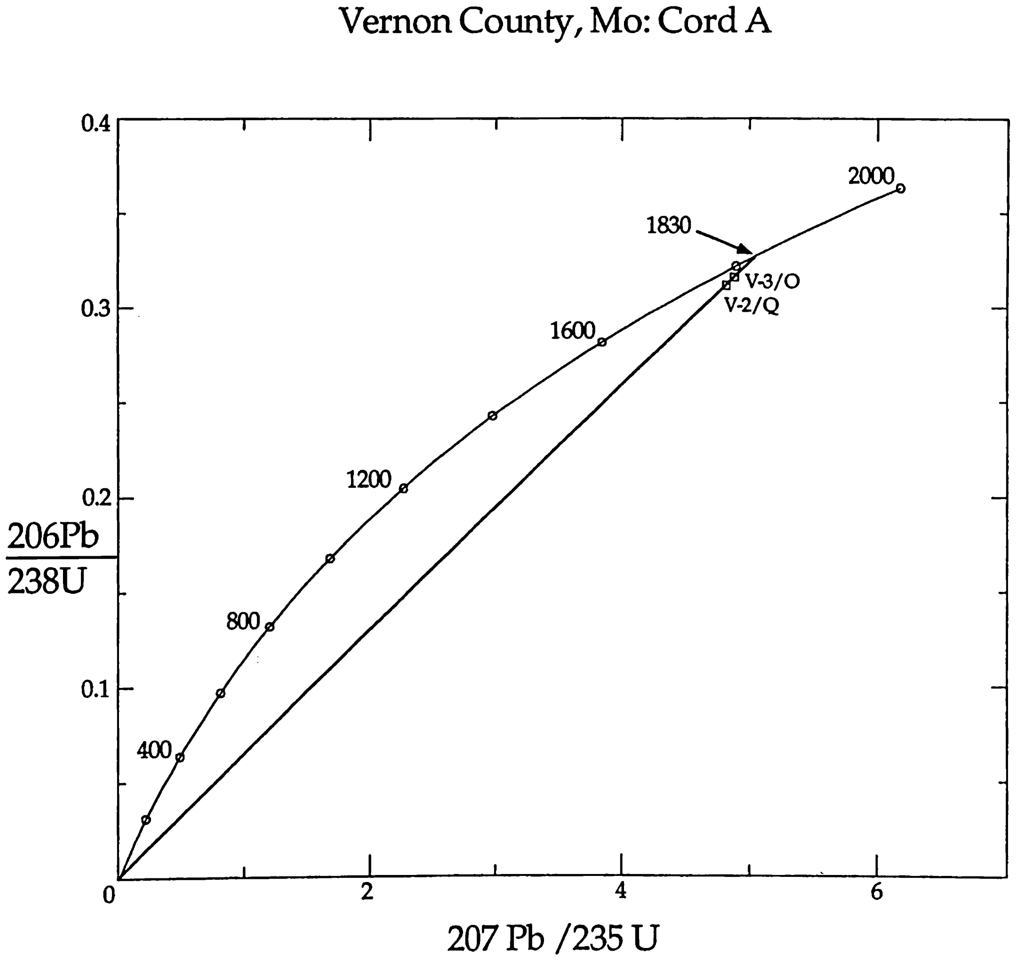


Figure 10. Concordia diagram of grains from the O and Q quartzites of V-2 and V-3, that fall on the cord A. Forced through zero, the data yield a 206Pb/207Pb age of 1830±2 Ma.

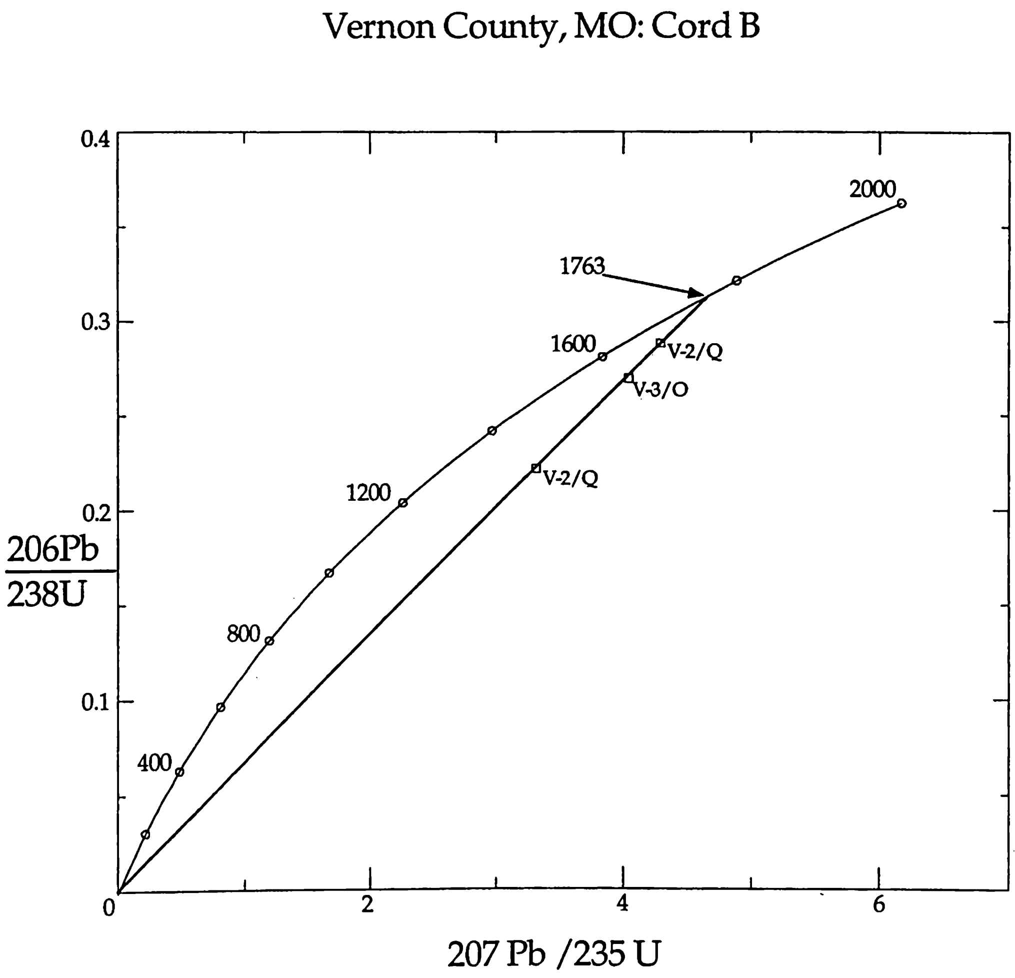


Figure 11. Concordia diagram of grains from the O and Q quartzites of V-2 and V-3, that fall on the cord B. Forced through zero, the data yield a 206Pb/207Pb age of 1763±66.

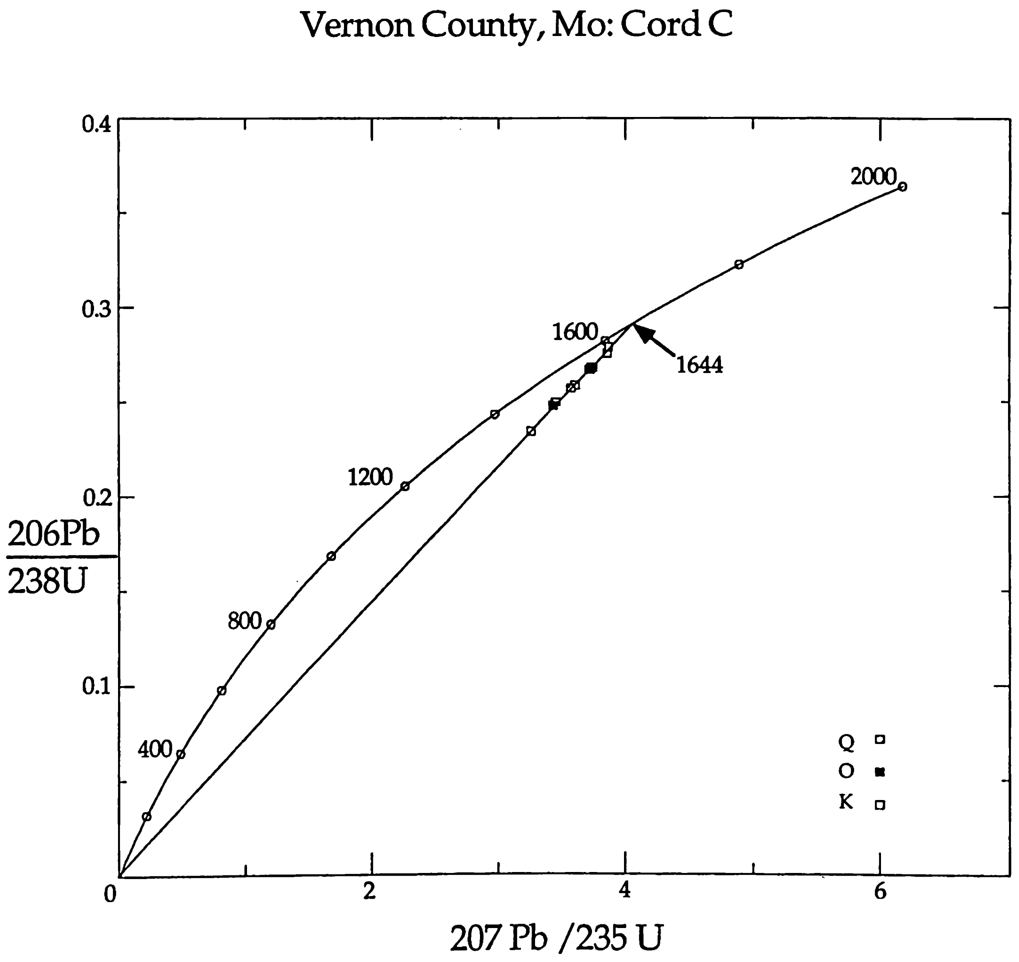


Figure 12. Concordia diagram of grains from the Q, O and K quartzites of V-2 and V-3, that fall on the cord C. Forced through zero, the data yield a 206Pb/207Pb age of 1644±3 Ma.

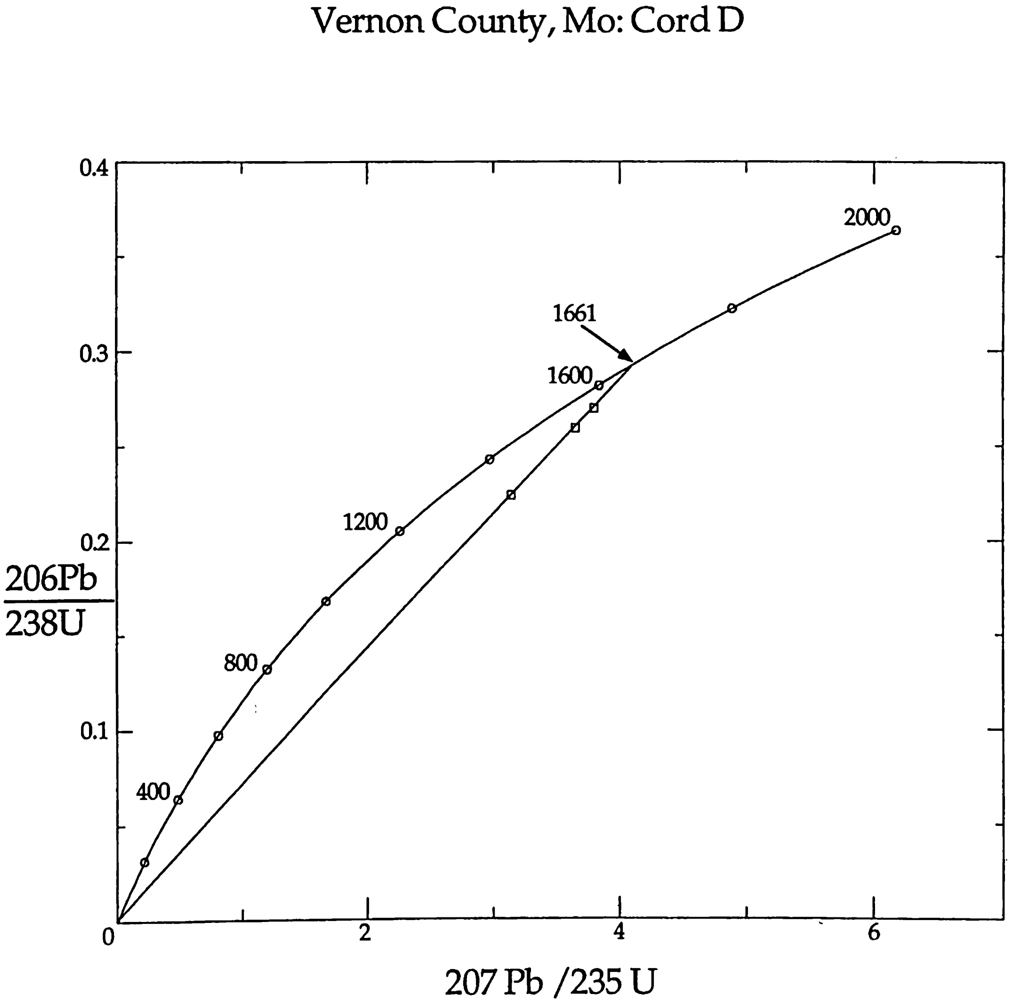


Figure 13. Concordia diagram for grains from the O quartzite of V-3, that fall on the cord D. Forced through zero, the data yield a 206Pb/207Pb age of 1661±6 Ma.

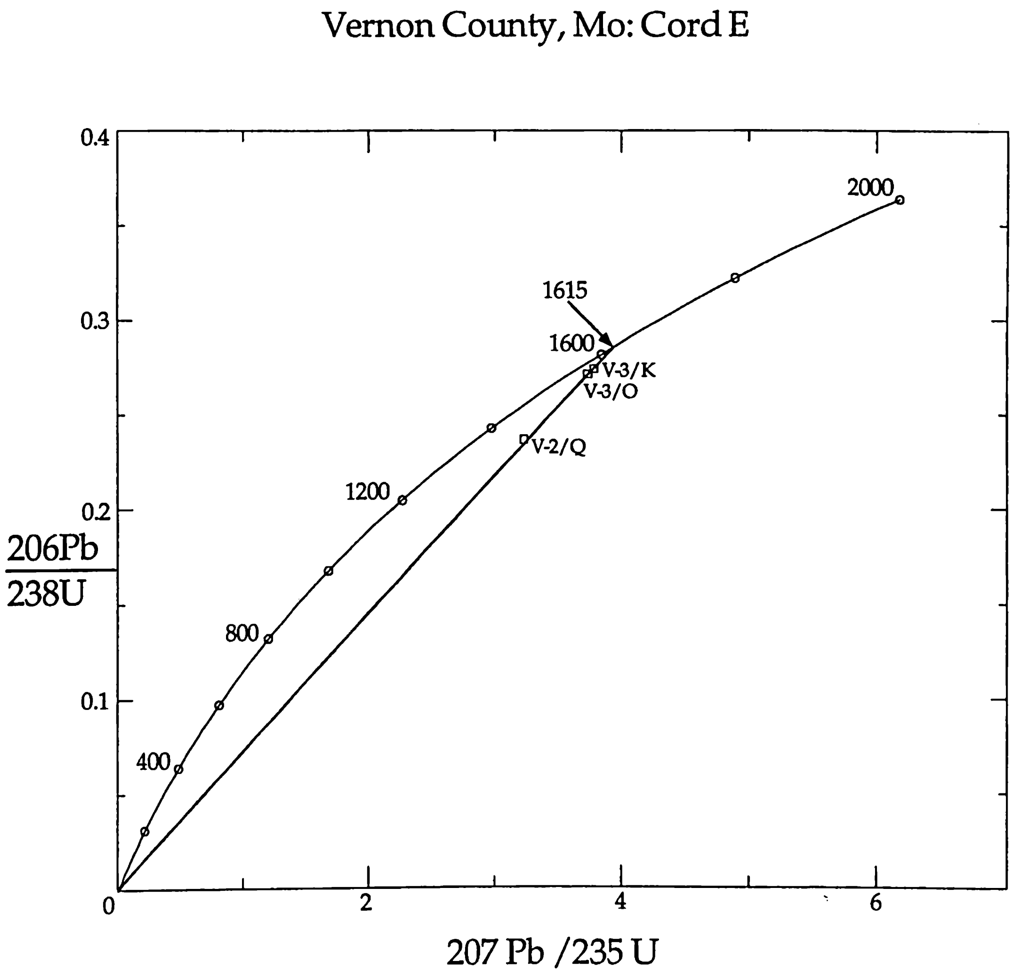


Figure 14. Concordia diagram for grains from the Q, O and K of V-2 and V-3, that fall on the cord E. Forced through zero, the data yield a 206Pb/207Pb age of 1615±62.

Cedar County, MO: MOCE1

Figure 15 shows a concordia plot of all zircon fractions analyzed from the meta-arkose of MOCE1. Again, I interpret the data scatter to represent mixed sources, and those grains that appear to fall on a cord as being from the same source.

It is apparent that MOCE1 predominantly received detritus from 1.60-1.80 Ga rocks. Four possible cords are drawn, B, C, D and E. These cords are roughly in line with the same cords of V-2, V-3 and KSBB3. Cords are forced through zero with $^{207}Pb/^{206}Pb$ ages of 1756±6; 1650±7; 1685±10, and 1595±20 Ma respectively. In addition to these fractions there is a suite of three zircons that plot near and on concordia at ~1000 Ma.

What is interesting and unique to this well are the three fractions that cluster on concordia at around 1.0 Ga. This places an upper (older) limit for deposition of this arkose at 1.0 Ga. 1.37-1.47 Ga source rocks are not represented in the sample analyzed, even though rhyolite clasts were observed in hand sample. This may suggest an inherent bias in the sampling, which is unlikely, or it may suggest that the rhyolite is not from the SGR or EGR provinces. This is not immediately clear and perhaps a larger section of the core should be analyzed further to gain a more complete picture.

Given the data as they stand, it appears that the dominate source rocks range in age from 1.6-1.8 Ga. The presence of 1.0 Ga zircons, may indicate a Grenvillian source, which suggests a roughly east to west (present day direction) sediment transport direction. This transport direction is supported by the work of Rainbird et al. (1992) who encountered a large suite of 1.0 Ga detrital zircons in quartzarenites from northwestern Canada. The only other known potential 1.0 Ga source is the Pike's Peak batholith of Colorado; however, it in unknown if the batholith was exposed in Neoproterozoic time.

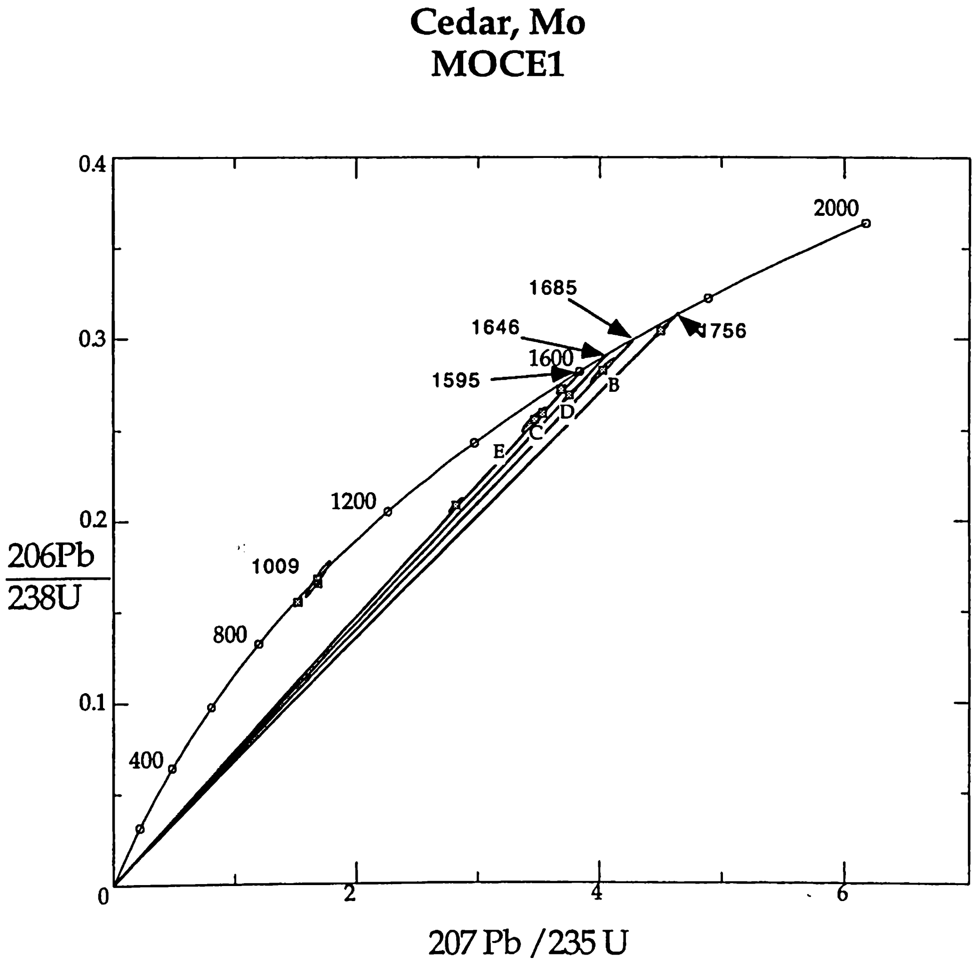


Figure 15. Concordia diagram of single detrital zircons recovered from the meta-arkose of MOCE1, Cedar County, MO. Most grains fall on similar cords (B-E) as the Vernon County wells. They yield 206Pb/207Pb ages of 1756±6; 1646±7; 1685±10 and 1595±20, respectively. Three grains are nearly concordant and yield an average age of 1009±24 Ma.

Bourbon County, Kansas: KSBB3

Figure 16 is a concordia diagram for single zircon data from the metagreywacke, KSBB3. Utilizing the same interpretation logic as for previous wells, a couple of grains fall on a cord (C) that has a forced upper intercept of 1660±26 Ma. Two isolated grains, forced through zero, yield upper intercepts of 1754±7 Ma and 1992 ± 53 Ga. In addition to this suite of >1.6 Ga zircons, there are three zircons that fall on a cord that has an unforced upper intercept of 621 ± 3 Ma. One zircon is reversely discordant. It is again unclear as to the cause of this discordance, however, it is interesting to note that it is in line with the 621 Ma suite and an unforced cord drawn through all the fractions yield an upper intercept of 620 ± 3 Ma.

In line with the mixed-source interpretation, it appears that the metagreywacke also received detritus from a series of rocks >1.6 Ga. In addition there is a suite of zircons from a 620 Ma source. This is most interesting, for it is unclear from where these zircons were derived. It is unlikely that they represent contamination. The drill cuttings were thoroughly examined to remove contamination, and given the rather homogeneous lithology of the metagreywacke, contamination from the overlying Lamotte and Reagan sandstones was obvious and therefore easily removed when observed. Regardless, the data provide a maximum (older) age for deposition of the greywacke at ~620 Ma. Minimum age is provided by the overlying Cambro-Ordovician Reagan-Lamotte sandstone. Again, the 1.37-1.47 Ga zircons are not represented in the data.

A comparison of data from all wells yields some interesting results. Many of the zircons fall along the same linear trends common to all wells. The similarities have been demonstrated for the three quartzites of Vernon County (Fig. 10-14). Figures 17 and 18 show two cords, C and B, that are common for all wells. Cord C gives a forced upper intercept at 1644 ± 4 Ma and B gives an intercept of 1763±17 Ma. This commonality between wells strongly suggests that they received detritus from mostly the same source rocks, regardless of present sedimentary lithology.

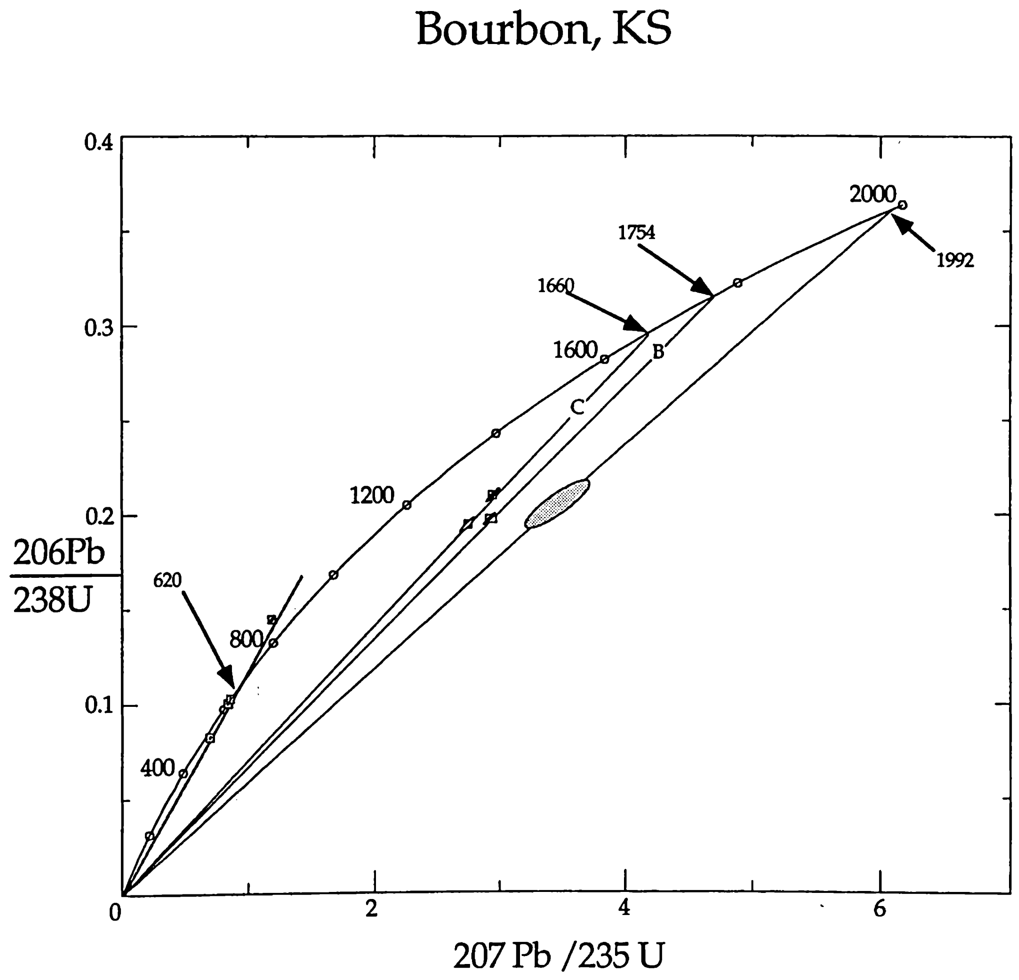


Figure 16. Concordia diagram for single detrital zircons recovered from the metagreywacke of KSBB3, Bourbon County, KS. Two grains fall on a cord, C, that is shared by grains recovered from theVernon County wells and MOCE1, and yield a 206Pb/207Pb age of 1660±26 Ma. One grains falls on the cord B of Vernon County and MOCE1, and has an age of 1754±7 Ma. Three nearly concordant grains, when forced through zero, yield an age of 620±3 Ma. One other grain with large errors yields an age of 1992±53 Ma.

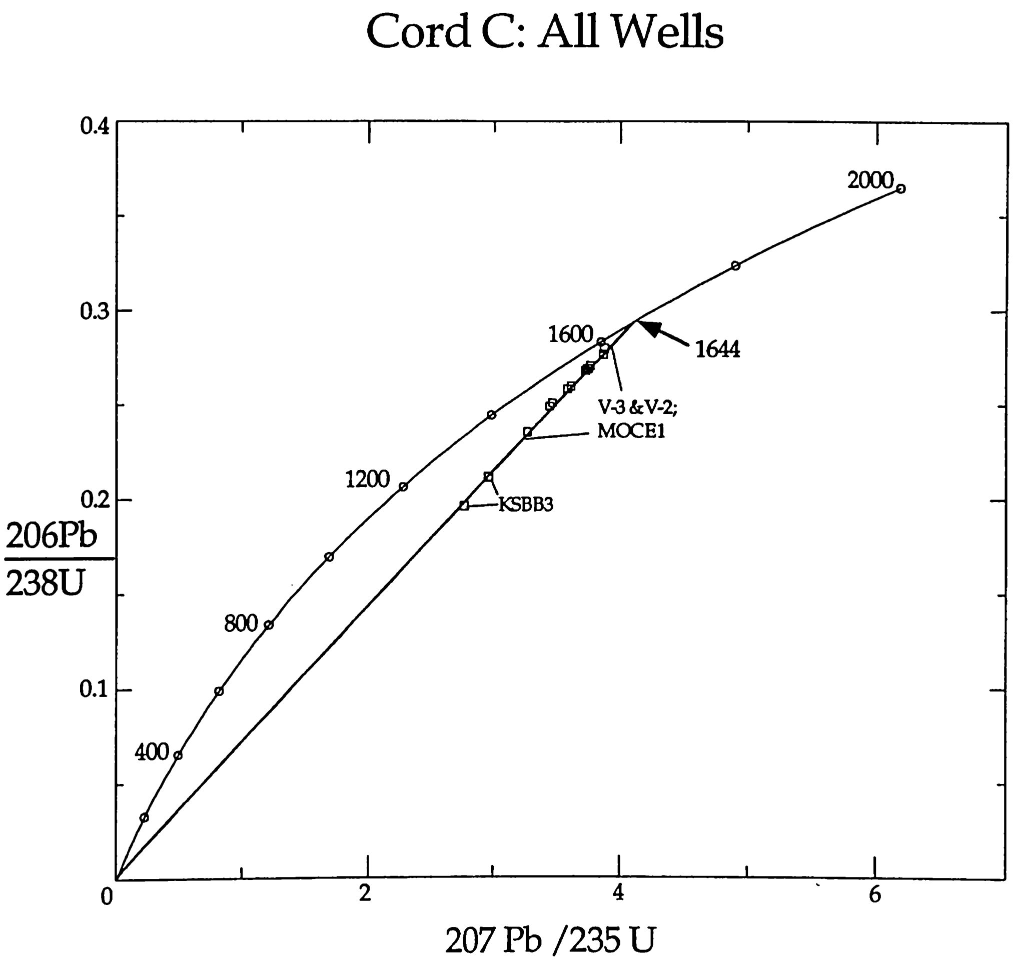


Figure 17. Concordia diagram for all grains from all wells that fall on the cord C. All grains yield a 206Pb/207Pb age of1644±4, forced through zero.

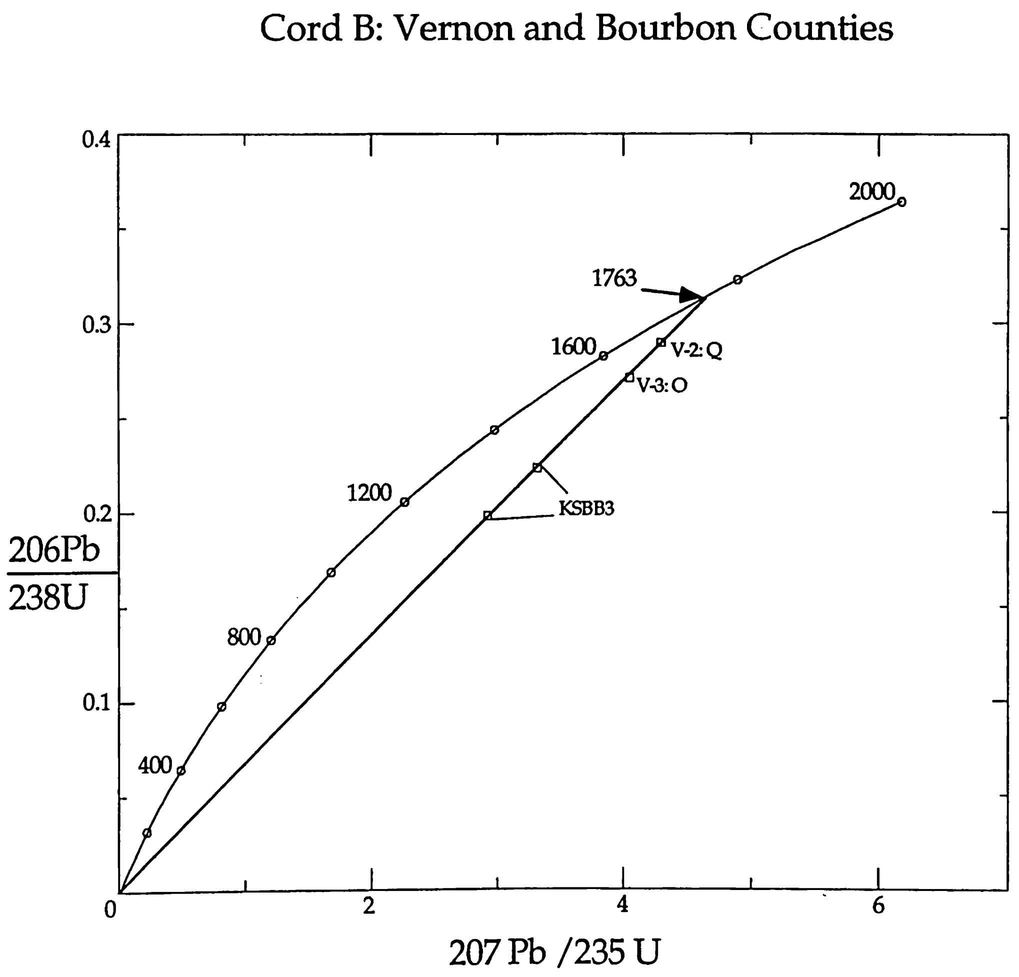

Cord B: Vernon and Bourbon Counties

Figure 18. Concordia diagram of grains from Vernon and Bourbon County wells that fall on the cord B. When forced through zero the data yield a 206Pb/207Pb age of 1763±17 Ma.

Sm-Nd Isotopic Data

Sm-Nd isotopic data were collected in order to determine if rocks of the Eastern Granite-Rhyolite terrane (T(DM)<1.6 Ga) were a probable source (Table 3). The model ages are an average of all source rocks, but an input of mantle-derived components could lower the model age. None of the rocks studied show a distinct input from the EGR. All model ages are >1.70 Ga and indicate derivation from older, continental crustal rocks.

Figure 19 is a plot of present epsilon Nd versus Th/Sc ratios for all samples, where epsilon Nd represents the deviation of $^{143}Nd/^{144}Nd$ ratio from average chondritic meteorites (bulk earth). Th/Sc is used as an indicator of bulk composition of the source rocks, where Th behaves incompatibly and Sc behaves compatibly. In other words, higher Th/Sc ratios are an indication of a more differentiated source, or a more felsic source. The opposite is true of mafic source rocks. Given that all of the samples are Precambrian in age, and that there is no known source of young, juvenile crust, I expect all data to plot well below εNd=0. What is interesting to note is that MOCE1 sits apart from the main cluster, with a lower Th/Sc ratio. It is not a terribly significant difference, but this might be a subtle suggestion of a minor mafic component for the meta-arkose of MOCE1.

Geochemistry

Trace and REE Data

Major, trace and REE data are provided in Table 4. REE patterns can also be used to distinguish provenance. The patterns are useful in distinguishing between source rocks that fractionate HREE over LREE. REE patterns also distinguish source rocks that have fractionated plagioclase which produces a significant negative Eu anomaly. The latter is seen in most upper continental crustal rocks. Figure 20 displays chondrite normalized REE patterns for the three wells. PAAS (post-Archean Australian shales, from Taylor and McLennan, 1985), is included for reference. Patterns for all three wells are roughly similar to PAAS, except

Table 3. Sm/Nd Results from Basement Samples

Sample Identification	Nd (ppm)	Sm (ppm)	^{147}Sm / ^{144}Nd	^{143}Nd / ^{144}Nd ± 2s (today)	$\varepsilon_{Nd}(0)^1$ (Ma)	$(t)^2$ (Ma)	$\varepsilon_{Nd}(t)^3$ (Ga)	T_{DM}^4
KSBB-003								
1943'-1953' (metagreywacke)	55.25	8.59	0.09402	0.511654 ± 10	-19.2	600	-11.3	1.77
2002′ " "	39.44	7.20	0.11036	0.511737 ± 10	-17.6	600	-11.0	1.93
2098′ " "	40.14	7.44	0.11204	0.511729 ± 10	-17.7	600	-11.3	1.97
2167′ " "	45.10	8.61	0.11540	0.511769 ± 10	-17.0	600	-10.7	1.98
2233′ " "	49.08	9.01	0.11100	0.511720 ± 8-17.9	600	-11.4	1.97	
CEDAR COUNTY, MOCE-1/USGS NS-2A								
1635' meta-arkose	46.03	7.66	0.10055	0.511766 ± 10	-17.0	1000	-4.72	1.72
VERNON CTY, MO								
V-2/P 1272′ shale	54.37	9.76	0.10854	0.511721 ± 8-17.9	600	-11.1	1.92	
V-3/N 1600′ shale	51.54	9.31	0.10923	0.511749 ± 9-17.3	600	-10.7	1.89	
V-3/L 1960′ shale	41.01	7.85	0.11574	0.511881 ± 8-14.8	600	-8.6	1.81	

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1. Calculated assuming ^{143}Nd/^{144}Nd today=0.512638 with data normalized to ^{146}Nd/^{144}Nd=0.72190 $\varepsilon_{Nd}(0)=((^{143}Nd/^{144}Nd[sample, now]/0.512638)-1) \times 10^4$.
2. Age estimated for all samples based on U-Pb zircons ages.
3. $\varepsilon_{Nd}(t) = ((^{143}Nd/^{14} Nd[sample,t]/^{143}Nd/^{144}Nd[CHUR,t])-1) \times 10^4$. CHUR = Chondrite Uniform Reservoir (cf. DePaolo, 1981).
4. Calculated follwing model of Depaolo (1981).

Table 4. Results of geochemical analyses of low-grade metasedimentary. Data from Cullers and Berendsen (1993, 1995) are included.

Elements	MOCE-1	V-3/N	V-2/P	V-3/L	BB: 1943	BB: 2002	BB: 2098	BB: 2167	BB: 2233	Lm-3	M-2	M-5	P5396' Ak
Oxides in wt %	[--------------------				this study			--------------------]		(SMCR, Cullers & Berendsen, 1993, 1995)			
SiO2	76.04	66.17	68.11	68.30	67.13	67.30	68.34	67.80	67.94	65.10	95.00	71.10	59.80
Al2O3	12.23	18.52	16.38	14.16	17.72	17.24	16.48	15.44	17.13	13.00	2.20	13.70	16.00
Fe2O3	3.64	4.87	5.31	5.42	5.25	5.35	4.96	5.41	5.25	7.97	0.13	2.16	5.76
TiO2	0.54	1.05	1.22	0.71	0.80	0.89	0.76	0.86	0.84	1.07	0.08	1.02	0.98
MnO	0.05	0.02	0.04	0.04	0.07	0.08	0.08	0.14	0.07	0.05	0.01	0.05	0.08
CaO	0.26	0.20	0.36	1.10	0.15	0.14	0.34	1.02	0.15	0.41	0.11	0.49	1.48
MgO	1.69	0.89	0.85	1.26	1.15	1.14	1.22	1.36	1.14	2.23	0.44	1.94	3.50
K2O	3.76	4.92	4.29	4.68	3.72	4.02	3.69	3.16	3.66	5.30	1.09	5.20	4.69
Na2O	0.13	0.80	0.92	0.70	0.68	0.57	0.74	1.12	0.68	0.08	0.01	0.11	3.31
Total	99.98	100.40	100.26	99.89	99.75	99.77	99.78	99.91	99.98	99.16	99.67	99.24	100.77
L.O.I.	1.64	2.96	2.78	3.52	3.08	3.04	3.17	3.60	3.12	3.95	0.60	3.47	5.17
Trace and REE in ppm													
Ni	37.88	22.26	56.30	79.58	26.38	33.43	36.49	27.79	56.80	44.00	4.80	68.00	18.00
Nb	14.50	19.98	20.99	18.47	16.85	18.75	17.71	19.64	17.30	15.00	4.00	8.00	6.50
Cs	6.91	19.94	14.05	17.50	9.39	10.40	9.83	9.52	9.53	5.40	0.19	5.20	0.40
La	67.26	69.89	79.31	54.96	54.45	45.97	45.27	53.17	56.49	43.70	8.40	27.30	15.60
Ce	142.85	151.59	171.47	128.57	115.13	95.03	102.23	121.31	120.53	82.60	19.50	65.40	38.20
Pr	15.27	15.81	17.58	12.96	12.08	10.38	10.25	12.08	12.51	NA	NA	NA	NA
Nd	58.13	61.23	67.36	50.99	47.24	39.68	39.88	47.43	49.09	NA	NA	NA	NA
Sm	10.01	11.52	12.78	10.26	8.91	7.68	7.68	9.45	9.54	9.16	0.74	8.45	5.78
Eu	2.00	1.98	1.97	1.96	1.56	1.41	1.45	1.69	1.69	1.48	0.10	1.56	1.19
Gd	8.14	9.72	10.49	1.56	7.54	6.85	6.86	8.41	8.07	NA	NA	NA	NA
Tb	1.25	1.56	1.65	9.39	1.21	1.16	1.13	1.37	1.31	0.93	0.07	1.08	0.78
Dy	6.75	8.73	9.39	8.86	6.89	7.07	6.65	7.68	7.38	NA	NA	NA	NA
Ho	1.34	1.86	2.00	1.99	1.47	1.58	1.47	1.65	1.59	NA	NA	NA	NA
Er	3.52	5.06	5.51	5.43	3.95	4.37	4.01	4.34	4.33	NA	NA	NA	NA
Tm	0.54	0.80	0.87	0.90	0.62	0.71	0.66	0.69	0.67	NA	NA	NA	NA
Lu	0.46	0.73	0.80	5.52	0.54	0.62	0.57	0.60	0.57	0.53	0.08	0.62	0.42
Yb	3.28	4.95	5.35	5.52	3.74	4.22	3.99	4.16	3.95	3.44	0.53	4.04	2.83
Hf	7.22	13.96	18.70	9.11	6.77	8.43	8.19	8.71	7.05	9.60	2.10	12.00	7.50
Ta	1.08	1.56	1.60	1.42	1.27	1.33	1.31	1.44	1.30	1.10	0.13	1.10	0.90
Pb	5.91	27.83	31.18	21.40	15.86	16.06	15.72	16.84	16.35	NA	NA	NA	NA
Th	15.32	23.04	28.78	14.75	15.68	17.50	16.68	17.55	16.26	11.20	4.50	12.50	8.90
U	3.30	6.66	7.33	3.73	3.89	4.46	4.61	4.77	4.04	NA	NA	NA	NA
Sc	27.78	15.56	15.29	13.73	14.78	15.08	14.49	14.15	14.82	14.50	0.46	13.70	10.00
V	144.14	76.22	77.36	44.28	66.25	63.61	63.14	59.79	66.26	NA	NA	NA	NA
Cr	229.79	47.44	60.76	26.01	51.93	54.22	49.56	49.29	50.15	60.00	1.90	62.00	58.00
Co	22.05	11.83	12.46	9.47	12.79	13.81	13.77	13.03	13.18	16.70	0.84	18.80	7.90
Rb	153.92	233.29	192.69	142.18	168.33	182.68	174.77	172.22	169.03	143.00	13.00	155.00	
Sr	18.48	58.15	73.77	63.86	184.94	139.73	88.36	132.87	195.09	37.00	4.80	15.00	77.00
Y	39.70	53.62	58.65	48.92	40.89	45.43	40.90	43.09	43.95	17.00	1.80	30.00	33.00
Zr	255.69	509.33	710.86	316.84	229.87	291.77	284.36	278.81	235.47	360.00	111.00	443.00	315.00
Ba	737.21	609.98	447.49	929.21	576.06	629.39	633.98	599.64	577.94	471.00	16.00	372.00	583.00
Elemental Ratios (by weight)													
Th/U	4.65	3.46	3.92	3.95	4.03	3.93	3.62	3.68	4.03	NA	NA	NA	NA
Th/Sc	0.55	1.48	1.88	1.07	1.06	1.16	1.15	1.24	1.10	0.80	9.80	0.90	0.89
Sc/Th	1.81	0.68	0.53	0.93	0.94	0.86	0.87	0.81	0.91	1.29	0.10	1.10	1.12
La/Th	4.39	3.03	2.76	3.73	3.47	2.63	2.71	3.03	3.47	3.90	1.87	2.18	1.75
La/Sc	2.42	4.49	5.19	4.00	3.69	3.05	3.12	3.76	3.81	3.00	18.30	2.00	1.56
Co/Th	1.44	0.51	0.43	0.64	0.82	0.79	0.83	0.74	0.81	1.49	0.19	1.50	0.89
La/Yb	20.49	14.11	14.81	69.64	14.56	10.89	11.36	12.79	14.29	12.70	15.85	6.76	5.51
Zr/Sc	9.20	32.73	46.49	23.08	15.55	19.35	19.62	19.70	15.89	24.83	241.30	32.34	31.50
Eu/Eu*	0.68	0.57	0.52	0.61	0.58	0.60	0.61	0.58	0.59	NA	NA	NA	NA
Chondrite normalized elements and elemental ratios													
La n	183.28	190.45	216.09	149.76	148.38	125.25	123.34	144.89	153.91	119.07	22.89	74.39	42.51
Sm n	43.34	49.88	55.34	44.41	38.55	33.23	33.24	40.91	41.28	39.65	3.20	36.58	25.02
Gd n	26.59	31.77	34.27	30.68	24.66	22.38	22.41	27.49	26.36	NA	NA	NA	NA
Yb n	13.23	19.98	21.59	22.25	15.08	17.02	16.07	16.77	15.94	13.87	2.14	16.29	11.41
Eu n	22.95	22.73	22.64	22.51	17.95	16.26	16.67	19.38	19.42	17.01	1.15	17.93	13.68
Gd n/Yb n	2.01	1.59	1.59	1.38	1.64	1.31	1.39	1.64	1.65	NA	NA	NA	NA
La n/Yb n	13.85	9.53	10.01	6.73	9.84	7.36	7.67	8.64	9.66	8.58	10.71	4.57	3.72

Table 4 continued

Elements	P5404' Sst	P7153' Sst	P8052' Ak	P8476' Sst	P9160' Ak	P9170' Ak	P10513 Ak	F2330-60' Sh	F2410-20' Sh
Oxides in wt %	[————————Texaco 1 Poersch and Finn Wells————————]								
SiO2	60.30	56.20	71.70	57.50	71.90	70.50	71.30	60.30	55.10
Al2O3	16.00	13.40	12.90	17.90	12.20	13.20	13.00	14.80	14.30
Fe2O3	7.76	6.42	2.37	8.73	3.03	3.43	3.13	6.95	6.82
TiO2	0.97	0.72	0.30	0.92	0.46	0.53	0.43	1.60	1.69
MnO	0.08	0.07	0.03	0.08	0.03	0.04	0.03	0.04	0.09
CaO	1.48	8.62	2.56	1.05	2.62	3.21	1.63	1.55	5.32
MgO	3.52	2.48	0.55	3.59	0.44	0.84	0.53	4.34	3.65
K2O	4.69	2.57	4.08	5.03	3.38	3.65	2.88	3.38	3.49
Na2O	3.42	3.18	3.32	2.53	3.95	3.50	4.86	1.93	1.88
Total	100.70	100.50	100.00	100.30	99.77	100.50	98.93	99.84	99.20
L.O.I.	2.48	6.80	2.23	3.00	1.77	1.60	1.14	4.92	6.83
Trace and REE in ppm									
Ni	47.00	47.00	12.00	52.00	9.00	11.00	20.00	27.00	17.00
Nb	7.70	1.00	3.00	10.00	9.00	12.00	7.80	NA	NA
Cs	9.90	6.90	2.40	12.70	1.10	1.60	1.20	5.00	5.20
La	34.90	33.40	22.30	38.10	37.90	33.30	22.50	43.80	33.50
Ce	81.70	69.70	47.10	92.30	74.90	71.50	51.40	81.60	63.80
Pr	NA	NA	NA	NA	NA	NA	NA	NA	NA
Nd	NA	NA	NA	NA	NA	NA	NA	NA	NA
Sm	5.56	6.59	3.83	5.47	6.01	5.84	4.35	8.36	7.09
Eu	1.48	1.24	0.89	1.02	1.09	1.13	0.91	1.42	1.16
Gd	NA	NA	NA	NA	NA	NA	NA	NA	NA
Tb	0.87	0.86	0.48	0.86	0.75	0.75	0.57	1.06	0.90
Dy	NA	NA	NA	NA	NA	NA	NA	NA	NA
Ho	NA	NA	NA	NA	NA	NA	NA	NA	NA
Er	NA	NA	NA	NA	NA	NA	NA	NA	NA
Tm	NA	NA	NA	NA	NA	NA	NA	NA	NA
Lu	0.54	0.47	0.29	0.76	0.43	0.49	0.34	0.69	0.60
Yb	2.78	3.06	1.90	4.32	2.89	3.17	2.34	4.53	3.96
Hf	4.50	5.00	4.40	6.50	6.70	8.30	4.60	5.90	5.30
Ta	1.10	1.20	0.70	1.80	1.20	1.10	0.87	1.60	1.30
Pb	NA	NA	NA	NA	NA	NA	NA	NA	NA
Th	8.40	10.90	6.70	20.50	12.20	11.60	7.30	14.60	12.30
U	NA	NA	NA	NA	NA	NA	NA	NA	NA
Sc	21.80	14.20	4.60	22.00	5.60	6.80	6.60	18.20	15.10
V	NA	NA	NA	NA	NA	NA	NA	NA	NA
Cr	57.00	57.00	20.00	94.00	27.00	32.00	27.00	93.00	75.00
Co	33.10	23.00	5.40	21.00	4.10	7.70	5.80	23.70	20.10
Rb		NA	NA	NA	NA	NA	NA	NA	NA
Sr	65.00	95.00	113.00	22.00	119.00	292.00	86.00	48.00	100.00
Y	26.00	38.00	22.00	37.00	31.00	26.00	26.00	NA	NA
Zr	150.00	180.00	183.00	225.00	272.00	285.00	155.00	NA	NA
Ba	1030.00	531.00	739.00	879.00	653.00	671.00	557.00	391.00	356.00
Elemental Ratios (by weight)									
Th/U	NA	NA	NA	NA	NA	NA	NA	NA	NA
Th/Sc	0.39	0.77	1.46	0.93	2.18	1.71	1.11	0.80	0.81
Sc/Th	2.60	1.30	0.69	1.07	0.46	0.59	0.90	1.25	1.23
La/Th	4.15	3.06	3.33	1.86	3.11	2.87	3.08	3.00	2.72
La/Sc	1.60	2.35	4.85	1.73	6.77	4.90	3.41	2.41	2.22
Co/Th	3.94	2.11	0.81	1.02	0.34	0.66	0.79	1.62	1.63
La/Yb	12.55	10.92	11.74	8.82	13.11	10.50	9.62	9.67	8.46
Zr/Sc	6.88	12.68	39.78	10.23	48.57	41.91	23.48	NA	NA
Eu/Eu*	NA	NA	NA	NA	NA	NA	NA	NA	NA
Chondrite normalized elements and elemental ratios									
La n	95.10	91.01	60.76	103.81	103.27	90.74	61.31	119.35	91.28
Sm n	24.07	28.53	16.58	23.68	26.02	25.28	18.83	36.19	30.69
Gd n	NA	NA	NA	NA	NA	NA	NA	NA	NA
Yb n	11.21	12.34	7.66	17.42	11.65	12.78	9.44	18.27	15.93
Eu n	17.01	14.25	10.23	11.72	12.53	12.99	10.46	16.32	13.33
Gd n/Yb n	NA	NA	NA	NA	NA	NA	NA	NA	NA
La n/Yb n	8.48	7.38	7.93	5.96	8.86	7.10	6.50	6.53	5.73

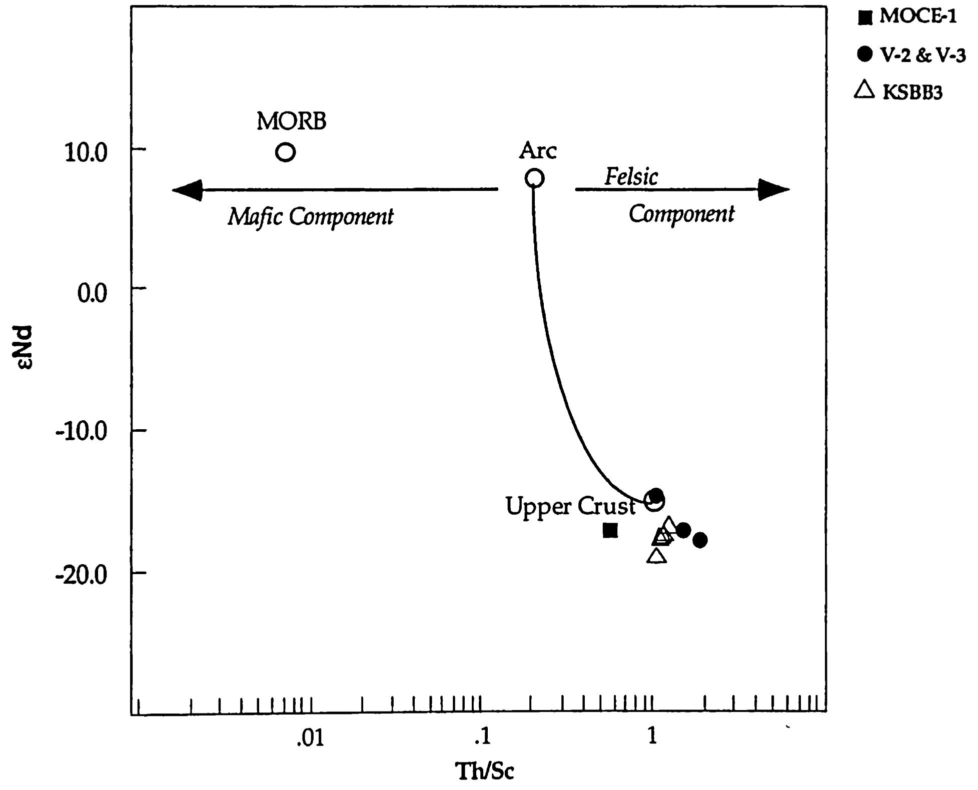

Figure 19. Plot of epsilon Nd versus Th/Sc ratio for study samples. MORB, arc, upper crust and mixing lines from McLennan et. al. (1990). All samples plot around upper-older crustal values. MOCE1 plots on the mafic side of all samples studied.

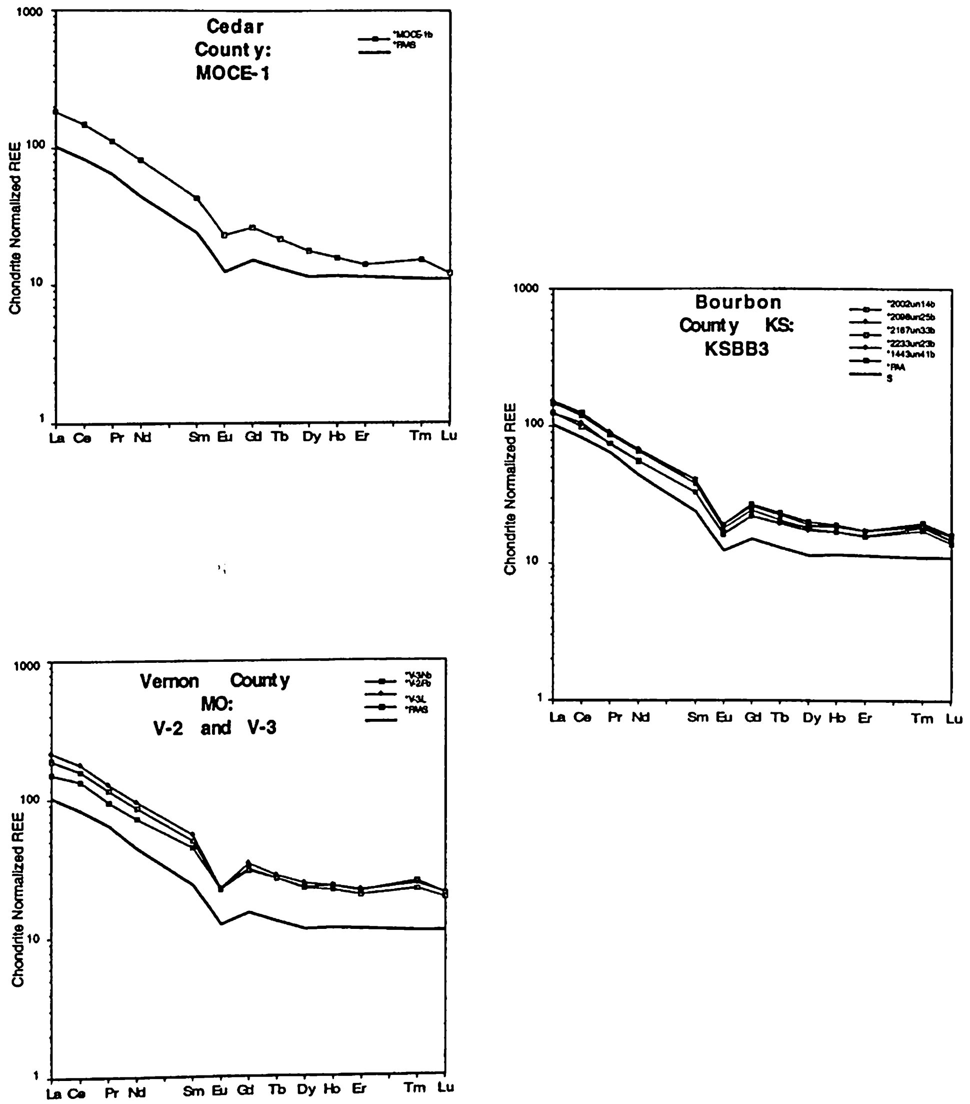

Figure 20. Chondrite normalized REE diagrams for samples from each well studied. All are plotted in comparison to PAAS (Post-Archean Australian Shale). Samples' REE patterns coincide with PAAS but in greater abundance, therefore representing post-Archean upper crustal values. MOCE1 has a steeper HREE pattern.

all three show greater REE abundances. All three have typical upper continental crust patterns, characterized by LREE enrichments, relatively flat HREE (Gd_N/Yb_N=1.0-2.0) and a consistently negative Eu anomaly ($Eu/Eu^* \approx 0.6$). The patterns illustrate a fairly average upper-crustal source for the sedimentary rocks. A mafic component is not evident from the REE data.

The Th/U ratio for most upper-crustal rocks is about 3.5 to 4.0. Lower Th/U ratios are generally indicative of mantle-derived volcanic rocks (McLennan et.al., 1993). A plot of Th/U versus Th (ppm), Figure 21, for the samples studied shows that they cluster around average upper-crustal values. MOCE1's Th/U ratio is elevated from the rest of the samples, which may be a result of dissolution and loss of U during the sedimentary process.

A plot of Cr/V versus Y/Ni (Fig. 22) is a useful tool for distinguishing between mafic and felsic source rocks. This ratio is useful in that Cr/V ratio acts as an index of enrichment of Cr over other ferromagnesian elements, while Y/Ni is a measure of the level of ferromagnesian elements relative to HREE (McLennan et al., 1993). Mafic rocks tend to concentrate ferromagnesian elements, thus such a source rock should have lower Y/Ni. Cr is also concentrated in more mafic rocks due to the presence of chromite. Also shown on the plot is a mixing line derived from two end-member concentrations from a study by McLennan et al., (1993). MOCE1 plots on the mixing line as it arcs towards a mafic end-member, while all other samples fall in the characteristically felsic region. This suggests a possible, yet minor mafic component to the MOCE1 meta-arkose.

Figures 23, 24, and 25 are multi-element plots for each well normalized against upper continental-crust (UCC) values. The metagreywacke KSBB3 (Fig. 23) shows Cr-Ni-Ti enrichments, suggestive of a mafic component. However, V, which generally behaves like Cr, has normal UCC values. The deepest sample (2233') has Ni greater than all samples, followed by 2098' and 2002', suggesting some vertical variation in deposition and possibly source. On the other hand, it might indicate heterogenous zones of Ni-rich fluids that moved through the section. Cs

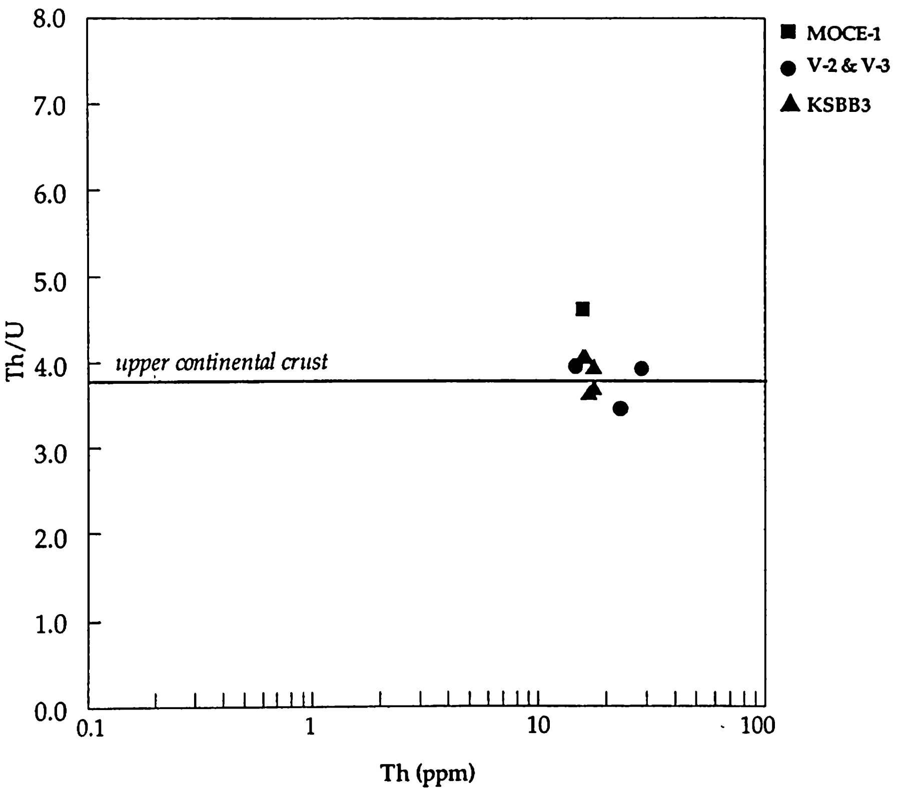

Figure 21. Plot of all samples looking at Th/U ratios against Th ppm. Th/U values for upper crust average around 3.8 (Taylor & McLennan, 1985). All values plot around upper crust values, except for MOCE-1 which show higher Th/U values.

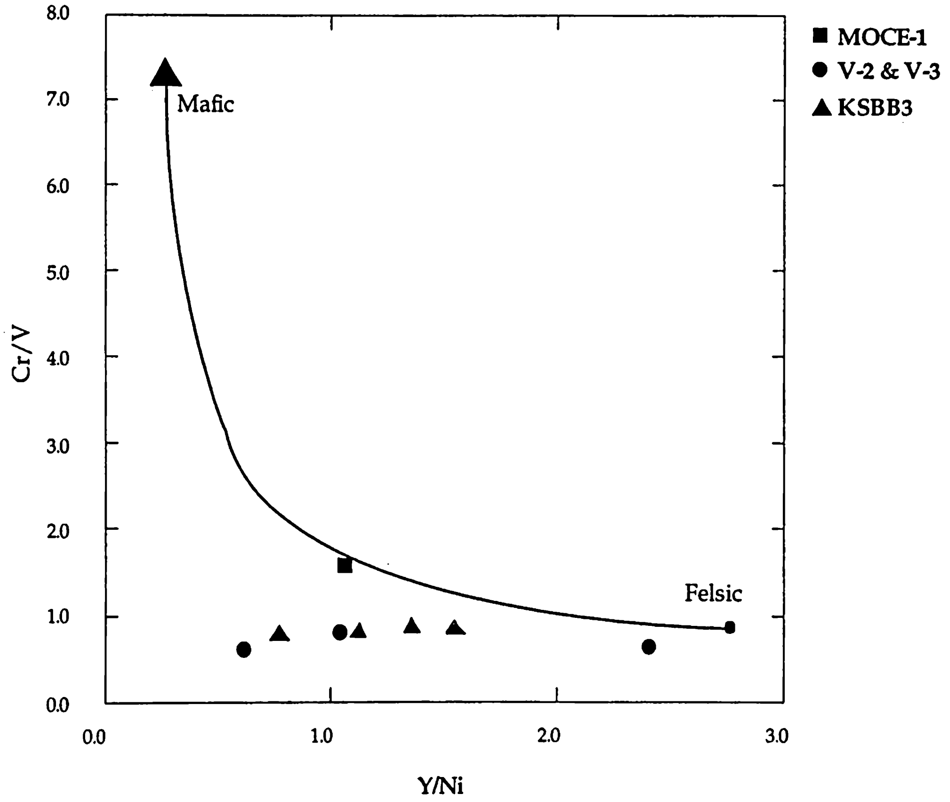

Figure 22. Plot of Cr/V versus Y/Ni for samples from all wells studied. The Cr/V ratio acts as an index of Cr over other ferromagnesian trace elements, and Y/Ni monitors ferromagnesian elements relative to HREE values (Y as a proxy for HREE). Included on plot is a two-member mixing line between mafic and felsic compositions. Most samples plot in the felsic compositional range, while MOCE1 plots on the mixing line towards the mafic end member.

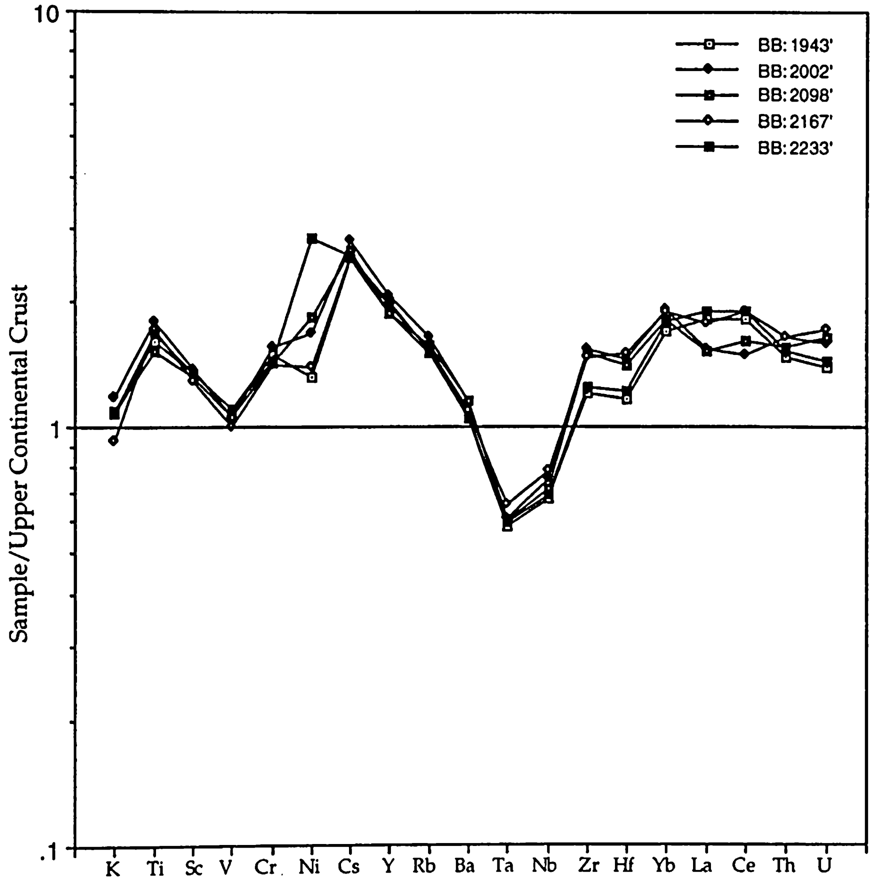

Figure 23. Multi-element plot normalized against average upper continental crust values (Taylor & McLennan, 1985) for metagreywackes from KSBB3, Bourbon County, KS. Sample is characterized by a negative Ta-Nb anomaly and a positive Cr-Ni (notably 2233' for Ni) Cs and Ti anomalies, also enriched in the refractory elements.

values are anomalously high. Concentration of Cs could be a weathering effect, but it is unclear if this is so. All samples show enrichments in Zr and Hf, which suggests concentration of heavy minerals. Interestingly, the deepest and shallowest intervals are less enriched in Zr and Hf. A negative Nb-Ta anomaly is also evident, which is indicative of felsic-intermediate magmatic arc rocks. This anomaly is seen in all wells, however, less pronounced in the Vernon County samples.

V-3 and V-2 (Fig. 24) show a great deal of variance. The relatively extreme behavior of V-3/L could be a result of analytical error, but it is unclear at this time. All three show an extreme positive Cs anomaly. N and P shales are enriched in Ti, Sc, V and Cr, with Ti highest. Interestingly, the N shale drops in Ni conentration relative to UCC, while P and L values are much greater relative to UCC. In addition all three shales show enrichments in Zr and Hf, as well as the elements Yb-Th. Again, this is suggestive of a mixed source with a possible, minor mafic component. Interestingly, there appears to be compositional variance amoung these shale units. This could be a result of heterogeneous hydrothermal fluid migration, or depositional, i.e. source variance.

MOCE1 (Fig. 25) has positive Sc-V-Cr-Ni anomalies. Ti, however, is closer to UCC values. Extreme Cr enrichment coupled with Sc, V, and Ni enrichment is highly suggestive of a mafic component. At the same time, MOCE1 has enrichments of La-Ce and Th relative to UCC, suggesting a very mixed source of predominantly upper crustal rocks with a minor mafic component. A two-component mixing model of Cr/Th versus Sc/Th ratios (after Floyd et al., 1990), with mafic and felsic end members supports this idea (Fig. 26). MOCE1 plots along the mixing line towards the basalt end, while all other samples studied cluster between felsic arc and upper continental crustal values. MCR clastic-rock data from previous studies (Cullers and Berendsen, 1995) are also plotted. These samples plot along the mixing line, yet cluster about arc and UCC values. The samples studied, excepting MOCE1, plot within the range of the MCR samples, but are more tightly clustered. They do not show a similar range of compositions, which may be a result of sedimentary recycling.

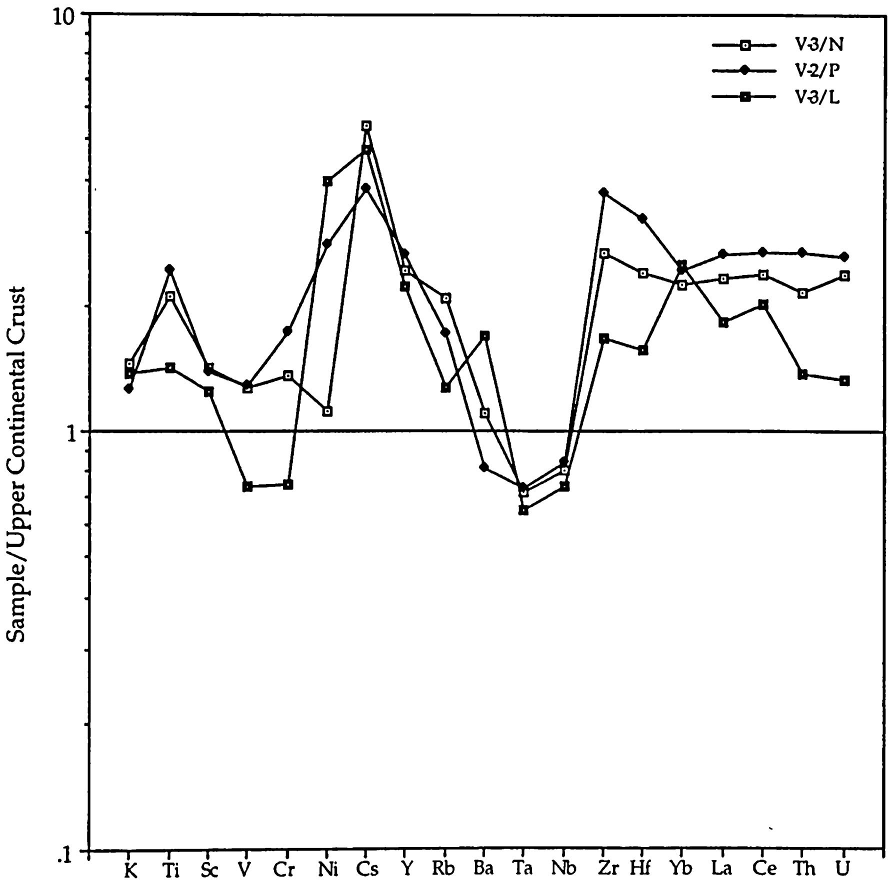

Figure 24. Multi-element plot normalized against average upper continental crust values (Taylor & McLennan, 1985) for the shales from V-2 & V-3, Vernon County, MO. Samples are characterized by negative Ta-Nb and positive Cs anomalies as well as high Zr and Hf. V-3/L and V-2/P show high Ni.

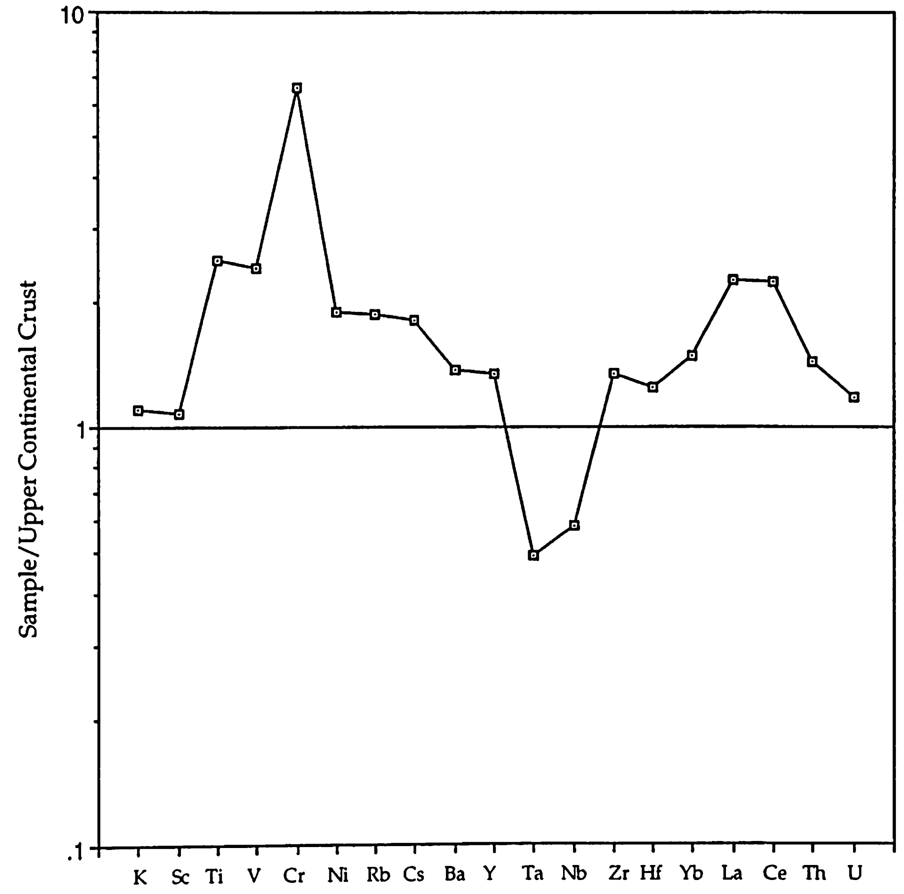

Figure 25. Multi-element plot normalized against average upper continental crust values (Taylor & McLennan, 1985) for the arkose from MOCE1, Cedar County, MO. Sample is characterized by a negative Ta-Nb and a positive V-Cr-Ni and La-Ce.

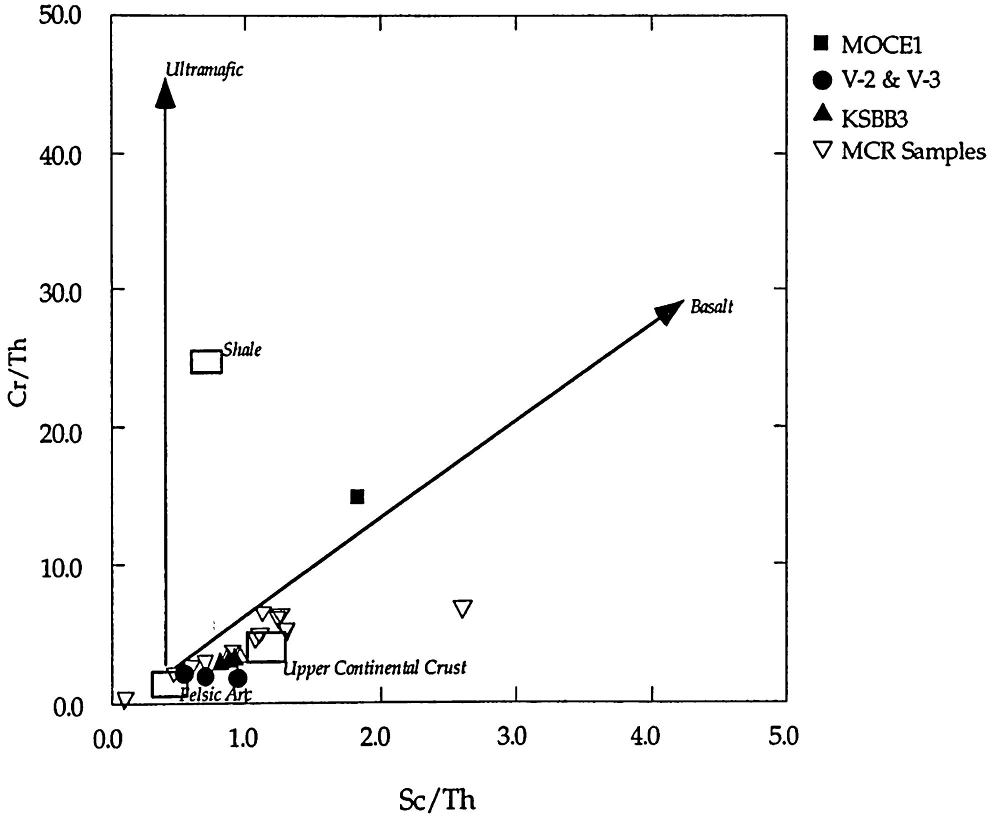

Figure 26. Plot of Cr/Th versus Sc/Th for all metasedimentary rocks from all wells studied and for data from a study of clastic rocks from the 1.1-1.2 Ga southern Midcontinent Rift (Cullers and Berendsen, 1995). Included are possible source end-member compositions and their proportional influence on the compositions of the sedimentary rocks (end-member compositions taken from Floyd et. al., 1990). Most of the samples studied plot between the Upper Continental Crust and Felsic Arc compositions, while MOCE1 plots towards the basaltic end member.

La-Th-Sc ternary plots have been demonstrated by several researchers (Bhatia and Crook 1986; Basu et al., 1990; McLennan et al., 1993) to discern effectively amoung tectonic settings from which sedimentary rocks were derived. Data that plot from La towards Sc are more indicative of a basaltic to oceanic island arc terrain, while upper continental crust plots more towards the La corner. Figure 27 illustrates the samples studied plus MCR clastic samples on a La-Th-Sc plot. The majority of the samples plot within the compositional range of UCC. This particular range is indicative of active continental margin to passive margin settings, or intracratonic setting (Bhatia and Crook, 1986; Basu et al., 1990; McLennan et al., 1993). Many of the samples fall in the range of continental island arcs, which may suggest a contribution from rocks of the CPO. Some of the MCR samples extend towards the Sc vertex, suggesting a possible, yet minor mafic influx.

Cullers and Berendsen (1995) compared clastic rocks of the southern MCR (SMCR) to those of the northern rift related rocks in Minnesota and Wisconsin (Oronto and Bayfield Groups). They conclude that the range of elemental ratios of the rocks of the SMCR are more in line with Holocene sands derived from mainly granitoid sources as opposed to a basaltic source. For a comparison of the samples studied to those of the SMCR, I utilize the same parameters from their study .

Figures 28 and 29 are La-Cr-Th and La-Co-Th ternary plots, respectively. The samples studied in addition to samples from SMCR clastic rocks are plotted for comparison. MCR data, granitoid and basalt values are from Cullers and Berendsen (1995) and Cullers and Berendsen (1993). From the La-Cr-Th plot (Fig. 28) it is apparent that the samples studied plot along the same trend as the MCR samples. The V-3 shales extend more to a granitoid composition, while MOCE1 leads the trend towards the basaltic composition. However, on the La-Co-Th plot (Fig. 29), all samples studied cluster more in the compositional range of a granitoid source. The MCR data show more scatter stepping out towards a basaltic composition. Again, the study samples and the MCR samples show strong similarities in composition. However, the samples studied have lesser concentrations of Co than MCR samples, yet are comparable in

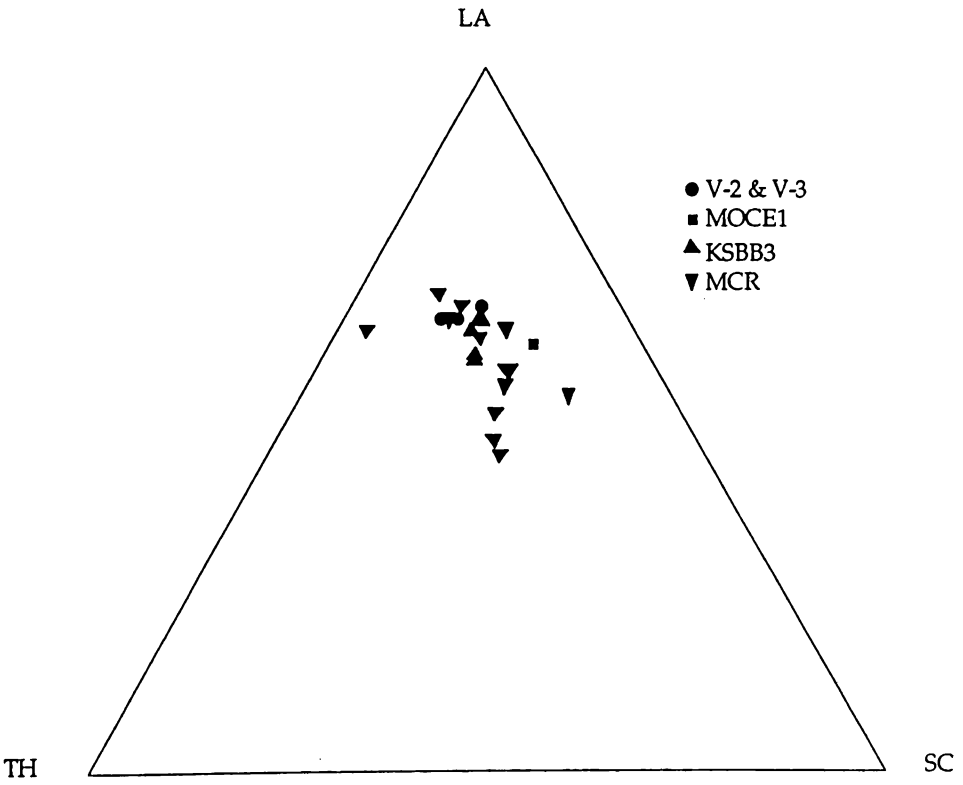

Figure 27. La-Sc-Th ternary plot for all study samples and data from clastic rocks of the MCR (Cullers and Berendsen, 1995). Most data fall within the compositional range of upper continental crust, including MCR samples. A few MCR samples and MOCE-1 extend towards Sc suggesting a minor mafic component.

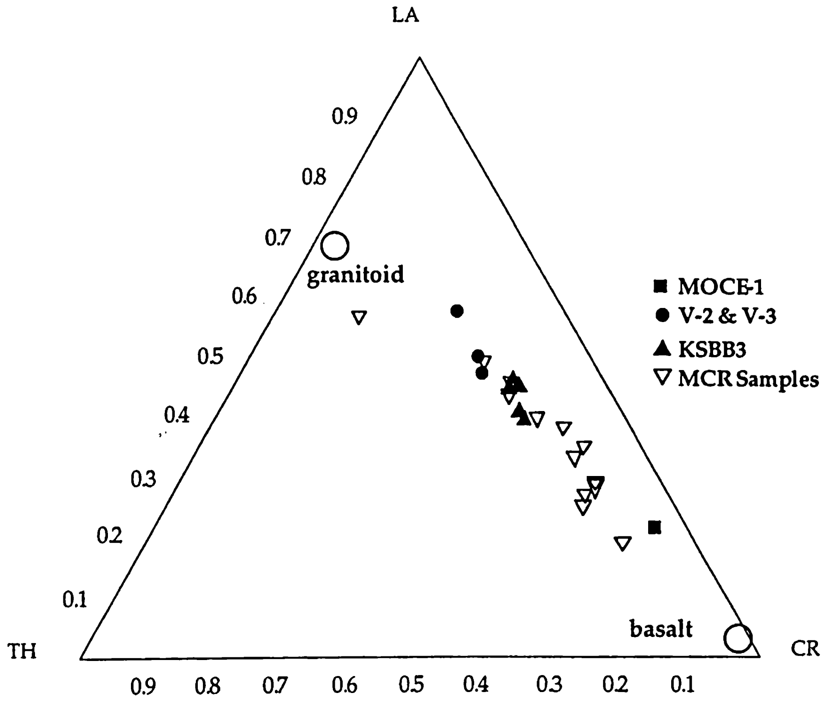

Figure 28. La-Th-Cr ternary plot of clastic rocks studied plotted in comparision with clastic rocks from the Midcontinent Rift (values from Cullers and Berendsen, 1995). Samples studied fall within the compositional range of the rift sedimentary rocks, however, most plot towards granitiod composition. MOCE1 leads the trend towards a basaltic composition.

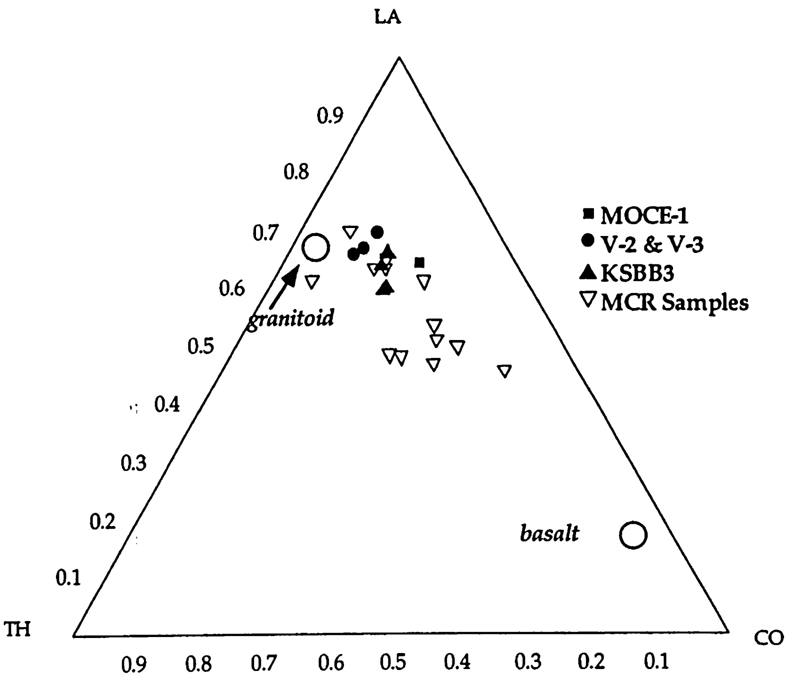

Figure 29. La-Th-Co ternary plot of clastis rocks studied plotted in comparision with data from clastic rocks from the 1.1-1.2 Ma Midcontinent Rift (Cullers and Berendsen, 1995). The samples studied fall within the compositional range of some of the MCR clastic rocks, and are closer in composition to granitoid source rocks.

Cr concentrations. The reason for this is unclear, however, the samples studied appear to be more sedimentalogically mature than the MCR rocks (greater quartz content, depleted in Na_2O, CaO and Sr), and Co could have been preferentially fractionated during the sedimentary process.

For a broader comparison, Figures 30, 31, and 32 show elemental ratios of the samples studied relative to the SMCR. The Vernon County shales (Fig. 30) show strong similarities in SiO_2, K_2O, and Al_2O_3 values. All V-3 shales are more enriched in Ni, TiO_2, Fe_2O_3. The N and P shales are relatively enriched in Cr as well. Eu/Eu* for the three shales are slightly, but not significantly, lower than SMCR. The N and P shales also show enrichments in Zr and Hf, suggesting enrichments in heavy minerals, which is unusual for shales. The V-shales are also relatively enriched in incompatible elements.

KSBB3 (Fig. 31) appears to be the most similar to SMCR. All intervals do show enrichments in Ni (most notably 2233'), Cr, TiO_2, and Sc. All intervals are also enriched in incompatible elements relative to rocks of the SMCR.

MOCE1 (Fig. 32) shows strong similarities to SMCR. Interestingly, the exceptions are relative enrichments in the elements, Sc, Ni, Cr and MgO. MOCE1 appears to have a stronger mafic component than the SMCR rocks. Coupled with those elements are enrichments in Sm, Th, and La, which are incompatible elements that are more indicative of granitoid source rocks. It appears that MOCE1 is predominantly derived from granitoid rocks, but does show a distinct mafic signature. What is interesting is that it is a stronger signature than the SMCR rocks; rocks that were deposited directly in the central rift basin of the MCR as well as in flanking basins.

Interestingly, all samples studied show enrichments relative to SMCR for the majority of trace and REE elements, which could be an artifact of a higher percentage of quartz in the samples studied. Exceptions include relative depletions in Sr, which may be a result of the samples' extended sedimentary life relative to the immature sediments of the SMCR. Eu/Eu* values are consistently lower than SMCR, but not significantly so. What stands out in this comparison is that the sediments studied appear to show a stronger mafic component, as well as a stronger UCC component. Common to all samples studied is the distinct positive Cs anomaly. It is unclear at this time as to the cause of this anomaly, but it may be an indication of the samples' more mature sedimentary history. In addition there are consistent depletions in CaO and Na_2O relative to SMCR. This, too, could be a result of sedimentary processes, as well as burial processes that may have preferentially leached CaO and Na_2O.

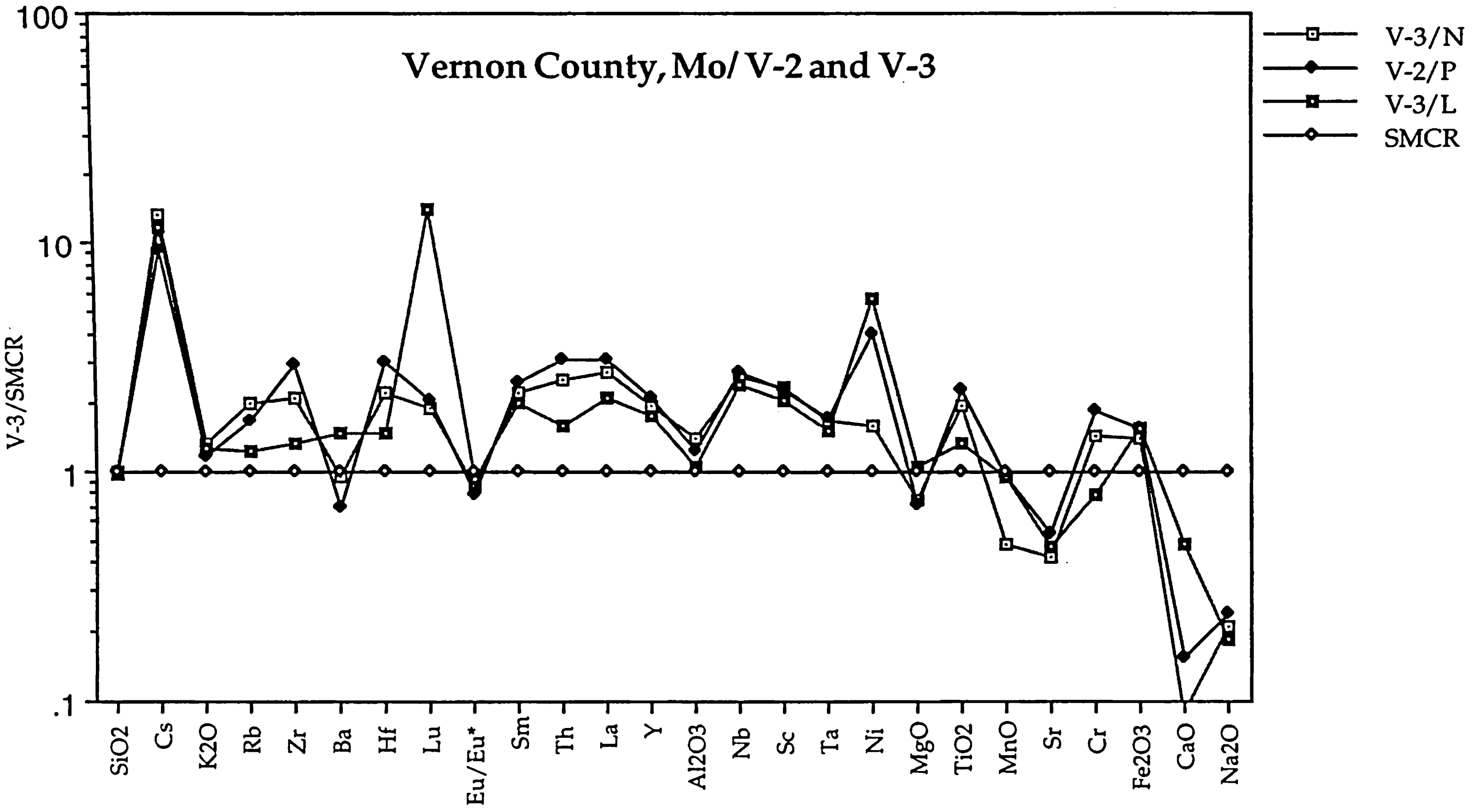

Figure 30. An elemental plot of samples from V-2 and V-3, Vernon County, Mo, normalized to the average composition of clastic rocks of the southern Midcontinent Rift (SMCR) (values from Cullers and Berendsen, 1995). All samples show enrichments in Ni, Ti, Sc, as well as in Sm, Th, La and Y relative to rocks of the SMCR. Enrichments in Cs, and depletions in Ca, and Na are interpreted as weathering effects.

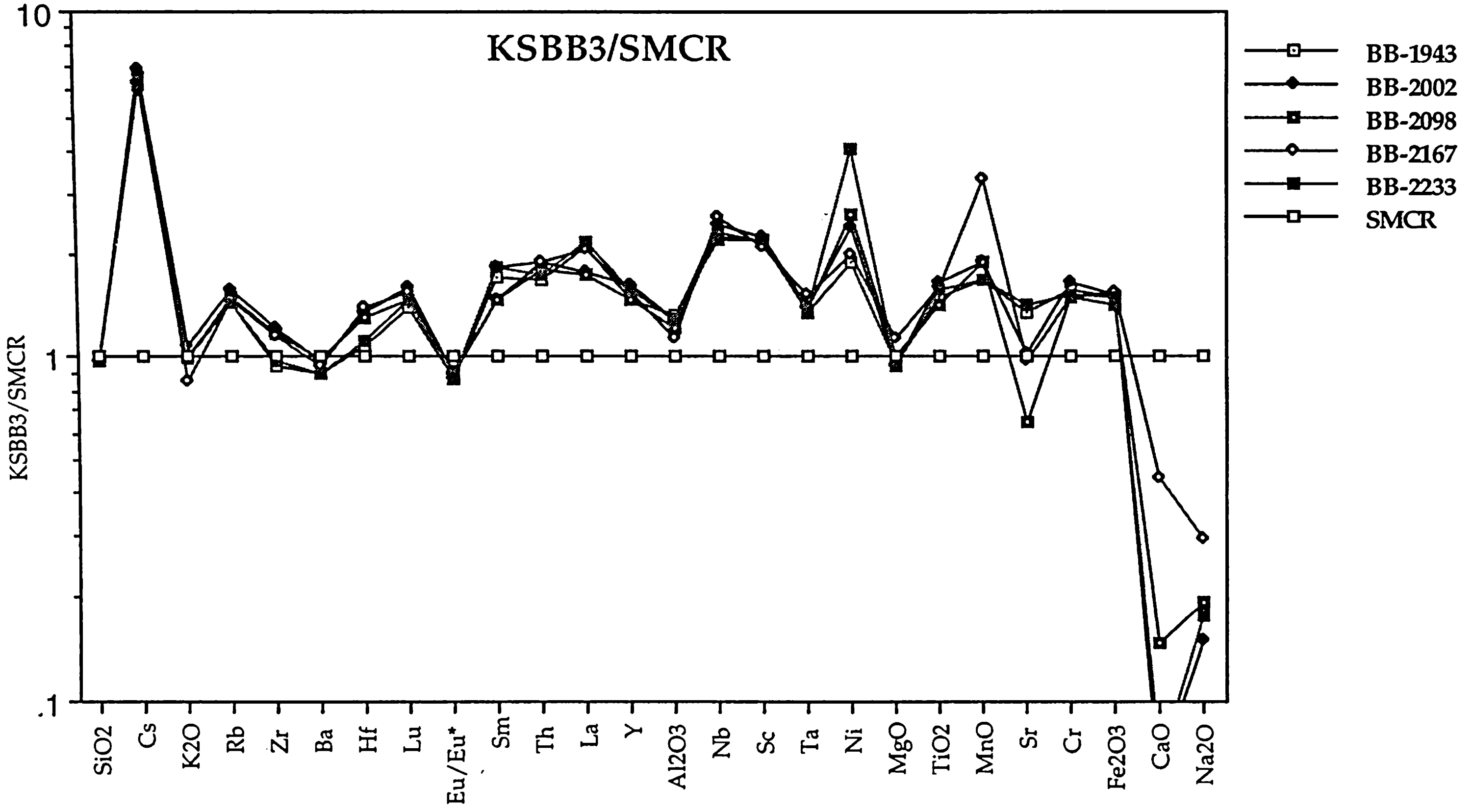

Figure 31. An elemental plot of samples from KSBB3, Bourbon County, KS normalized to the average composition of clastic rocks of the southern Midcontinent Rift (SMCR) (values from Cullers and Berendsen, 1995). All samples show enrichments in Cr, Ni, Ti, Sc, as well as in Sm, Th, La and Y relative to rocks of the SMCR. Enrichments in Cs, and depletions in Ca, and Na are interpreted as weathering effects.

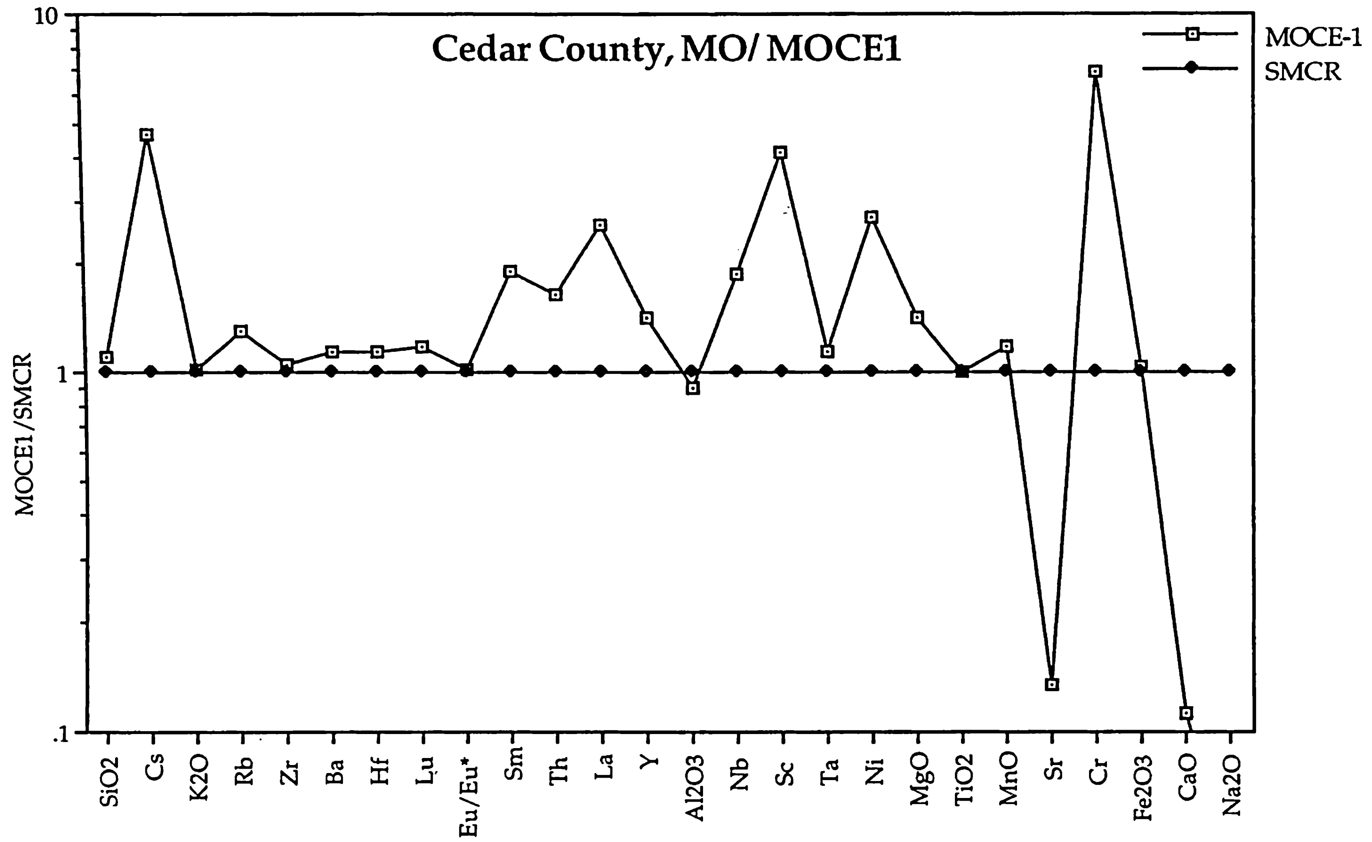

Figure 32. An elemental plot of MOCE1, Cedar County, Mo, normalized to the average composition of clastic rocks of the southern Midcontinent Rift (SMCR) (values from Cullers and Berendsen, 1995). MOCE1 shows enrichments in Cr, Ni, Sc, as well as in Sm, Th, La and Y relative to rocks of the SMCR. Enrichments in Cs, and depletions in Ca, and Na are interpreted as weathering effects.

DISCUSSION

U-Pb isotopic analyses from a variety of single detrital zircon morphologies provide relatively young age constraints on the age of deposition for at least two of the wells studied. For MOCE1, 1.0 Ga zircons provide a maximum age constraint for deposition of the meta-arkose. Minimum age of deposition is provided by the overlying Cambro-Ordovician Reagan and Lamotte sandstones. Given that the meta-arkose sample was in the form of core, I am confident that the 1.0 Ga zircons were in situ and are representative of the provenance of the meta-arkose. Additional provenance ages range from 1.60-1.76 Ga

For KSBB3, 0.62 Ga zircons provide a maximum age constraint for deposition of the metagreywacke. Minimum age of deposition is provided by the overlying Cambro-Ordovician Reagan and Lamotte sandstones. Even though the metagreywacke samples were in the form of cuttings, I am reasonably confident that the zircons analyzed were in situ. Contamination from overlying sandstones was easily distinguished from the consistently fine-grained, dark gray metagreywacke. In addition the cuttings were approximately 2-5 mm in size, which allowed for a reasonably confident assessment of lithology. Analyses yielded additional provenance ages that ranged from 1.66-1.99 Ga.

Detrital zircons from the two Vernon County wells, V-2 and V-3, primarily yielded provenance ages that range from 1.60 to 1.83 Ga. The only exception is the presence of 525 Ma zircons from the stratagraphically lowest K-quartzite. I am less confident as to the veracity of this data, for contamination was most difficult to distinguish in the Vernon County wells. This is due to the fact that the drill cuttings were sand-sized and disaggregated. Even after examination and characterization of the overlying Lamotte and Reagan sandstones, it was often difficult to distinguish infall from the in situ rock.

Geochemical provenance and tectonic setting analyses indicate that these sedimentary rocks were primarily derived from average upper continental crust source rocks from an intracratonic setting. The majority of the samples yield higher concentrations of Cr, Ni, Ti, and V relative to upper continental crust values, which may indicate a minor (<5%) mafic source contribution. An elemental comparison of the rocks studied to clastic rocks of the southern Midcontinent Rift indicates enrichments relative to SMCR rocks in Cr, Ni, Ti, and Sc, as well as enrichments in Th, La, and Y relative to SMCR.

The data do not support the supposition that the clastic rocks of this study were derived from clastic rocks of the Midcontinent Rift. A geochemical comparison of the data indicate that the rocks studied plot in generally the same compositional range (Figs. 26-29), however this compositional range is also that of average upper continental crust and this test is therefore non unique. In addition, the rocks studied yield a subtle indication of a mafic source component not seen in clastic rocks of the MCR.

U-Pb analyses of single detrital zircons also do not support, and, in fact, argue against derivation from clastic rocks of the MCR. The Martin et al. (1993) study of detrital zircons from clastic rocks of the MCR indicate that they were derived from proximal basement rocks ranging in age from 1.7-1.8 Ga, 1.4-1.5 Ga, and 1.1-1.2 Ga. No zircons analyzed from the current study were from the age range 1.4-1.5 Ga or 1.1-1.2 Ga, and only a few zircons fell in the range 1.7-1.8 Ga. The majority of the zircons from this study fell in the age range of 1.6-1.7 Ga; a range not represented in the Martin et al. (1993) study.

Rocks of the Central Plains orogen (CPO) could be a possible source for the zircons that range in age from 1.63-1.76 Ga. Ages greater than 1.8 Ga and less than 1.63 Ga are atypical for the CPO. A specific source for the suite of 1.60 and 1.83 Ga zircons is unknown at this time. More work is needed to identify these source rocks. They may be from a continental block that was subsequently rifted away during the Early Cambrian breakup of Laurentia, or they are merely in the subsurface of the Midcontinent and have yet to be analyzed.

The only two known potential source areas for the suite of 1.0 Ga zircons from MOCE1 are the 1.0 Ga Pike's Peak batholith located in Colorado, or the 1.3-1.0 Ga Grenville orogen. It is unknown when Pike's Peak was uncovered; however, there is evidence that the batholith was deeply eroded prior to deposition of overlying Ordovician rocks. There is no current evidence to rule out Pike's Peak batholith as a source.

Synorogenic intrusions of the Grenville orogen, ranging in age from 1.25-1.0 Ga (Rankin and others, 1993), are a more probable source. This supposition is supported by the work of Rainbird et al. (1992, 1997). Their U-Pb detrital zircon study of quartzarenites in the McKenzie mountains of northwestern Canada yielded a large suite of 1.25-1.0 Ga zircons. Their data coupled with an examination of paleocurrent data suggested a pan-continental river system that drained the Grenville orogen and transported sediments in a northwesterly direction (Fig. 33). I suggest that the meta-arkose of MOCE1 received detritus originating in the Grenville orogen and that the arkose may represent a proximal part of this proposed river system. I encourage further isotopic study of these rocks and other similar rocks, such as the Tillman Metasedimentary group, in the Midcontinent region to assess the validity of this idea.

The maximum age for deposition for the metagreywacke of Bourbon County, KS is provided by the 620 Ma suite of zircons. This provides a window of approximately 120 million years for deposition of the greywacke, faulting that formed the graben, and a period of erosion to remove the surrounding sedimentary cover. Peneplanation would then be followed by deposition of the Cambro-Ordovician (~503 Ma) Sauk sequence.

A specific source for the 620 Ma zircons is unknown at this time. It is of importance to note, however, that this age is coincident with Neoproterozoic to Early Cambrian continental rifting and the subsequent breakup of Laurentia. Continental breakup is believed to have occurred in at least two pulses, the first at about 700-760 Ma and the second one about 550-600 Ma (Rankin and others, 1993). The latter pulse led to continental separation. Rocks associated with the younger phase of rifting are scattered along the western Appalachian orogen and up into Newfoundland (Rankin and others, 1993). Although, there is presently no known source of 620 Ma zircons, it is still possible that they are a product of activity associated with continental breakup.

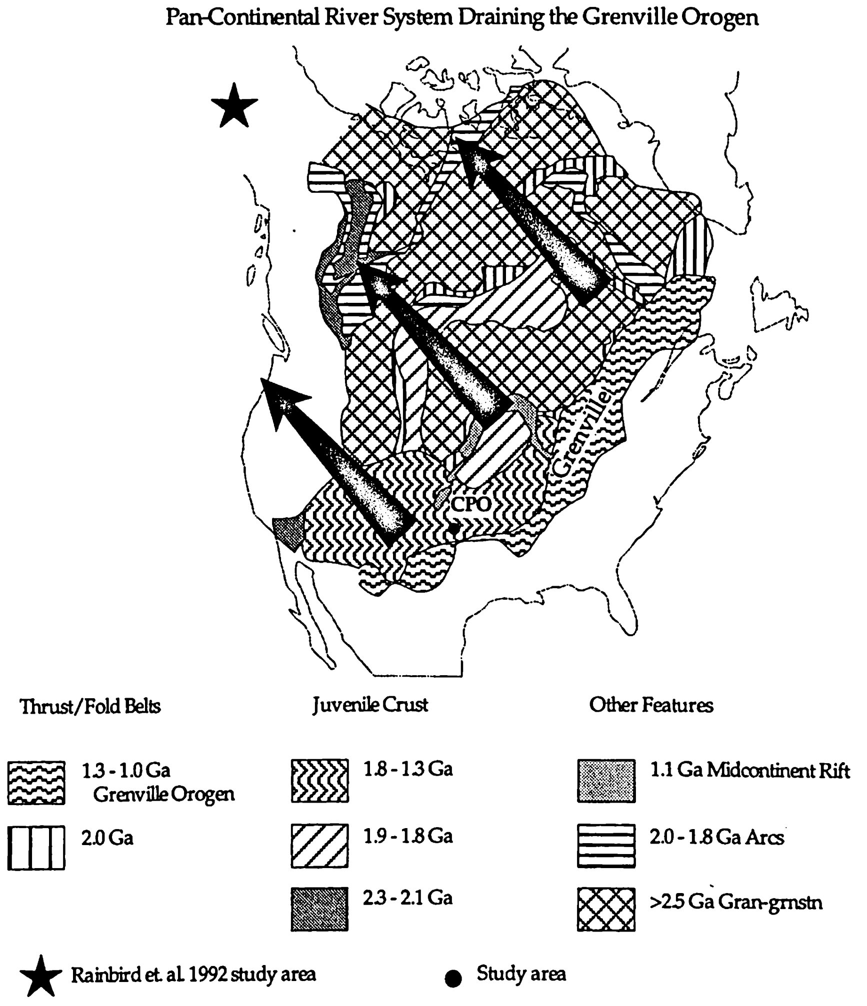

Figure 33. Proposed transport direction of a pan-continental river system draining the Grenville Orogen, suggesting a northwesterly (present day direction) transport direction. (Modified from Rainbird, Heaman and Young, 1992)

On the other hand, the 620 Ma zircons may have been derived from rocks of a presently unknown continental block that was rifted away from the southeastern (present day directions) margin of Laurentia. Interestingly, ~620 Ma is the characteristic age of Pan African mobil belts (Toteu, et al., 1994); however, given current plate reconstructions for the Neoproterozoic, there are no known Pan African mobil belts proximal to the Midcontinent region. This problem can only be resolved with continued isotopic and tectonic research. Continued isotopic work on similar clastic sedimentary rocks in the basement of the Midcontinent may yield additional constraints on Neoproterozoic-Early Cambrian plate reconstructions.

The presence of 525 Ma zircons from the stratigraphically lowest K quartzite from the Vernon County, MO wells is surprising and unexpected. While these zircons are most likely a result of contamination from overlying Paleozoic units, it is odd that this age-suite is not represented in the shallower units, O and Q. If these zircons are accepted as inherent to the K quartzite, and given that this age-suite is not seen in the shallower quartzites, then it may be possible that we are observing unroofing recorded in the sediments. This would place a maximum age for deposition of the K quartzite at ~525 Ma, and a minimum age for deposition for the entire clastic sequence at ~503 Ma. However, it is unclear where and what was unroofed. It is also unclear when formation of the basin occurred. Faulting would have to have occurred sometime after deposition of the entire section. Subsequent to this faulting episode, a period of peneplanation would be required to remove the surrounding sedimentary cover. All of these events would have to have occurred before deposition of the Sauk sequence, within a period of approximately 22 million years.

Perhaps, the presence of 525 Ma zircons is an indication of high angle or thrust faulting. This suggestion, however, would require deposition of this entire package, followed by a period of faulting that created the graben, and a period of erosion; all before deposition of the ~503 Ma Lamotte and Reagan sandstones. While 22 Ma is an adequate amount of time for events of this magnitude, these ideas are untestable and untenable, given the data set presently available.

Contamination from overlying Paleozoic units is a more plausible explanation, and I therefore interpret the 525 Ma zircons as contamination from overlying Paleozoic rocks.

Perhaps the most enigmatic aspect of this study is the apparent lack of zircons from the 1.37-1.47 Ga Southern and Eastern Granite-Rhyolite provinces. This fact is enigmatic because rocks of this age range are pervasive within the basement of the Midcontinent. Given that rhyolite clasts were observed in the samples, and that the graben is bounded by rocks of the SGR province, it is surprising that no zircons of that age were analyzed. Sampling bias is unlikely, given the large and diverse data set, it is statistically unlikely that if 1.37-1.47 Ga zircons were present in the sample, that they were not sampled.

There are three other possibilities to explain the absence of 1.37-1.47 Ga zircons. One explanation is that they were simply not deposited, in other words, the rocks predate the SGR province. The data, for at least MOCE1 and KSBB3, however indicate that the rocks are younger than the SGR province.

A second possibility is that the 1.37-1.47 Ga zircons were eroded away. It is unlikely, however, that these zircons were preferentially eroded away. The zircon populations from all wells were diverse in morphology and size, thus there is no apparent sedimentary sorting mechanism at work. It is also unlikely that a specific group of zircons would behave differently in the sedimentary cycle from other zircons.

A third explanation is that the rocks of the SGR and EGR provinces were covered during the time of deposition of the sedimentary units studied, or detritus did not make it to the study area. In other words, the paleodrainage patterns did not transport SGR and EGR detritus to the basin. It is not possible, given the rock record presently available, to determine paleodrainage patterns for this region. This is due to limited Precambrian sedimentary samples from this region, and to the nature of samples that are available (e.g. drill cuttings). It may be that rocks of the SGR and EGR provinces were already covered with a blanket of sedimentary rocks. The sedimentary units used in this study may represent units higher in the section of the Neoproterozoic sedimentary cover. The zircons that were analyzed could be from more distant highlands, such as the Grenville orogen, or a now missing continental block.

Final formation of the graben may have been a result of tectonic activity associated with Neoproterozoic-Early Cambrian rifting events that led to continental breakup. If so, rocks of the post-Grenville, Midcontinent sedimentary cover may have been trapped in the down-dropped block, while the surrounding region was upwarped, due to isostatic compensation during continental breakup. Peneplanation of the Midcontinent region removed most of the sedimentary cover prior to deposition of the Sauk sequence.

Continued isotopic, geochemical and petrographic work on Precambrian metasedimentary rocks is needed to test this idea. Most of the wells that penetrate metasedimentary rocks do not penetrate crystalline basement rocks. Thus, we do not presently know the depth of the sedimentary rocks. The only exception is V-3 which may have penetrated syenite at total depth. Isotopic analysis of the supposed syenite, plus deeper drilling is also needed to test these ideas.

CONCLUSIONS

U-Pb isotopic analyses of single detrital zircons provide relatively young age constraints on the age of deposition for at least two of the wells studied. For MOCE1 and KSBB3, 1.0 Ga and 0.62 Ga zircons provide maximum age constraints, respectively. Minimum age of deposition is provided by the overlying Cambro-Ordovician Reagan and Lamotte sandstones. Zircons from the Vernon County, MO wells, V-2 and V-3, yielded ages that range from 1.60-1.83 Ga. The suite of 525 Ma zircons from the stratagraphically lowest K-quartzite are interpreted as contamination from overlying Paleozoic rocks. Analyses from MOCE1 and KSBB3 also yielded provenance ages that range from 1.60-1.83 Ga.

A potential source for zircons that range in age from 1.64-1.8 Ga may be rocks of the Central Plains orogen. However, ages greater than 1.80 Ga and less than 1.64 Ga are not characteristic of the Central Plains orogen, and a source for those zircons is unknown at this time.

The apparent absence of zircons from the 1.37-1.47 Ga Southern and Eastern Granite Rhyolite provinces may be due to the fact that the region was covered. The sedimentary rocks from this study may represent rocks higher in the sedimentary section and therefore did not receive detritus from the SGR and EGR provinces. It is also possible that they did not receive detritus from the CPO, but from some presently unknown distant highland region. More isotopic work is required to address the problem.

Rocks of the 1.3-1.0 Ga Grenville orogen are the most likely source for the suite of 1.0 Ga zircons from MOCE1. This supposition is supported by the work of Rainbird et al. (1992, 1997). Their work suggests the existence of a pan-continental river system that drained the Grenville orogen and transported sediments in a northwesterly direction (Fig. 33). I suggest that the meta-arkose of MOCE1 received detritus originating in the Grenville orogen and that the arkose may represent a proximal part of this proposed river system.

A source for the suite of 620 Ma zircons from KSBB3 is unknown at this time. However, they may have been derived from rocks associated with the Neoproterozoic-Early Cambrian rifting events that led to continental breakup.

Geochemical provenance and tectonic setting analyses indicate that these sedimentary rocks were primarily derived from average upper continental crust source rocks from an intracratonic setting. The majority of the samples yield higher concentrations of Cr, Ni, Ti, and V relative to upper continental crust values, which may indicate a minor (<5%) mafic source contribution.

Overall, the data do not support the hypothesis that the clastic rocks of this study were derived from clastic rocks of the Midcontinent Rift. The rocks studied yield a subtle indication of a mafic source component not seen in clastic rocks of the MCR. In addition, U-Pb analyses of single detrital zircons do not support derivation from clastic rocks of the MCR. The Martin et al. (1993) study of detrital zircons from clastic rocks of the MCR indicates that they were derived from rocks ranging in age 1.7-1.8 Ga, 1.4-1.5 Ga, and 1.1-1.2 Ga. No zircons analyzed in this study were from the age range 1.4-1.5 Ga or 1.1-1.2 Ga, and only a few zircons fell in the range 1.7-1.8 Ga. The majority of the zircons from this study fell in the age range of 1.6-1.7 Ga, a range not represented in the clastic rocks of the Midcontinent Rift.

REFERENCES

Adams, J.W., 1959, Rocks of the Precambrian basement and those immediately overlying it in Missouri and parts of adjacent states: Umpublished M.S., Univ. of Missouri, 342 p.

Bally, A.W., 1989, Phanerozoic basins of North America, *in* Bally, A.W., and Palmer, A.R., eds., The Geology of North America-An overview: Boulder, Co, Geological Society of America, The Geology of North America, v. A., ch. 15.

Banerjee, D.M., Bhattacharya, P., 1994, Petrology and geochemistry of greywackes from the Aravalli Supergroup, Rajasthan, India and the tectonic evolution of a Proterozoic sedimentary basin, Precambrian Research 67, p. 11-35.

Basu, A.R., Sharma, M., and DeCelles, P.G., 1990, Nd-Sr-isotopic provenance and trace element geochemistry of Amozonian foreland basin flubial sands, Bolivia and Peru: Implications for ensialic Andean orogeny: Earth and Planetary Science Letters, v. 100, p. 1-17.

Berendsen, P., and Blair, K. P., 1995, Structural development of the Nemaha Tectonic Zone in Kansas, in: Structural Styles in the Southern Midcontinent, Johnson, K.S., ed. Oklahoma Geological Survey Circular 97, p. 208-214.

Bhatia, K.R., and Crook, A.W., 1986, Trace element characterisics of graywackes and tectonic setting discrimination of sedimentary basins: Contributions to Mineralogy and Petrology, v. 92, p. 181-193.

Bickford, M. E., and Van Schmus, W. R., and Zietz, I., 1986, Proterozoic history of the Midcontinent region of North America, Geology, v. 14, p. 492-496.

Bickford, M. E., Harrower, K. L., Hoppe, W. J., Nelson, B. K., Nusbaum, R. L., and Thomas, J. J., 1981a, Rb-Sr and U-Pb geochronology and distribution of rock types in the Precambrian basement of Missouri and Kansas; Geological Society of America Bulletin, Part 1, v. 92, p. 323-341.

Bond, G.C., Nickeson, P.A., and Kominz, M.A., 1984, Breakup of a supercontinent between 625 Ma and 555 Ma: new evidence and implications for continental histories, Earth and Planetary Science Letters, 70, p. 325-345.

Braile, L.W., Hinze, W.J., Keller, G.R., Lidiak, E. G., and Sexton, J.L., 1986, Tectonic development of the New Madrid rift complex, Mississippi embayment, North America: Tectonophysics, v.131, p. 1-21.

Cole, V.B., and Watney, W.L., 1985, List of Kansas wells drilled into Precambrian rocks, Kansas Geological Survey Subsurface Geology Series 7, 139 p.

Cullers, R.L., and Berendsen, P., 1993, Composition of rift-related igneous and sedimentary rocks of the Keweenawan Supergroup in the Poersch no. 1, OZ-1, Finn, and Friederich wells, northeastern Kansas, Kansas Geological Survey, Bulletin 235, pp. 55-72.

Cullers, R.L., and Berendsen, P., 1995, The provenance and chemical variation of sandstones associated with the northern mid-continent rift system compared to those in Kansas, U.S.A.

Denison, R. E., 1966, Basement rocks in adjoining parts of Oklahoma, Kansas, Missouri, and Arkansas [Ph.D. thesis]: Austin, University of Texas, 328 p.

DePaolo, D.J. and G.J. Wasserburg. 1976. Nd isotopic variation and petrogenic models. Geophysical Research Letters 3:249-252.

DePaolo, D.J., 1981, A neodymium and strontium isotopic study of the Mesozoic calc-alkaline granitic batholiths of the Sierra Nevada and Peninsular Ranges, California, Journal of Geophysical Research v. 86, pp. 10470-10488.

Faure, Gunter, 1986. Principles of Isotope Geology. John Wiley and Sons, Inc., New York, New York, 598p.

Floyd, P.A., Keele, Leveridge, B.E., Exeter, Franke, W., Giessen, Shail, R., Keele and Dorr, W., Giessen, 1990, Provenance and depositional environment of Rhenohercynian synorogenic greywackes from the Giessen Nappe, Germany, Geologische Rundschau, v. 79, no. 3, pp. 611-626.

Green, J.C., 1992, Proterozoic Rifts, *in* Condie, K.C. (ed) Proterozoic Crustal Evolution, Amsterdam Elsevier Science Publishers, 537 p.

Hoffman, P.F., 1989, Precambrian geology and tectonic history of North America, *in* Bally, A.W., and Palmer, A.R., eds., The Geology of North America-An overview: Boulder, Co, Geological Society of America, The Geology of North America, v. A., ch. 16.

Horrall, K.B., Hagni, R.D., and Kisvarsanyi, G., 1993, Mafic and Ultramafic Plutons Associated with the New Madrid Rift Complex-A Possible Major Source of the Copper-Cobalt-Nickel Mineralization of Southeast Missouri, Economic Geology, vol. 88, pp. 328-343.

Kisvarsanyi, E. B., 1974, Operation Basement - buried Precambrian rocks of Missouri- their petrography and structure: AAPG, Bulletin v. 58, no. 4, p. 674-684.

Kisvarsanyi, E. B., 1983, unpublished core description of basement rock from the well: USGS, Stockton #1, MGS # 28603 (NS-2/MOCE1), Missouri Department of Natural Resources.

Kisvarsanyi, E. B., 1984, The Precambrian tectonic framework of Missouri as interpreted from the magnetic anomaly map, Contribution to Precambrian Geology No. 14, Part B, Missouri Department of Natural Resources, Division of Geology and Land Survey.

Klasner, J.S., Cannon, W.F., and Van Schmus, W.R., 1982, The pre-Keweenawan tectonic history of southern Canadian Shield and its influence on formation of the Midcontinent Rift, The Geological Society of America, Memoir 156, pp. 27-46.

Krogh, T.E., 1982. Improved accuracy of U-Pb zircon ages by the creation of more concordant systems using an air abrasion technique. Geochimica et Cosmochimica Acta 46:637-649.

Krogh, T.E., 1973. A low-contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations. Geochimica et Cosmochimica Acta 37: 485-494.

Lidiak, E. G., 1972, Precambrian rocks in the subsurface of Nebraska: Nebraska Geological Survey Bulletin 26, 41 p.

Ludwig, K.R., 1993a. Isoplot: a plotting and regression program for radiogenic isotope data, verson 2.70. United States Geological Survey Open-File Report 91-445.

Ludwig, K.R., 1993b. Pbdat: a computer program for processing Pb-U-Th isotope data, version 1.24. United States Geological Survey Open-File 88-542.

Martin, M.W., Van Schmus, W.R., and Berendsen, P., 1993, Single grain U/Pb geochronology of detrital zircons from Midcontinent Rift arkoses, NE Kansas: implications for depositional history, Geological Society of America Abstracts with Programs, v. 25, no. 3, p. 65.

McLennan, S.M., 1989a, Rare earth elements in sedimentary rocks: influence of provenance and sedimentary processes: Mineralogical Society of America Reviews in Mineralogy, v. 21, p. 169-200.

McLennan, S.M., and Hemming, S., 1992, Samarium/neodymium elemental and isotopic systematics in sedimentary rocks: Geochimica et Cosmochimica Acta, v. 56, p. 887-898.

McLennan, S.M., Hemming, S., McDaniel, D.K., and Hanson, G.N., 1993. Geochemical approaches to sedimentation, provenance, and tectonics, Geological Society of America Special Paper 284, pp. 21-40.

Nance, W.B., and Taylor, S.R., 1976, Rare earth element patterns and crustal evolution-I. Australian post-Archean sedimentary rocks: Geochimica et Cosmochimica Acta, v.40, p. 1539-1551.

Nelson, B.K., and DePaolo, D.J., 1985, Rapid production of continental crust 1.7-1.9 b.y. ago: Nd and Sr isotopic evidence from the basement of the North American Midcontinent: Geological Society of America Bulletin, v. 96, p. 746-754.

Parrish, R.R., 1987, An improved micro-capsule for zircon dissolution in U-Pb geochronology, Isotope Geoscience v. 66, p. 99-102.

Patchett, P.J., and J. Ruiz. 1987. Nd isotopic ages of crust formation and metamorphism in the Precambrian of eastern and southern Mexico, Contributions to mineralogy and Petrology 96: 523-528.

Rainbird, R.H., Heaman, L.M., and Youn, G., 1992, Sampling Laurentia: Detrital zircon geochronology offers evidence for an extensive Neoproterozoic river system originating from the Grenville orogen, Geology, v. 20, p. 351-354.

Rainbird, R. H., McNicoll, V.J., Theriault, R.J., Heaman, L.M., Abbott, J.G., Long, D.G.F., and Thorkelson, D.J., 1997, Pan-continental river system draining Grenville orogen recorded by U-Pb and Sm-Nd geochronology of Neoproterozoic quartzarenites and mudrocks, Northwestern Canada, The Journal of Geology, v.105, p. 1-17.

Rankin, D.W., et al., 1993 Proterozoic rocks east and southeast of the Grenville front, The Geology of North America, v. C-2, Precambrian: Conterminous U. S., The Geological Society of America, p. 335-461.

Reed, J.C., Ball, T.T., Farmer, G.L., and Hamilton, W.B., 1993, A Broader View, The Geology of North America, v. C-2, Precambrian: Conterminous U. S., The Geological Society of America, p. 597-636.

Roberts, D.E., and Hudson, G.R.T., 1983, The Olympic Dam Copper-Uranium-Gold Deposit, Roxby Downs, South Australia, Economic Geology, vol. 78, no. 5, p. 799-824.

Sims, P.K., and Peterman, Z., E., 1986, Early Proterozoic Central Plains orogen-A major buried structure in the north-central United States: Geology, v. 14, 26, p. 488-491d.

Sims, P. K., Kisvarsnayi, E. B., and Morey, G. B., 1987, Geology and metallogeny of Archean and Proterozoic basement terranes in the northern Midcontinent, U.S.A.: An overview: U.S. Geological Survey Bulletin 1815, 51 p.

Skillman, M. W., 1948, Pre-Upper Cambrian sediments of Vernon County, Missouri: State of Missouri, Geological Survey and water Resources, Report of Investigations, no. 7, 17 p.

Stacey, J.S., and Kramers, J.D., 1975, Approximation of terrestrial lead isotope evolution by a two-stage model, Earth and Planetary Science Letters, v. 26; 2, p. 207-221.

Steiger, R.H. and E. Jager, 1977, Subcommission on Geochronology: convention on the use of decay constants in geo- and cosmochronology. Earth and Planetary Science Letters 36: 356-362.

Strong, D.F., O'Brien, S.J., Taylor, S.W., Strong, P.G., and Wilton, D.H., 1978, Aborted Proterozoic rifting in eastern Newfoundland, Canada Journal of Earth Science, 15, p. 117-131.

Taylor, S.R., and McLennan, S.M., 1985, The continental crust: Its composition and evolution: Blackwell, Oxford, 312 p.

Thomas, W.A., and Astini, R.A., 1996, The Argentine Precordillera: A Traveler from the Ouachita Embayment of North American Laurentia, Science, vol. 273, August 9, p. 752-757.

Toteu, S.F., Van Schmus, W.R., Penaye, J., and Nyobe, J.B., 1994, U-Pb and Sm-Nd evidence for Eburnian and Pan-African high-grade metamorphism in cratonic rocks of southern Cameroon, Precambrian Research, vol. 67, pp. 321-347.

Van Loon, J.C., 1980, Analytical atomic absorption spectroscopy, selected methods, Academic Press, New York, NY.

Van Schmus, W. R., and Bickford, M E., 1981, Proterozoic chronology and evolution of the Midcontinent region, North America, *in* Kroner, A., ed., Precambrian Plate Tectonics: Amsterdam, Elsevier Publishing Company, p. 261-296.

Van Schmus, W. R., and Hinze, W. J., 1985, The Midcontinent rift system: Annual Reviews of Earth and Planetary Science, v. 13, p. 345-383.

Van Schmus, W. R., et al., 1993, Transcontinental Proterozoic provinces, The Geology of North America, v. C-2, Precambrian: Conterminous U. S., The Geological Society of America, p. 171-334.

Walters, R.F., 1945, Buried Precambrian hills in northeastern Barton County, central Kansas, Geological Society of America Bulletin, v. 56; 12 part 2, p. 1210.