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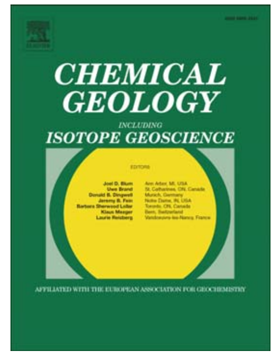

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Geology, age and field relations of Hadean zircon-bearing supracrustal rocks from Quad Creek, eastern Beartooth Mountains (Montana and Wyoming, USA)

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Abstract. Quad Creek Paleoarchean (≤3250 Ma) quartzites in southern Montana host Hadean (pre-3850 Ma) detrital zircons. Although an accessible resource for investigating early Earth processes distinct from other better known ancient zircon localities, the outcrop-scale geological and geochemical context of these rocks has not previously been well documented. New (1:250) mapping reveals a varied suite of isoclinally folded, sheared and variably deformed chromite-bearing banded and massive quartzites, garnetiferous siliceous (migmatitic) paragneisses, amphibolite, quartz-biotite schists and quartz+magnetite rocks (banded iron-formation; BIF). Conventional ion microprobe U-Pb zircon ages of populations from different quartzites and a paragneiss show outgrowth rim ages on older inherited detrital igneous zircon cores that match documented regional metamorphic events evidenced elsewhere in the Wyoming Craton. Weighted mean $^{207}Pb/^{206}Pb$ ages for the youngest concordant zircon cores of igneous derivation indicate the Quad Creek sediments were deposited by about 3250 Ma. Coupled with a large zircon $^{207}Pb/^{206}Pb$ age survey (n=1274), and an extended U-Th-Pb depth-profile of the oldest grain in our sample set, these data support the notion that the oldest crust tapped by these sediments was comparable in age to the ca. 4000 Ma Acasta Gneiss Complex. This similarity is suggestive of both of a linkage between the Wyoming Craton and the Western Slave Province, and the lingering influence of Hadean crust well into the Archean. **216 words**

KEYWORDS: zircon, Hadean, Paleoarchean, geochronology, Beartooth Mountains, Montana, Slave Craton, detrital, ion microprobe

1. **Introduction**

The presence of significant granitic crust in the Hadean eon (≥3850 Ma; definition of Bleeker, 2004) has been directly demonstrated through the discovery and characterization of hundreds of thousands of zircons (Holden et al., 2009) – including an ancient population as old as 4370 Ma – found in quartzites within the Narryer Gneiss Complex (NGC) at the Mt. Narryer (Froude et al., 1983) and Jack Hills localities on the margins of the Yilgarn craton in Western Australia (Compston and Pidgeon, 1986). Although alternative hypotheses have been offered for the genesis of these oldest zircons, including derivation from a mafic/gabbroic precursor (e.g. Galer and Goldstein, 1991; Kemp et al., 2010), mineral chemistry arguments most consistently favor granite-granitoid melt compositions (e.g. Maas and McCulloch, 1991; Mojzsis et al., 2001; Blichert-Toft and Albarède, 2008; Harrison, 2009; Hopkins et al., 2008, 2010; Trail et al., 2007, 2011).

It is worth mentioning that zircons this old are not exclusive to the NGC. Elsewhere in Western Australia, Wyche et al. (2004) identified detrital zircons from the Southern Cross Granite-Greenstone terrane as old as 4350 Ma. However, the geographic proximity of the Southern Cross terrane with the Narryer Gneisses could mean that they shared the same crustal source of very old zircons. By and large, because those studies are exclusively of detrital zircon grains orphaned from their parent rocks, only broad inferences can be made about probable source melt compositions that gave rise to them. Thus, ongoing debate revolves around the precise nature of Hadean rock types that could have given rise to the Hadean zircons (e.g. Valley et al., 2005; Kamber, 2007; Shirey et al., 2008; Kemp et al., 2010). No crustal remnants of such great antiquity have so far been identified on Earth; they may be buried, or they were destroyed long ago by, for example, the postulated Late Heavy Bombardment of the inner solar system (e.g. Abramov and Mojzsis, 2009).

As opposed to detrital zircon studies, direct analyses of Hadean rocks are limited to the few localities where actual 4 billion-year-old crust is documented with certainty. These are the Acasta Gneiss Complex (AGC) in the Northwest Territories of Canada (King, 1985; Bowring et al., 1989; Stern and Bleeker, 1998; Bowring and Williams, 1999), and certain components of the Mt. Sones gneisses within the Napier Complex of Antarctica (Harley and Black, 1997 and references therein). Although both the Acasta and Napier rocks are evidently older than ca. 3900 Ma (cf. Moorbath, 2005), the geology of their respective outcrops is as yet known only in broad terms, and further complicated by protracted histories of high grade poly-metamorphism and multiple episodes of intense deformation.

In addition, rare Hadean xenocrystic zircons have been found occluded in younger Eoarchean granitoid gneisses. One such 4183 Ma grain was recovered in drill core from near to Mt. Narryer (at the Jailor Well) in Western Australia (Nelson et al., 2000). A concordant ca. 4200 Ma xenocrystic zircon was discovered by Iizuka et al. (2006, 2007) in tonalitic gneiss from the Acasta area, but the field context of this sample is uncertain. A 3830-3850 Ma tonalitic orthogneiss from Akilia (Nutman et al., 1997; Amelin et al., 2011) within the southern Færinghavn terrane of the Itsaq Gneiss Complex (IGC) in West Greenland, yielded a concordant 4100 Ma zircon encased in biotite (Mojzsis and Harrison, 2002). In spite of this isolated report, and even though the IGC is regarded as the largest (>3000 km^2) and most comprehensively studied Eoarchean-Paleoarchean terrane on Earth (e.g. Nutman et al., 1996), no detrital zircons older than about 3890 Ma have been found there so far (Nutman et al., 2004).

Any new source of information on the Hadean Earth holds the potential to greatly enhance our understanding of the physical, chemical and possibly biological mechanisms that shaped the young planet. These would include: (i) the role of catastrophic impacts in the destruction of primordial crust; (ii) the plausibility of a nascent biosphere at that time; (iii) extent of continental-type crust; and (iv) what geophysical events could have led to the initiation of plate tectonics. In order to advance what we know of the geology of those places already identified to contain Hadean detritus, fine-scale mapping used to direct sample collection for geochronology and geochemistry of specific outcrops is warranted. With such knowledge, we can begin to build hypothesis tests for the origin of the oldest detrital rocks and minerals as well as to expand our inventory of Hadean crustal materials open for study.

One such example is from a fuchsite- (Cr-muscovite) bearing quartzite which hosts rare (~2% yield) pre-3900 Ma detrital zircons identified from samples in the northwestern part of the Wyoming Craton at the Quad Creek locality in southern Montana (Mueller et al., 1992, 1998; **Figure 1**). The Quad Creek metasedimentary enclaves are highly accessible at numerous road-cuts within granitoid gneisses and migmatites along Montana Rte. 12 south of Red Lodge (town), but remarkably little is known about their specific field relations. Some sketch maps of the area were published previously (Mogk and Henry, 1988), including a 1:600 scale map produced in the 1950s (Eckelmann and Poldevaart, 1957). Yet, the actual association of ancient zircon-bearing quartzites with other lithotypes, what those lithologies are, as well as the various modes of zircon occurrence, range of ages and compositions tied to specific lithologies, needs better definition. To this end, we performed 1:250 scale mapping to guide sampling for geochronology and geochemistry of the associated supracrustal rocks in the vicinity of the ancient zircon discovery site (Mueller et al., 1992, 1996). We use the output of these studies to propose a model for the origin of the various zircon populations.

2. **Geologic Background**

The Beartooth Mountains form a 100 km long by 50 km wide northwest-trending core of granite-granitoid gneisses flanked by migmatites and supracrustal enclaves, and cut by mafic dykes and leucogranitoid sheets (**Figure 1c**). It has long been known (Schafer, 1937) that occurrences of chromite-bearing quartzites (e.g. the metamorphic equivalents of heavy mineral “placer deposits”) and paragneisses in the Wyoming Craton are scattered throughout the northern and eastern Beartooth Mountains of southern Montana and northern Wyoming. Archean basement uplifted during the Cretaceous Laramide Orogeny and sculpted by glaciers in the Pleistocene means that outcrop exposure is good. The reason the Quad Creek outcrops have been the subject of study for so many years is that there are many quality road cuts astride the part of the Beartooth granite gneisses which hosts abundant supracrustal enclaves. The ~1000m relief of the area has steep canyon walls that also yields outcrop visible in three-dimensions. At Quad Creek proper, a diverse suite of tectonically interwoven lithologies comprises mafic gneisses, quartzites and other paragneisses, iron-formations, amphibolites, and some small outcrops of biotite schists of uncertain affinity (Poldevaart and Bentley, 1958). This kind of supracrustal assemblage is a general feature, for example, of the North Snowy block of the Montana Metasedimentary Province (MMP; Mogk et al., 1988; 1992) some 75 km northwest of the Quad Creek outcrops. A supracrustal sample from the Tobacco Root Mountains ~175 km northeast of Quad Creek yielded a discordant 3930 Ma zircon (Mueller et al., 1998), which testifies to a small background of Hadean detritus in the wider region that awaits further exploration. With the exception of the rare Hadean zircon record documented for various supracrustal enclaves in the Wyoming Craton, periods of Eoarchean and Paleoarchean crustal growth are inferred based on the compositions of gneisses with ca. 3900 Ma Sm/Nd model ages and highly radiogenic Pb isotopic compositions (Wooden and Mueller, 1988). These include rocks of the Sacawee block and MMP (Grace et al., 2006) as well as 3300-3700 Ma ages for the Granite Mountain region of central Wyoming (Fisher and Stacey, 1986; Langstaff, 1995). Ancient (ca. 4100 Ma) model ages have also been derived from interpretations of trends in calculated initial εHf values for Quad Creek zircons (Mueller and Wooden, 2012).

The Quad Creek rocks experienced magmatic injections probably associated with the final assembly of the Wyoming Craton; magmatism occurred in three separate phases in the southern margin of the terrane at 2710-2670, 2650-2620, and 2550-2500 Ma (Mueller and Frost, 2006). Proterozoic extension at 2100-2000 Ma and 1500-1400 Ma is also recognized, which saw the emplacement of mafic dike swarms associated with crustal thinning (Chamberlain et al. 2003). The Beartooth rocks were brought to granulite facies metamorphic conditions (T = 750-800°C, P = 5-6 kbar) sometime around 3250-3100 Ma (Henry et al. 1982) based mostly on Rb-Sr and Pb-Pb systematics and other indicators (Wooden et al. 1988a,b; Mogk et al. 1992). Granulite metamorphism was followed by retrograde amphibolite facies metamorphism and several later episodes of granitoid intrusions (Eckleman and Poldervaart, 1957; Mogk and Henry, 1988).

Various results from ongoing geochronological work on detrital and younger post-depositional (metamorphic) zircons from the northern part of the Wyoming Province were used to constrain a broader age range of 2700-3300 Ma for the quartzites (Mueller et al. 1988; Mueller and Wooden, 2012). The overall dominance of ca. 3300 Ma ages in all zircon U-Pb datasets thus far published could also be interpreted as representative of the maximum age of deposition of these supracrustals, if it can be shown that the youngest most concordant zircons in this age grouping have Th/U compositions consonant with equilibrium exchange of Th and U with magma (see below). In a study of 355 detrital zircons from the original Quad Creek sampling locality by Mueller et al. (1992, 1998), about 20% of the grains were found to be between 3400-4000 Ma and many of those were within 10% of concordia. More recently, Mueller and Wooden (2012) reported ages and Hf isotope compositions for 75 more zircons from Quad Creek (**Figure 2**). Datasets from the neighboring Ruby and Tobacco Root uplifts show that they too are no younger than about 3250 Ma (Mueller and Frost, 2006).

Overall, there is general agreement that the Paleoarchean igneous (as opposed to younger neoform metamorphic) zircon ages reflect the dominant influence to these sediments from crust of that age shed into the catchments (basins) that ultimately formed the Montana Metasedimentary Province. However, what was the source terrane of the most ancient zircons at Quad Creek and surrounding supracrustal enclaves? Something ancient was nearby because both Sm-Nd model ages and whole-rock and mineral (feldspar) Pb isotope models show that ca. 3900 Ma crust was present in the northern Wyoming province when the Beartooth quartzites (and probably the whole of the MMP) were deposited (Mueller et al. 2010); whole-rock Hafnium model ages of ca. 3850 Ma (Stevenson and Patchett, 2000) and zircon Lu/Hf and εHf data (Mueller and Wooden, 2012) also support this view.

3. Methods

This study reports in detail on a small (185 × 210 m) area of outcrop with good exposure (~50-75%) that includes the discovery location of Mueller et al. (1992). New conventional zircon U-Pb ion microprobe ages (n=118) were combined with a large scale survey (^{204}Pb-corrected) of detrital zircon age determinations (n=1156) to compare to all existing datasets of these rocks (**Figure 2**).

"Conventional" ion microprobe geochronology in this case refers to the routine U-Th-Pb analyses of zircons performed in spot mode with the results averaged through 10-15 cycles of the secondary ions accelerated through a large radius sector magnet before focusing into an electron multiplier; because the primary ion beam is de-focused to a ~20 μm diameter spot on the sample, the 2-D spatial selectivity of the ion microprobe is limited by the diameter of the primary beam. A variation of this technique is to extend the analysis time (~150-200 cycles) so that the primary ion beam continues to sputter into the sample while at the same time collecting data that is transformed into a continuous age and composition profile of several micrometers (Mojzsis and Harrison, 2002). Further details of a depth-profiled ca. 4000 Ma grain (*Bear-2_5-6*) from the Quad Creek locality described in Trail (2006) and Trail et al. (2007) are reported here. In "rapid survey mode", the ion microprobe collects only the ^{204}Pb, ^{206}Pb, ^{207}Pb and ^{208}Pb secondary ion beams into a multi-collector system of electron multipliers at high primary ion beam currents in the span of less than 10s per analysis (Holden et al., 2009). In this manner, age estimates for thousands of zircons can be quickly determined. Our purpose in using this technique here was to to explore the frequency of zircons of specific ages in these Paleoarchean sediments via the statistics of large numbers. When available, we also compared measured $[Th/U]_{zrc}$ for individual zircon analyses with age against expected values for crystals grown in an igneous environment, and as a function of ($^{207}Pb/^{235}U$ age vs. $^{207}Pb/^{206}Pb$ age) concordance (see Cates and Mojzsis, 2009). We used these data to assess the probability density of geochronological data tied to a particular composition (e.g. $[Th/U]_{zrc}$) and ascribe a maximum age for deposition of the Quad Creek sediments from the ages of the youngest detrital zircon of igneous heritage. Acquisition of whole-rock major-, minor- and trace element geochemistry is also described below. Collectively we used these data to assign protolith(s) based on mineralogy and composition, and maximum ages of deposition of igneous zircons to suggest geochemical links with other ancient rock localities mentioned above.

3.1 Field Mapping

The Quad Creek exposure was mapped with a 25 × 25 m E-W oriented grid (**Figure 3**) annotated to show sample locations with photo-documentation of specific outcrops discussed in the text. The focus of the work was on quartzites which could contain detrital zircons. Overall, the exposure is dominated by strongly deformed isoclinally folded supracrustal rocks comprising abundant massive quartzites (*Aqm*) and banded paragneisses (*Aqb*) with locally highly-variable fuchsite contents (labeled *f* on the map where locally enriched in Cr-mica). Paragneisses range from massive to banded and patchily garnetiferous (*gt*); these are cut by at least one generation of mafic dikes (*Md*). Subordinate units include a finely banded but strongly deformed and sheared quartz magnetite rock (BIF *s.l.*) restricted to the easternmost mapped area and bordered by garnet-bearing amphibolite (*Amg*). No carbonates were noted here (*cf.* Mogk et al., 1992). The sheared east-west trending isoclinal folding within the supracrustal sequence is not a structure shared by the underlying massive intrusive granitoid (trondhjemitic) gneisses (*Gb*). To the best of our knowledge, the original sampling locality of old detrital zircons reported by Mueller et al. (1992) is within grey-green quartzites directly at a road cut of Montana Rte. 212 at the western boundary of the mapped area as indicated in **Figure 1b**.

3.2 Ion Microprobe U-Pb Zircon Geochronology

Ion microprobe U-Pb zircon geochronological analyses of zircons from two supracrustal lithologies (three quartzite samples *Aqm*, and three paragneiss samples *Agb*) are reported in Supplementary Data accompanying this paper (**Table S.1)**. Rock samples were prepared for geochemistry and zircon separations using standard techniques (e.g. Cates and Mojzsis, 2006, 2007) and a brief summary is provided here: Approximately 5 kg of *Aqm* samples BT0606, -08 and -11 and *Agb* samples BT0603, -04 and -10 from the mapped area**,** and 10 kg of sample BT1 – previously collected from the "HRQ" location noted in Mueller et al. (1998) – were chosen for zircon extractions. These large samples were reduced by crushing and sieving to <350 μm. Geochemistry for sample BT1 is not reported here but mineralogically it is identical to *Aqm* sample BT0606 and mapping shows they are part of the same unit. Powders for zircon extractions went through two stages of clean heavy liquid separations, rinsing in reagent-grade acetone and ultrapure water, followed by hand-magnet and then two stages of Frantz magnetic separations to screen out minerals of different magnetic susceptibilities from the densest residues. Individual zircons were handpicked from the least magnetic grain fractions under a binocular microscope and a wide spectrum of morphologies and aspect ratios were chosen to diminish sampling bias. These were placed on double-sided adhesive tape and cast in 2.52 cm diameter moulds with Buehler© epoxide resin alongside grains of standard zircon AS3 (Paces and Miller, 1993; Black et al. 2003). The sample disks were then beveled and polished in stages to 0.25 μm alumina until grain centers were exposed. Transmitted and reflected optical micrograph mount maps were created, followed by imaging with back-scattered electrons of polished centers on a JEOL JXA-8600 electron microprobe at the University of Colorado under standard operating conditions. To reduce common Pb contamination prior to ion microprobe analysis, all grain mounts were pre-cleaned in 1N HCL solution at room temperature, washed in ultrapure water, air dried in a 50 ºC oven, and sputter coated with ~100 Å of Au to facilitate conductivity.

All conventional zircon U-Pb ion microprobe geochronology on our sample zircons was performed using the UCLA Cameca *ims*1270 high-resolution SIMS under standard operating conditions (e.g. Cates and Mojzsis, 2006), a brief synopsis is provided here: a ~6-nA O_2^- primary beam was focused to a 25 -µm spot and operated at a mass resolving power of ΔM ~6000 to exclude molecular interferences. To increase the Pb^+ ion yields, oxygen flooding to a pressure of 2.7×10^{-5} torr was used (Schumacher et al., 1994). Ages for unknown zircons were determined by comparison with a working curve defined by multiple measurements of standard AS3 that yields concordant $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages of 1099.1± 0.5 Ma. Data were reduced and the output used to construct Tera-Wasserburg diagrams ($^{207}Pb/^{206}Pb$ vs. $^{238}U/^{206}Pb$) with the Isoplot software package (Ludwig, 2001). All individual conventional ion microprobe zircon ages are reported at the 1σ level based on asymmetric weighted regressions except when noted. For our large-scale ^{204}Pb-corrected age survey (sample BT-1) we used the Australian National University SHRIMP-II in automated mode on two separate zircon mounts; analytical conditions as well as relative accuracies for individual age estimates are described in Holden et al. (2009) and data are reported in **Table S.2**.

3.3 Whole-rock geochemistry

Duplicate whole-rock sample splits were prepared by subdividing ~2 kg unweathered rock pieces and powdering in pre-cleaned ceramic mills. Analysis of major-, minor- and trace elements (**Table 1**) was undertaken by XRF and ICP-MS at Activation Laboratories (ACTLABS; Ontario, Canada). Comparison of recommended and analyzed standards from ACTLABS show small deviations (<1.5%) for oxides, except MnO (6.3%), Na_2O (6.5%) and P_2O_5 (23.1%) and for trace elements <20% relative, except Ni (21.4%), Pr had a 47.6% relative error. Granitoid rock assignments are from Barker (1979) based on normative modes of albite (Ab), orthoclase (Or) and anorthite (An); (trond = trondhjemite).

4. Geochemical results and sample descriptions

4.1 Quartzites (*Aqm*) BT0606 (45°01.890' N, 109°24.560' W), BT0608 (45°01.881' N, 109°24.550' W), BT0611 (45°01.839' N, 109°24.631' W)

The dominant rock type exposed in the mapped area is a quartzite with local dark green micaceous banding. Most are massive, grey to greenish in color. However certain sections locally preserve distinctive "sedimentary" bands rich in chromite, sulfide, Cr-mica, zircon and other minerals; some of these appear to show cross-bedding. Bulk compositions of the *Aqm* rocks are strongly enriched in SiO_2 (93.2-95 wt. %) befitting their protolith as typical Archean "super-mature" quartz sands with a heavy mineral suite dominated by zircon, chromite and rutile and the narrow variability in SiO_2 content is accompanied by different relative abundances of heavy minerals. The quartzites have Al_2O_3 contents that vary by a factor of ~2 (2.86-4.57 wt. %). Different quartzite samples show an order-of-magnitude range of Cr abundances (40-360 ppm) but generally lower Zr concentrations (37-81 ppm) compared to granitoids. Primitive mantle normalized multi-element plots (**Figure 4**) show negative Nb, Sr, and Ti anomalies consistent with weathering and transport from prevailing felsic sources to the sediment with a small mixture of mafic component. Chondrite normalized REE patterns also display enriched LREE and depleted HREE, with a negative Eu anomaly observed only in sample BT0608.

4.2 Paragneiss (*Agb*) BT0610 (45°01.866' N, 109°24.632' W)

A suite of banded quartz±garnet paragneisses appear in the field as white to grey rocks with bands of darker more mafic minerals rich in garnet. In outcrop, they tend to weather to a beige-orange color. Sample BT0610 has a similar Cr-enrichment (230) ppm to some quartzites, but has lower SiO_2 contents (75.09%) and is relatively enriched in alumina (13.66%). Zirconium content is greatly elevated in the paragneiss with respect to the typical *Aqm* lithologies (348 ppm) which may denote its origin as less mature quartz-rich to pelitic sediments. In a multi-element plot, the *Agb* rocks show negative Sr and Ti anomalies along with a concave-upward trend from Dy-to Yb. Overall REE contents show enriched LREE compared to HREE with a positive Eu anomaly.

4.4 Quartz-magnetite rock (*BIF*) BT1006 (45^{o}01.829' N, 109^{o}24.572' W)

A small and narrow outcrop of silicate-facies BIF is sandwiched between sections of an amphibolite which defines a tight fold axis that plunges eastwards. On the map, the amphibolite limbs are bounded by quartzites on one side and trondhjemite on the other (**Figure 3**). The amphibolite was not sampled for geochemistry. The BIF unit is iron rich (51 wt. % $Fe_2O_{3)}$ with 44% SiO_2 and minor Al_2O_3 (~3%). It also contains 50 ppm Cr and 26 ppm Zr consistent with a small detrital component. Trends in primitive mantle-normalized multi-element REE plots reflect this in negative Sr and Ti anomalies and show that the BIF has some similarities to the quarztites and paragneiss with which it is (presumably) co-genetic in the supracrustal sequence. In a chondrite normalized REE plot, LREE are enriched over HREE and show a small negative Eu anomaly. With respect to Y/Ho ratio, the Quad Creek quartz-magnetite rock is low (28.7) in comparison to most Archean BIFs (Bolhar et al., 2004), as well as relatively low in molar Ni/Fe (Konhauser et al., 2009) and Cr contents (Konhauser et al., 2011) compared to averages for other BIFs of broadly similar age (ca. 3300 Ma).

4.5 Trondhjemitic Granitoid Body (*Gb*) BT1004 (45°01.783' N, 109°24.468' W) **and quartz-biotite schist (A*qbc*) BT1002** (45°01.860' N, 109°24.642' W)

In several places within the supracrustal succession, pockets of a granitoid penetrate through the outcrop, and the whole locality is underlain by a large body of trondhjemitic compositions (BT1004) as defined by normative Ab-An-Or of Barker (1979; **Figure S.1**). We also identified a quartz-biotite schist (conglomerate? BT1002) near the base of the Rte. 212 road cut and slightly west of sample site HRQ (**Figure S.2)**. As this rock was not found to crop out in the mapped area it is not marked on the map but we interpret it to be part of the same package of supracrustals near the "base" of the sequence. Both the quartz-biotite schist and the trondhjemite show similar SiO_2 and Al_2O_3 values to the paragneiss with 77.3% SiO_2, and 14.3% Al_2O_3 for the conglomerate and 72.6% SiO_2 and 15.4% Al_2O_3 for the trondhjemite, respectively. The quartz-biotite schist contains 70 ppm Cr and 49 ppm Zr, whereas the trondhjemite is Cr-poor (below detection limit), and relatively low in Zr (167 ppm) compared to granites but is entirely consistent with trondhjemite.

4.6 Mafic Dike (*Md*) BT0602 (45°01.879' N, 109°24.671' W)

Sample BT0602 is a black to dark grey unit bordered by paragneisses. It contains 47.58% SiO_2, 14.46% Al_2O_3, 12.54% Fe_2O_3, and 10.93% CaO with 310 ppm Cr and 45 ppm Zr. To determine if the mafic dike is part of the calc-alkaline or tholeiite series, we plotted its composition on a AFM diagram but this was inconclusive as the result lies between the determining lines of Kuno (1968) and Irvine and Baragar (1971) (**Figure S.3**). However, on a K_2O vs. silica diagram, using the subdivisions of Rickwood (1989) the mafic dike appears more akin to calc-alkaline magmas with medium to low K.

5. Geochronological Results

5.1 U-Pb zircon ion microprobe geochronology with correlated $[Th/U]_{zrc}$

During crystal growth in magmas, zircons partition trace elements such as REEs, U and Th in predictable ways, and this incorporation can be de-convolved to values reflective of crustal compositions. As outlined in Mojzsis and Harrison (2002), zircons grown from melts with Th/U values typical of crust (~4; Taylor and Mclennan, 1985) are expected to have a $[Th/U]_{zrc}$ ~0.8±0.2 provided that $D_{Th/U}^{zrc/melt} = 0.2 \pm 0.15$ (e.g. Mahood and Hildreth, 1983; Blundy and Wood, 2003). On the other hand, zircons grown in aqueous metamorphic fluids, from solid-state recrystallization, or via hydrothermal growth, tend to deviate strongly in $[Th/U]_{zrc}$ compared to the relatively narrow range ($[Th/U]_{zrc}$~0.4-0.8) of ordinary igneous values. Many (but not all) metamorphic zircons preserve exceptionally low $[Th/U]_{zrc}$ values, frequently ~10^{-1} – 10^{-3} (e.g. Rubatto, 2002). This $[Th/U]_{zrc}$ criterion has been used in conjunction with other indicators such as Ti^{xln} temperatures and REE partitioning calculations (e.g. Trail et al., 2007; Cates and Mojzsis, 2009) to discriminate zircon domains of igneous derivation from those wholly or in part of non-igneous origin. We applied this test to investigate $[Th/U]_{zrc}$ vs. $^{207}Pb/^{206}Pb$ ages for zircons reported here and in the literature.

Zircons were extracted from three fuchsitic quartzites (BT0606, -08 and -11) and three (banded) paragneisses (BT0603, BT0604, and BT0610) from the mapped area shown in **Figure 3**. Values of $[Th/U]_{zrc}$ vs. age (**Figure S.4)** for data $\leq$ 30% discordant appear similarly scattered for different age bins and vary by several orders of magnitude in $[Th/U]_{zrc}$. Filtering data to the least disturbed ages (<5% discordant; **Figure 5**) yields distinct age groupings at (i) 2800 Ma with a $[Th/U]_{zrc}$ ~1.1×10^{-2} (ii) 3300-3100 Ma ($[Th/U]_{zrc}$ =0.14-1.5); (iii) 3400-3500 Ma ($[Th/U]_{zrc}$ =0.32-.57); and (iv) ≥3700 Ma with $[Th/U]_{zrc}$ of 0.35-0.45. Eoarchean to Hadean (3650-3902 Ma) zircons were found in several of the banded paragneiss samples in our mapped area, but the majority of ages reside in the ca. 3300 Ma population. As expected, younger (metamorphic) zircons show a large scatter in $[Th/U]_{zrc}$ with ratios mostly well below that expected for igneous compositions. **Figure 6** shows that there is a pronounced age grouping at ca. 3250 Ma and ca. 3450 Ma with $[Th/U]_{zrc}$ consonant with igneous derivation (0.4-0.5) for the peak around 3450 Ma, and more variable ratios for younger zircons at about 3250 Ma (range of $[Th/U]_{zrc}$ = 0.4 to 1.2). A subset of 3200 Ma and younger zircons is also evident with variable (but low) $[Th/U]_{zrc}$ as well as internal textures (**Figure S.5**) visible in electron microscopy (spongy appearance, abundant inclusions, mundane/faint/sector zoning, absence of zoning) that are attributable to *in situ* metamorphic growth (Corfu et al. 2003; Hoskin and Schaltegger, 2003) likely during one of several of the metamorphic episodes described above.

The 3250 Ma zircons are of igneous origin, as shown by their $[Th/U]_{zrc}$ values. Thus 3250 Ma represents a putative maximum age for the quartzites and paragneisses, in general agreement with previous work (Chamberlain and Mueller, 2007; Mueller and Wooden, 2012). Of the 118 zircons analyzed in this study by conventional U-Pb zircon geochronology, 70 were less than 30% discordant. One of the four oldest zircons in our analysis pool (3866 Ma) is from the paragneiss (*Agb* sample BT0610), and the three others (3902, 3756, and 3690 Ma) are from two fuchsitic quartzites (*Aqm* sample, BT0608 and BT0611). Altogether, we find that our age populations from both conventional and survey-mode ion microprobe zircon geochronology tend to be somewhat younger than the oldest ages in the data tables published in Mueller et al. (1992) and Mueller and Wooden (2012) (**Figure 2**).

5.2 U-Th-Pb depth profile of the oldest zircon at Quad Creek

Approximately 10 kg of sample BT-1 (HRQ of Mueller et al., 1992) yielded thousands of zircon grains of diverse morphologies (Trail, 2006). From this sample pool we prepared two polished zircon grain mounts for large scale geochronological surveys; this work yielded two zircons with ages ≥3960 Ma, later verified by depth profile analysis on one grain (*Bear-2_5-6*) to have a weighted mean age of 3997±5 Ma (2σ; mswd = 1.9) and $[Th/U]_{zrc}$ = 0.503±0.002 (**Table S.3**). Zircon sample BEAR-2_5-6 is thus far the oldest zircon documented from the Quad Creek locality and it is of unambiguous igneous origin.

In the tabulated data points provided by Mueller et al. (1992), two pre-3900 Ma *HRQ* zircons were within 1% of concordia: their "grain 6" was 3964 Ma $[Th/U]_{zrc}$=0.403 and "grain 45" had an average age of 3936 Ma and $[Th/U]_{zrc}$ = 0.513, that was nearly identical to our zircon sample *Bear-2_5-6*. That these oldest grains are large (~120-160 μm), concordant zircons with a limited range of igneous $[Th/U]_{zrc}$ values can in principle provide clues as to their source rocks. New data reported in Mueller and Wooden (2012) extend this theme farther with 75 documented data points; the five oldest zircons reported therein are within 3% of concordia and range in age from 3910 Ma ($[Th/U]_{zrc}$ = 0.34) to 3981 Ma ($[Th/U]_{zrc}$ = 1.05).

6. Discussion

Zircon geochronology for the Quad Creek rocks shows evidence of three different events, the precise geological order and context of which are uncertain due to the deformational overprint and the limited information from beyond the mapped area.

6.1 Geochronological relations at Quad Creek

Based on what is known so far, the first event in its history was the establishment in the Paleoarchean of a sedimentary depo-center typified by psammitic quartzites rich in detrital placer minerals (chromite, minor sulfides and zircon), emplacement of the protolith to the amphibolite (as extrusive basalt?) and deposition of the BIF around 3250 Ma. The stratigraphic context and order of these events is unclear. This appears to have been followed by a period of deformation coinciding with metamorphism at the granulite facies beginning at ca. 3200 Ma. Afterwards, crustal thinning was accompanied by the intrusion of mafic dikes. Subsequently, an intrusive trondjhemite/granodiorite was responsible for local partial melting of the sediments. Finally, a quartz and biotite leucogranitoid was emplaced in and around the supracrustal rocks. Pervasive hydrothermal alteration affected much of the area. Uplift was followed by denudation and erosion of younger rocks to expose the oldest core of the Beartooth Mountains.

6.2 Zircon morphology

The uncertain distinction between zircons of (primary) igneous, or (secondary) metamorphic and hydrothermal origin continues to befuddle age analysis in ancient complexes. However, different petrogenetic origins of different zircon populations in the same rock can sometimes be reconciled on crystal chemical grounds (Th/U, REE partitioning, Ti^{xln}; e.g. Cates and Mojzsis, 2009) coupled with morphological analysis of grain habit and internal texture. Igneous zircons tend to have relatively high aspect ratios and are euhedral due to their semi-continuous growth in a magma chamber; detrital zircons of whatever petrogenetic origin tend to be rounded because they get abraded during sedimentary transport. As outlined in Corfu et al., (2003) metamorphic zircons can have a host of textures depending for the most part on host rock composition and degree of metamorphism.

Zircons in this study – collected from sedimentary protoliths – tend to have subhedral habit with variable aspect ratios; based on morphology correlated with composition it is certain that some grew in situ during metamorphism, others have overgrowths on rounded cores, and still others show complex internal morphologies indicative of resorption/recrystallization **(Figure S.5).** Back-scattered electron images of the oldest and most concordant zircons in this study (>3.6 Ga) show that they are subhedral and display clear overgrowths consistent with neoform zircon growth, re-melting, resorption and/or recrystallization (e.g. Hay et al., 2010). For example, sample grain #1 of BT0611 (sample BT0611_1), as well as BT0608_6, and BT0610_5, are cracked with rounded tips, while one of the oldest zircons in our sample suite: BT0608_4 (3902 Ma) shows little to no fracturing with quite angular (sub-rounded) tips. Twinning (BT0608_4) is also observed.

Gross morphological analysis in BSE and optical microscopy of some of the youngest demonstrably igneous age populations (from 3400-3500 Ma) shows that they are sub-rounded inclusion-rich grains with obvious rim overgrowths; zircons of this age population are generally within a few percent of concordia. The youngest igneous zircons from within the ca. 3300 Ma population tend to be euhedral with metamorphic rims, and are generally concordant. All zircons equal to or younger than about 3200 Ma are stubby crystals with some fracturing, and are rich in inclusions. A significant proportion of grains from this grouping are >30% discordant and show evidence for radiation damage in BSE images. The youngest metamorphic populations (2700-2900 Ma) show a wide variety of habit from highly rounded to broken with fracturing and overgrowths with highly variable concordance.

6.3 Zircon chemistry

The Th/U values of the zircons from the paragneiss and quartzites are comparable (**Figure 6**) and suggestive of the same sediment source. Making sense of the overall highly variable $\leq$ 30% discordant zircons with diverse $[Th/U]_{zrc}$ ratios (**Figure S.4**) remains problematic unless they are separated in terms of U-Pb age populations. We interpret the large scatter in $[Th/U]_{zrc}$ for the 3200 Ma age grouping as representative of the first widespread metamorphic event that triggered zircon growth in the granulite facies (Mueller et al., 1998). This is a feature that has been widely documented for other ancient supracrustal rocks which have experienced ancient and protracted high grade metamorphic histories (e.g. Manning et al., 2006).

6.4 Geochemistry and protolith assignment

Sample BT0608 was mapped as a paragneiss, however, the geochemistry shows its protolith is closer to quartzitic; it should be noted then that the quartzite may extend down further in this location or the paragneiss and quartzite are intermixed here. In a multi-element diagram (**Figure 4**), felsic lithologies (detrital and igneous) show enriched large ion lithophile elements, and negative Nb anomalies with depletions in Sr and Ti for all lithologies except the mafic dike. This would seem to indicate that both the quartzites and paragneiss had the same source. Paragneisses and quartzites follow expected weathering trends (Nesbitt and Young, 1989) for a mixed granitoid + mafic source; higher proportions of quartz led to the quartzites, with less mature sediments represented by the paragneisses (**Figure 7**).

6.5 Widespread detrital contamination from an ancient "Slave Continent" in the Archean?

Soon after their discovery, it was realized that the oldest ages for the Beartooth zircons were akin to those of the oldest tonalitic and granodioritic gneisses in the ca. 4000 Ma Acasta Gneiss Complex (AGC). The AGC is about 2250 km to the north of Quad Creek at the westernmost margin of the Slave craton, Northwest Territories, Canada (Bowring and Williams, 1999). Its areal extent is at least 180 km^2 (Iizuka et al., 2007 and references therein); what exists now almost certainly represents the last vestige of a much larger block (Bleeker, 2003). Presently, the main exposure of the AGC is dominated by layered mafic gneisses and felsic gneisses with blocks of mafic- intermediate gneisses (Iizuka et al., 2007). The oldest components of the AGC were emplaced in the timeframe 4030-3940 Ma, but record evidence for possibly older rocks from a 4200 Ma xenocrystic zircon (Iizuka et al., 2006). The initial AGC magmatic emplacement was followed by two Eoarchean igneous intrusions at 3740-3720 Ma and

3660-3590 Ma. The last of these was accompanied by crustal anatexis and recrystallization of older units (Bowring and Housh, 1995; Iizuka et al., 2007). Subsequent intrusions and modifications of the AGC continued into the Proterozoic, culminating with regional metamorphism at 1900-1800 Ma related to the Wopmay Orogen (King, 1985; Sano et al., 1999). Many of these pre-3300 Ma AGC ages find complements in the zircon age spectra for Quad Creek and we can begin to ask if there exists a wider context of Hadean detritus in Archean metasediments of North America.

Approximately 1500 km to the northeast of the Beartooth Mountain locality, ca. 3900 Ma ages for detrital zircons have been reported in the Assean Lake Complex (ALC). The ALC is a ~120 km^2 west-northwest trending slice of largely Neo- to Mesoarchean rocks bounded to the north by the Paleoproterozoic Trans-Hudson Orogen and the Neoarchean Northwest Superior Province to the south (Böhm et al., 2000, 2003, 2007). Within the ALC there are at least two ca. 3200-3250 Ma supracrustal packages of quartz-biotite schists ("meta-greywacke" *s.l.*) that yield Eoarchean and Hadean detrital zircons. These supracrustal rocks were intruded by 3100 Ma tonalites, which in turn were modified by later granitoids. Neodymium model ages of the oldest tonalites and various schists are all >3500 Ma, and some are as old as 4200 Ma, strongly indicative of the role of reworked Hadean/Eoarchean crust. The Assean Lake rocks underwent multiple metamorphic episodes and migmatization. Little else is known of these rocks. A solitary detrital 3940 Ma zircon was reported from a drill core from the ca. 1700 Ma Thelon Basin in Nunavut (Palmer et al., 2004), and detrital zircons from a fuchsitic quartzite of the Rae Province in northern Canada to the east of the AGC likewise contain a sprinkling of old detrital zircons with age distribution peaks at 3860, 3760 and 3720 Ma (Hartlaub et al., 2006).

6.6 Source(s) of the oldest detrital zircons of the Narryer Gneiss Complex do not appear to be represented outside of Western Australia

It is worth noting that the dominant population of pre-3800 Ma ages for detrital zircons from ca. 3300 Ma Narryer Gneisses as tabulated in Holden et al. (2009) resembles the published ages of the oldest (igneous) components of the Acasta Gneiss Complex (ca. 4020-4050 Ma; e.g. Stern and Bleeker, 1998). Nevertheless, compelling evidence is lacking for a link betweeen the Narryer Gneiss complex and any other rock outside of the terranes captured within the Yilgarn Craton.. Significantly, the long tail in the distribution of older ages reported in Holden et al. (2009) from the Jack Hills to 4380 Ma is so far unmatched by any other detrital zircon locality yet discovered (Nutman et al., 2001). Such a substantial difference in the age distributions between the Australian and North American Paleoarchean detrital zircon record may be used to build the case that a distinct very old continental core with diverse primordial crustal components (accreted terrane? recycled supracrustal belt?) existed in the vicinity of what is now the Yilgarn block in Western Australia about 3300 million years ago.

Turning attention now to sources of Hadean zircons in North America, other clues about the origin(s) of the Quad Creek zircons may be found in the composition and population statistics of zircons from the (younger) ca. 2800 Ma Central Slave Cover Group (CSCG) in Canada (Sircombe et al., 2001). Quartzites of CSCG unconformably overlay 3000-4000 Ma tonalitic to dioritic gneisses and foliated granites of the Central Slave Basement Complex (Bleeker et al., 1999; Pietranik et al., 2008). The oldest zircon noted from the CSCG comes from fuchsitic quartzite at Dwyer Lake and was dated at 3918±5 Ma (spot 65.1, 101% concordant, $[Th/U]_{zrc}$ = 0.6 as reported in Sircombe et al., 2001). The remainder of the Dwyer Lake zircons range from highly discordant (66%) minimum ages of 2439 Ma to within 6% of concordia at 3885 Ma ($[Th/U]_{zrc}$=0.560) and 3901 Ma ($[Th/U]_{zrc}$=0.486). Like the Quad Creek zircons investigated here, the oldest CSCG ages from Dwyer Lake are evocative of contamination from an ancient source (Bleeker 2003; Reddy and Evans, 2009), perhaps a previously by a more extensive “Slave Continent”?

7. Conclusions

Fine-scale geology and geochemistry of the eastern Beartooth Mountains provide a valuable snapshot in miniature of the long and complex history of the Wyoming Craton. Detrital/xenocrystic zircons with Eoarchean to Hadean ages confirm that older crustal components of the Wyoming Craton existed in the vicinity of the sedimentary sources of these quartzites and happen to be comparable to the oldest ages reported for the Acasta Gneiss Complex. Our work bolsters the case for a genetic link between at least some parts of the Wyoming Craton (e.g. the Beartooth quartzites) and the geology of the Western Slave Province as previously suggested by Mueller et al. (1992). We further propose that the Assean Lake Complex (Bohm et al., 2000) was also extensively contaminated by a background of "Slave Continent" detritus. Our comparison of the $[Th/U]_{zrc}$ ratios and $^{207}Pb/^{206}Pb$ ages of the most concordant grains (<5% discordant) of this study with those of zircons from the Beartooth Mountains, Assean Lake Complex and the Central Slave Cover Group shows highly variable $[Th/U]_{zrc}$ values at 3200 Ma, but similar age spectra and compositions for the oldest and most concordant grains (**Figure 6**). Hadean zircons shed from a previously larger and more exposed "Slave Continent" that was variably exposed and eroded at different times in geologic history could explain this result.

Based on our current state of knowledge, the oldest zircons terrestrial that are found in the Narryer Gneisses and neighboring terranes came from a unique Yilgarn source that seems not to have affected any other Paleoarchean sedimentary catchments thus far sampled outside of Western Australia.

Our new data contribute to resolving the relation of ages with the regional geology of this part of the Wyoming Craton, and provide additional information towards correlating ancient terranes (Reddy and Evans, 2009). Paleoarchean sedimentary enclaves occupy much of the supracrustal inventory of southwestern Montana (e.g. Tobacco Root Mountains and MMP). The oldest sediment source(s) of the

Beartooth quartzites may have a common origin with that which contaminated the supracrustals of the Assean Lake Complex (Manitoba), and much later, the Thelon Basin (Nunavut) and other quartzites on the Slave Craton with pre-3900 Ma zircons. If our hypothesis is correct, this would mean that some other Paleoarchean supracrustals of northern North America, like those captured as enclaves in the Wyoming craton, were at one time flanking a larger Slave landmass If the ca. 3960 Ma Acasta Gneisses are the core remnants of this landmass now buried or destroyed (Ernst and Bleeker, 2010), it would be the logical source of this detritus. Our model predicts that other Paleoarchean catchments such as in the Minnesota River Valley (Bickford et al., 2006) should also contain some low level Hadean/Eoarchean detritus. Future studies ought to therefore consider an expanded campaign of directed sample searches for pre-3900 Ma zircons in such enclaves in the broader effort to quantify the extent that Hadean crust lingered on in the Archean. (**6880 words**)

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Supplementary Data

Supplementary data including complete data for geochemistry and extended geochronology (ages only), depth profile, and cathodoluminescence image of Bear-2_5-6, back-scattered electron images of several zircons for each age population of this study, as well as field photographs can be found in the online version at doi: XXXXXXXXXXXX.

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Figure Captions

Figure 1. a. Generalized sketch map of Archean and Proterozoic rocks of North America. **b.** Discovery sample site of Mueller et al. (1992; sample "HRQ"). FOV = 200 m. **c.** Location map (1:600) of the Quad Creek site in the Hellroaring Plateau, southern Montana (modified from Eckelmann and Poldevaart, 1957 and updated with new data).

Figure 2. Comparative cumulative frequency plots of Beartooth Mountain zircon $^{207}Pb/^{206}Pb$ ages from this study (light grey), Mueller et al. (1992, 2012; black), and Trail (2006; dark grey).

Figure 3. Geologic map (1:250) of the Quad Creek study area.

Figure 4. **(a,c)** Chondrite-normalized REE plots, and (**b,d)** Primitive mantle-normalized multi-element plots of the different lithologies in the Quad Creek study area.

Figure 5. Plot of relative probability and $[Th/U]_{zircon}$ vs. $^{207}Pb/^{206}Pb$ zircon age filtered for analyses that are <5% discordant reported in Table S1.

Figure 6. Probability density plot of $[Th/U]_{zrc}$ vs. $^{207}Pb/^{206}Pb$ age based on data reported here (see legend), Trail et al. (2007), Mueller et al. (1992), the average oldest, most concordant zircon from the Assean Lake Complex (Böhm et al. 2003), and the oldest most concordant zircon from the Central Slave Cover Group (Sircombe et al. 2001). The different colors are of increasing probability density; blue is least dense and red is most dense. There is one broadly distinctive age vs. $[Th/U]_{zrc}$ cluster with a calculated age of 3250 Ma and igneous $[Th/U]_{zrc}$ values. Similar ages and Th/U ratios are evident for the oldest Quad Creek zircons in this study to those reported from other ancient detrital zircon localities in North America.

Figure 7. $Na_2O + CaO – Al_2O_3 – K_2O$ diagram showing weathering trends for the samples in this work. Quartzites (BT0606, -08, 11) are shown as gray asterisks, the paragneiss (BT0610) is shown as an open triangle, the conglomerate an open circle, the BIF an open square, the trondhjemite (BT1004) a filled

gray square, and the mafic dike (BT0602) a filled black diamond. The arrow shows the average weathering trend predicted for upper continental granite from Nesbitt and Young (1984).

Tables

Table 1. Representative bulk-rock compositions from Quad Creek, southern Montana

Supplementary Data Files

Figure S.1 Granitic assignment using the Anorthorsite-Albite-Orthoclase (An-Al-Or) composition. The black division lines from Barker (1979).

Figure S.2 Field photographs of the key lithologies described in the text. **a.** Fuchsitic quartzite (*Aqm*). **b.** Banded paragneisses (*Agb*). **c.** Mafic dike (*Md*). Note scales.

Figure S.3 a. Alkalis-Fe oxides-Mg oxides (AFM) diagram showing the boundary between the calc-alkaline field and the tholeiitic field from Kuno (1968; solid black line) and Irvine and Baragar (1971; dashed black line). Mafic dike BT0602 (black square) plots ambiguously in between the boundaries. **b**. Black lines showing the subdivision of subalkalic rocks from Rickwood (1989) using a K_2O vs. silica diagram. BT0602 (black square) plots low in the medium K, calc-alkaline series region.

Figure S.4 a. Tera Wasserburg Plot of the Beartooth zircons. **b**. Relative probability and Th/U vs. age plot of zircons that are ≤30% discordant. The Th/U values of the quartzites are marked as hollow squares and the paragneisses as filled squares. The different shades of gray for **a** and **b** correspond to different age populations as indicated in the legend.

Figure S.5 Representative back-scattered electron micrographs showing the internal structure and morphology of the different age populations reported here. The black ovals indicate the location of the ion probe spots.

Figure S.6 Cathodoluminesence image of the oldest zircon from our sample set (3999 Ma) Bear-2_5-6.

Table S.1 Conventional ion microprobe U-Pb analyses of zircons from Quad Creek, southern Montana.

Table S.2 ^{204}Pb-corrected results of SHRIMP-II U-Pb zircon age survey of sample BT1.

Table S.3 Results of depth-profiling study of zircon Bear-2_5-6.

Table 1

Representative bulk-rock compositions from Quad Creek, southern Montana

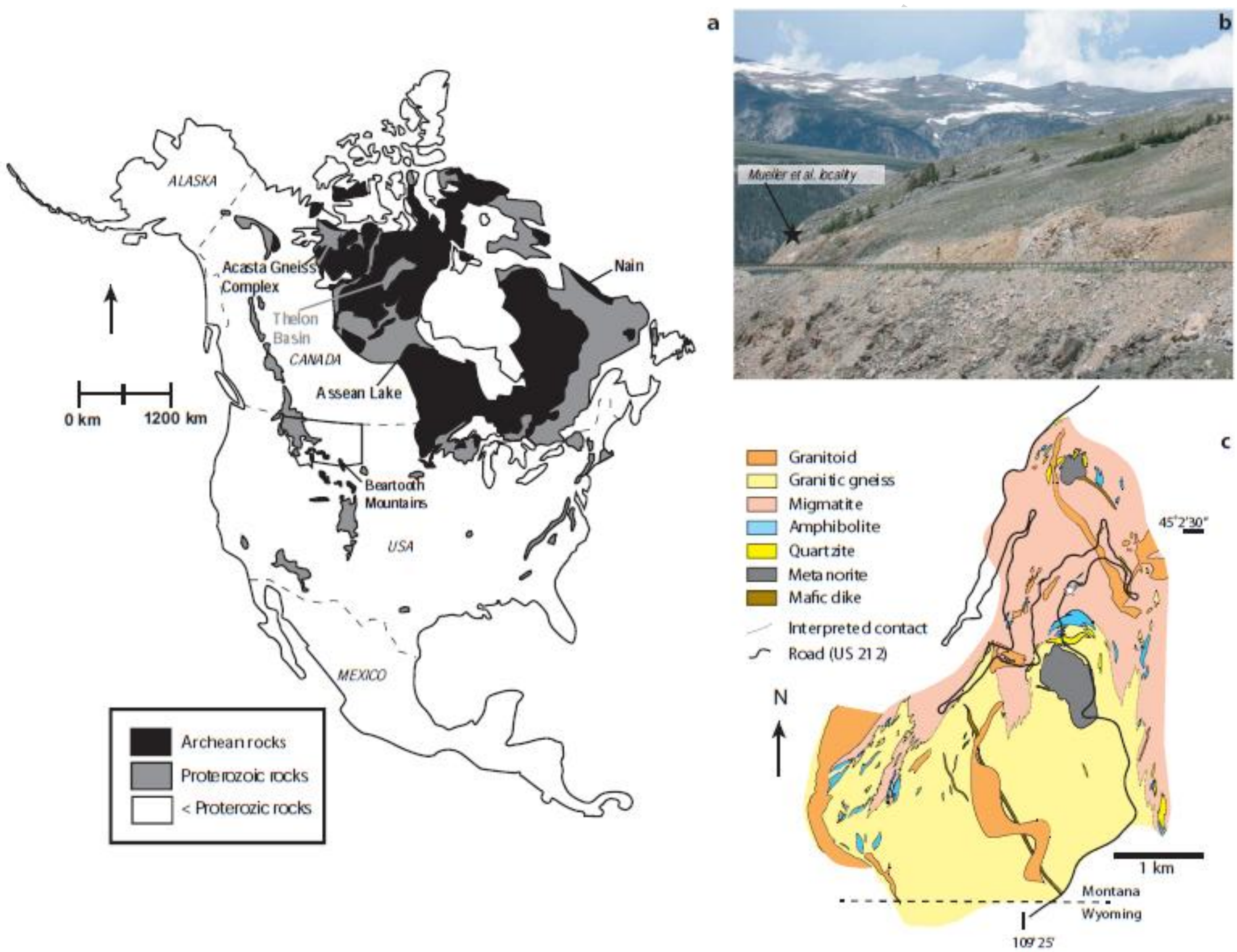
lithotype	Md	Aqm	Aqm	Agb	Aqm	Aqbc	Gb	BIF
sample #	BT0602	BT0606	BT0608	BT0610	BT0611	BT1002	BT1004	BT1006
SiO_2	47.58	93.46	93.18	75.09	94.96	77.26	72.58	43.84
$Al2O_3$	14.46	4.57	4	13.66	2.86	14.34	15.35	2.9
$Fe_2O_3(T)$	12.54	0.22	0.81	1.41	0.69	0.76	1.37	50.84
MnO	0.204	0.004	0.011	0.009	0.004	0.028	0.016	0.376
MgO	9.54	0.1	0.41	0.25	0.17	0.52	0.36	2.22
CaO	10.93	0.04	0.32	0.35	0.03	3.13	2.08	1.82
Na_2O	2.29	0.65	0.53	1.37	0.14	2.59	4.98	0.04
K_2O	0.55	0.88	0.54	6.23	0.65	0.88	2.09	0.04
TiO_2	0.823	0.023	0.144	0.203	0.078	0.165	0.166	0.104
P_2O_5	0.06	0.03	< 0.01	0.03	< 0.01	0.03	0.05	0.16
LOI	1.66	0.77	0.84	0.73	0.63	1.2	0.72	-1.45
Total	100.6	100.7	100.8	99.34	100.2	100.9	99.77	100.9
Sc	46	< 1	4	3	2	3	2	3
Be	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
V	319	6	16	52	13	27	13	34
Cr	310	40	90	230	360	70	< 20	50
Co	54	1	4	12	8	10	2	6
Ni	140	< 20	< 20	30	< 20	40	< 20	< 20
Cu	20	< 10	< 10	40	40	< 10	< 10	20
Zn	100	< 30	< 30	< 30	< 30	< 30	290	80
Ga	16	5	6	19	6	15	20	5
Ge	1.7	0.6	0.8	< 0.5	0.9	1.2	0.8	6.5
As	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Rb	15	30	23	126	12	21	48	1
Sr	113	25	22	169	14	121	256	8
Y	18.4	1.5	3.6	2.1	1.3	5.5	5.9	8.6
Zr	45	65	81	348	37	49	167	26
Nb	1.5	0.5	1.6	1.2	0.5	1.7	2.6	8.1
Mo	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Ag	< 0.5	< 0.5	< 0.5	0.8	< 0.5	< 0.5	< 0.5	< 0.5
In	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Sn	< 1	< 1	< 1	< 1	< 1	< 1	< 1	1
Sb	0.3	0.4	< 0.2	0.3	< 0.2	< 0.2	< 0.2	1.4
Cs	< 0.1	0.2	0.6	0.7	0.2	0.5	1.1	< 0.1
Ba	46	183	200	1173	195	429	584	33
La	2.74	21.8	15.7	41.6	6.07	24.1	40.6	2.41
Ce	7.04	38	30.5	73.1	10.7	40.8	71.8	5.68
Pr	0.9	3.16	2.74	6.08	1.09	4.18	5.95	0.77
Nd	4.78	10.3	9.72	20.4	3.58	14	19.6	3.34
Sm	1.82	1.42	1.51	2.42	0.58	2.34	3.2	0.92
Eu	0.603	0.345	0.18	1.02	0.173	1.47	0.567	0.256
Gd	2.43	0.89	1.05	1.04	0.42	1.78	2.14	1.08
Tb	0.47	0.09	0.13	0.09	0.05	0.23	0.27	0.21
Dy	3.09	0.39	0.67	0.42	0.29	1.17	1.31	1.4
Ho	0.65	0.06	0.12	0.08	0.05	0.19	0.2	0.3
Er	1.95	0.14	0.31	0.24	0.15	0.49	0.47	0.93
Tm	0.304	0.019	0.047	0.042	0.023	0.062	0.057	0.146
Yb	2.1	0.12	0.34	0.35	0.16	0.34	0.32	1.04
Lu	0.353	0.018	0.062	0.086	0.027	0.046	0.042	0.175
Hf	1.2		1.9	8.3	0.8	1.2	3.7	0.7
Ta	0.14	0.06	0.21	0.07	0.07	0.14	0.24	0.07
W	0.7	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Tl	0.06	0.1	0.1	0.55	0.06	0.1	0.23	< 0.05

Table 1

Representative bulk-rock compositions from Quad Creek, southern Montana

lithotype	Md	Aqm	Aqm	Agb	Aqm	Aqbc	Gb	BIF
sample #	**BT0602**	**BT0606**	**BT0608**	**BT0610**	**BT0611**	**BT1002**	**BT1004**	**BT1006**
Pb	< 5	10	< 5	15	< 5	8	27	< 5
Bi	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Th	0.76	6.89	8.31	18	3.14	5.85	25	2.44
U	0.42	0.44	0.81	1.44	0.63	0.6	1.46	0.78
Y/Ho	28.30769	25	30	26.25	26	28.947368	29.5	28.666667

Notes : Major elements reported as wt.% oxides; all others in ppm.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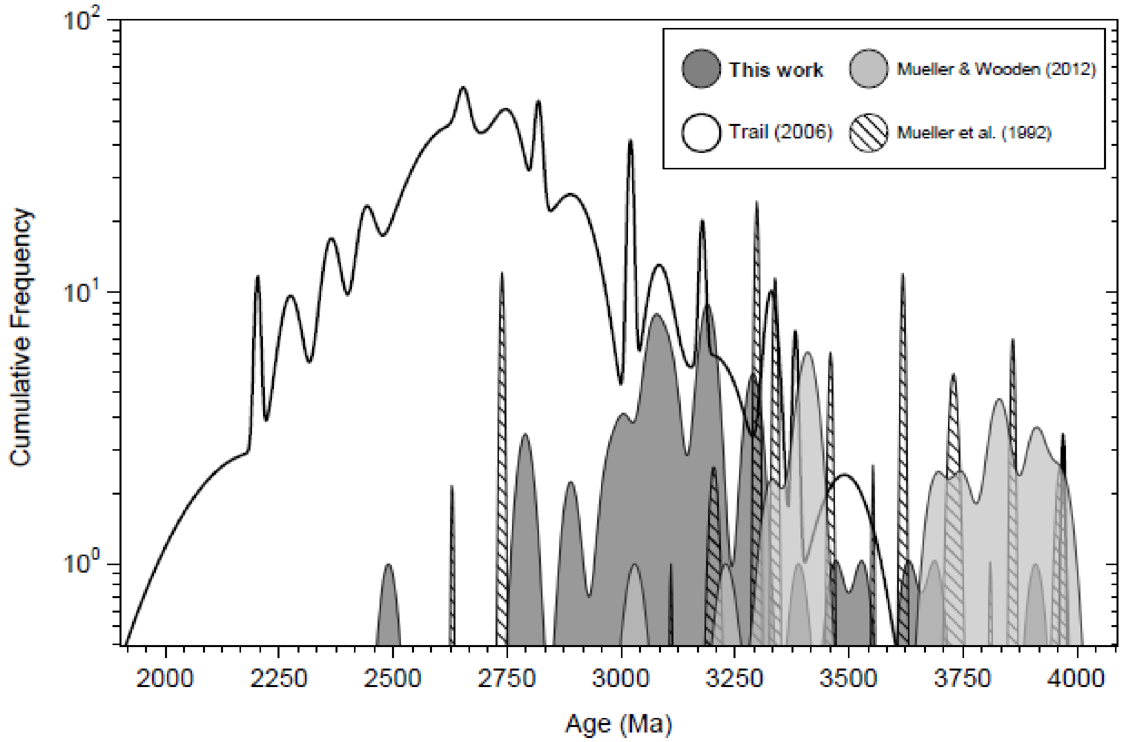
Acasta Gneiss Complex
Thelon Basin
CANADA
Nain
Assean Lake
0 km
1200 km
Beartooth Mountains
USA
MEXICO
Archean rocks
Proterozoic rocks
< Proterozoic rocks
a
b
Mueller et al. locality
c
Granitoid
Granitic gneiss
Migmatite
Amphibolite
Quartzite
Meta norite
Mafic dike
Interpreted contact
Road (US 212)
N
45°2'30"
1 km
Montana
Wyoming
109°25'

Figure 1



Cumulative Frequency
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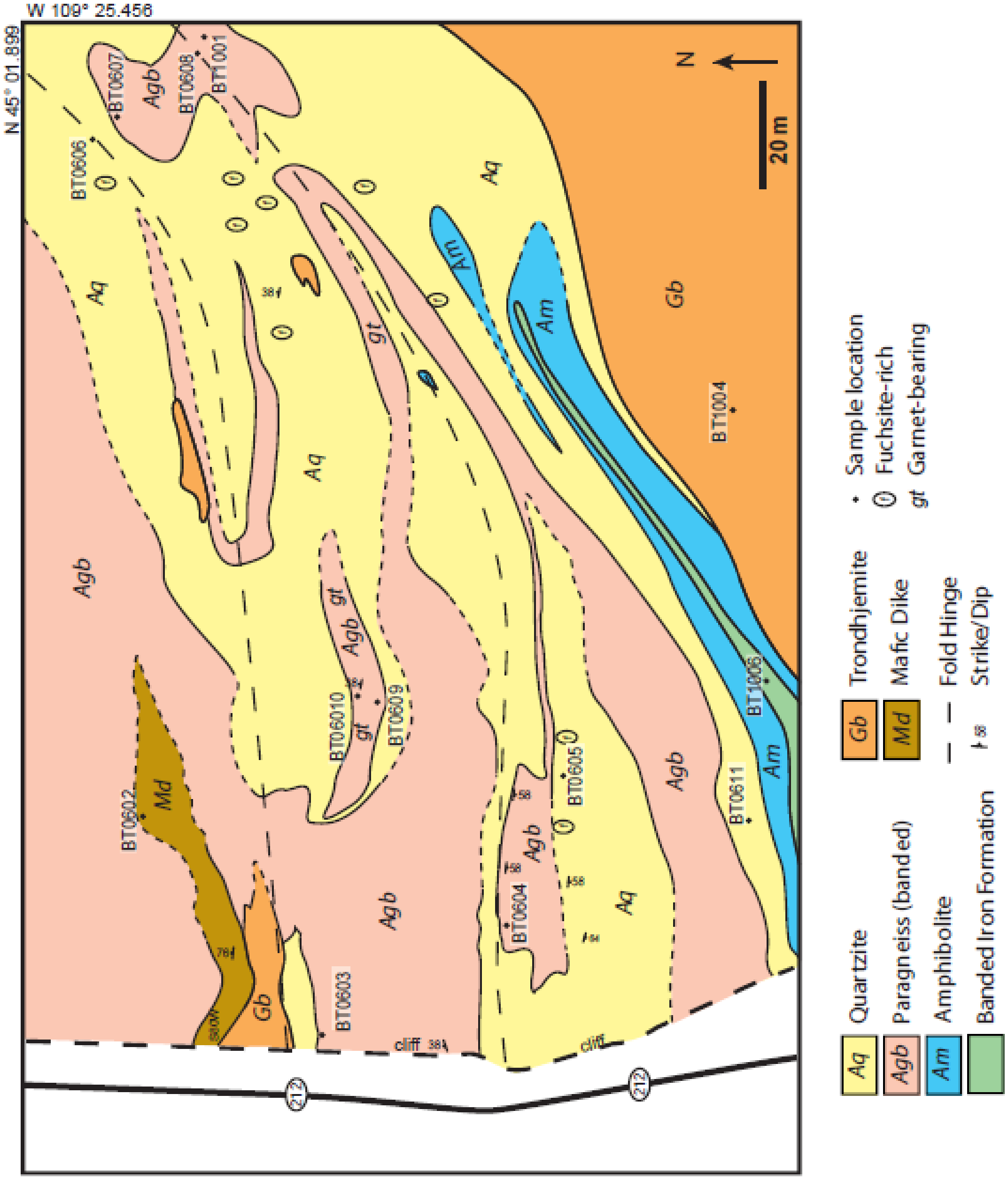
10^1
10^0
This work
Mueller & Wooden (2012)
Trail (2006)
Mueller et al. (1992)
2000
2250
2500
2750
3000
3250
3500
3750
4000
Age (Ma)

Figure 2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N 45° 01.899
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20 m
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BT0606
BT0607
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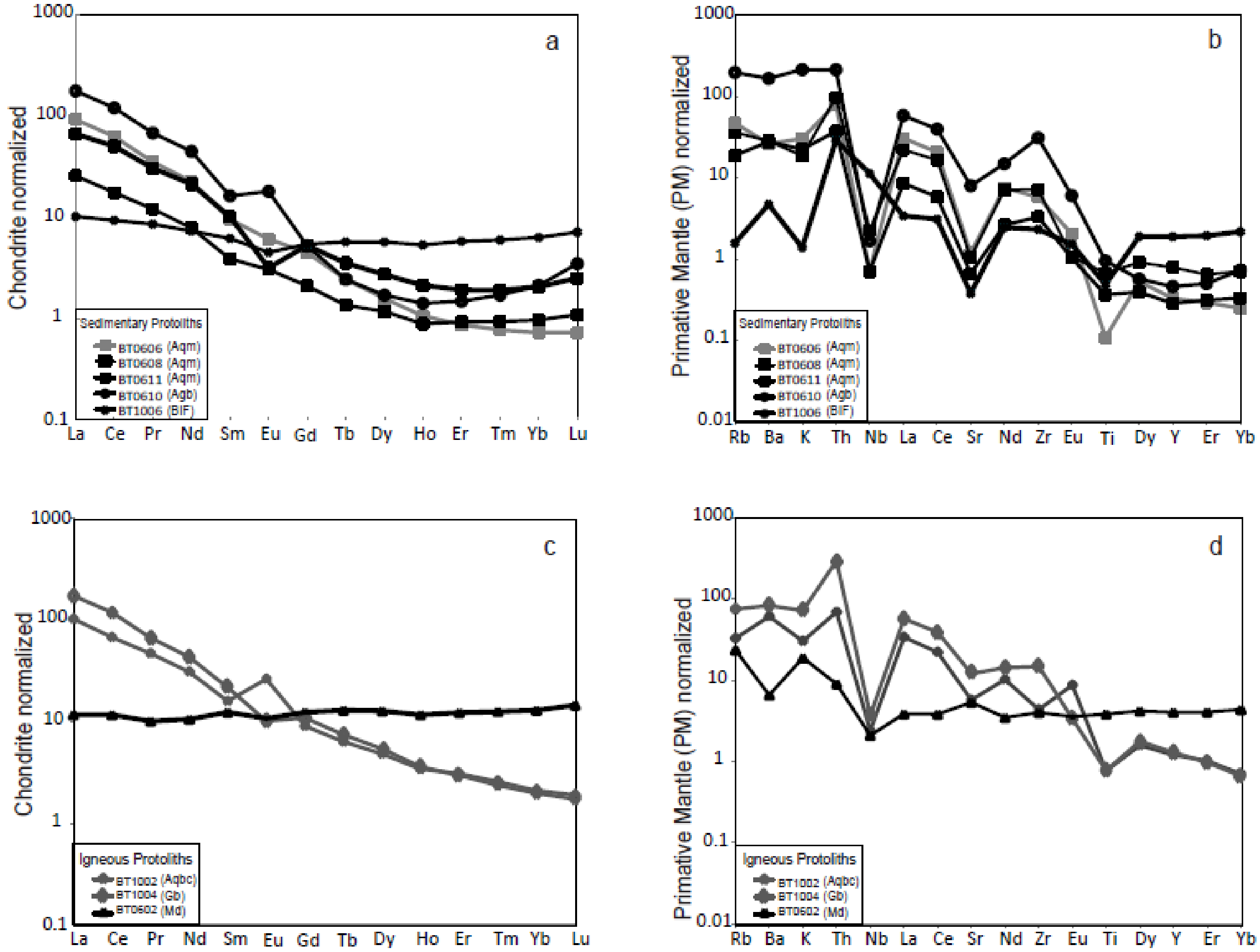
BT1004
BT06010
BT0609
BT0602
BT0603
BT0604
BT0605
BT0611
BT1006
cliff
212
Quartzite
Paragneiss (banded)
Amphibolite
Banded Iron Formation
Trondhjemite
Mafic Dike
Fold Hinge
Strike/Dip
Sample location
Fuchsite-rich
Garnet-bearing

Figure 3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b
c
d
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Primative Mantle (PM) normalized
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BT0608 (Aqm)
BT0611 (Aqm)
BT0610 (Agb)
BT1006 (BIF)
Igneous Protoliths
BT1002 (Aqbc)
BT1004 (Gb)
BT0602 (Md)
La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Rb Ba K Th Nb La Ce Sr Nd Zr Eu Ti Dy Y Er Yb
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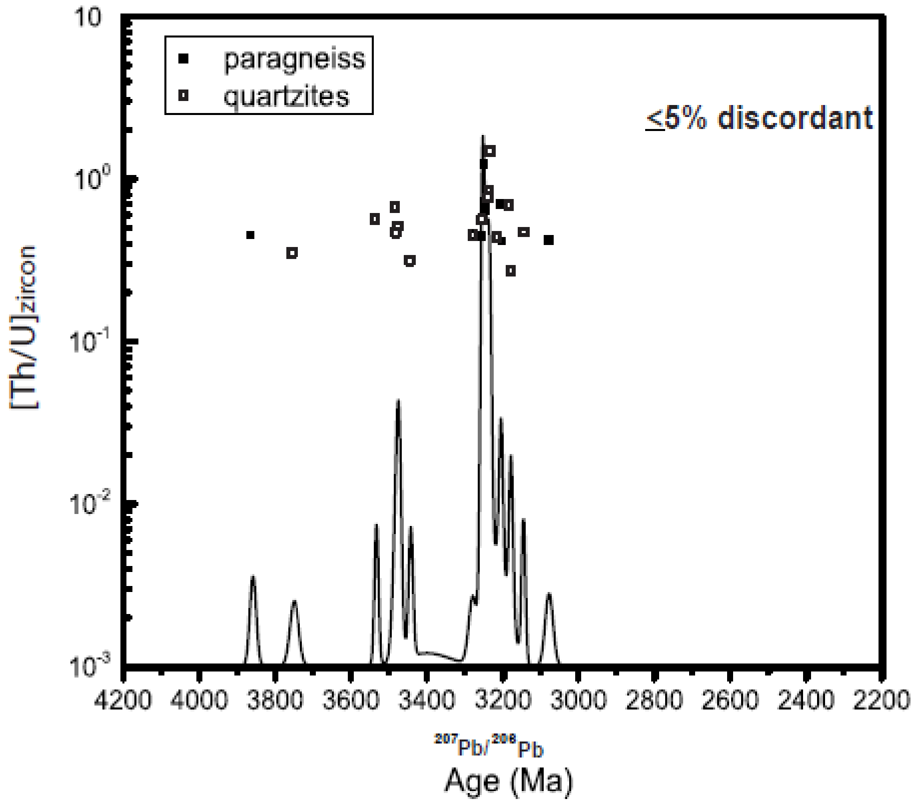
1
10
100
1000

Figure 4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quartzites
≤5% discordant
4200 4000 3800 3600 3400 3200 3000 2800 2600 2400 2200
207Pb/206Pb
Age (Ma)

Figure 5

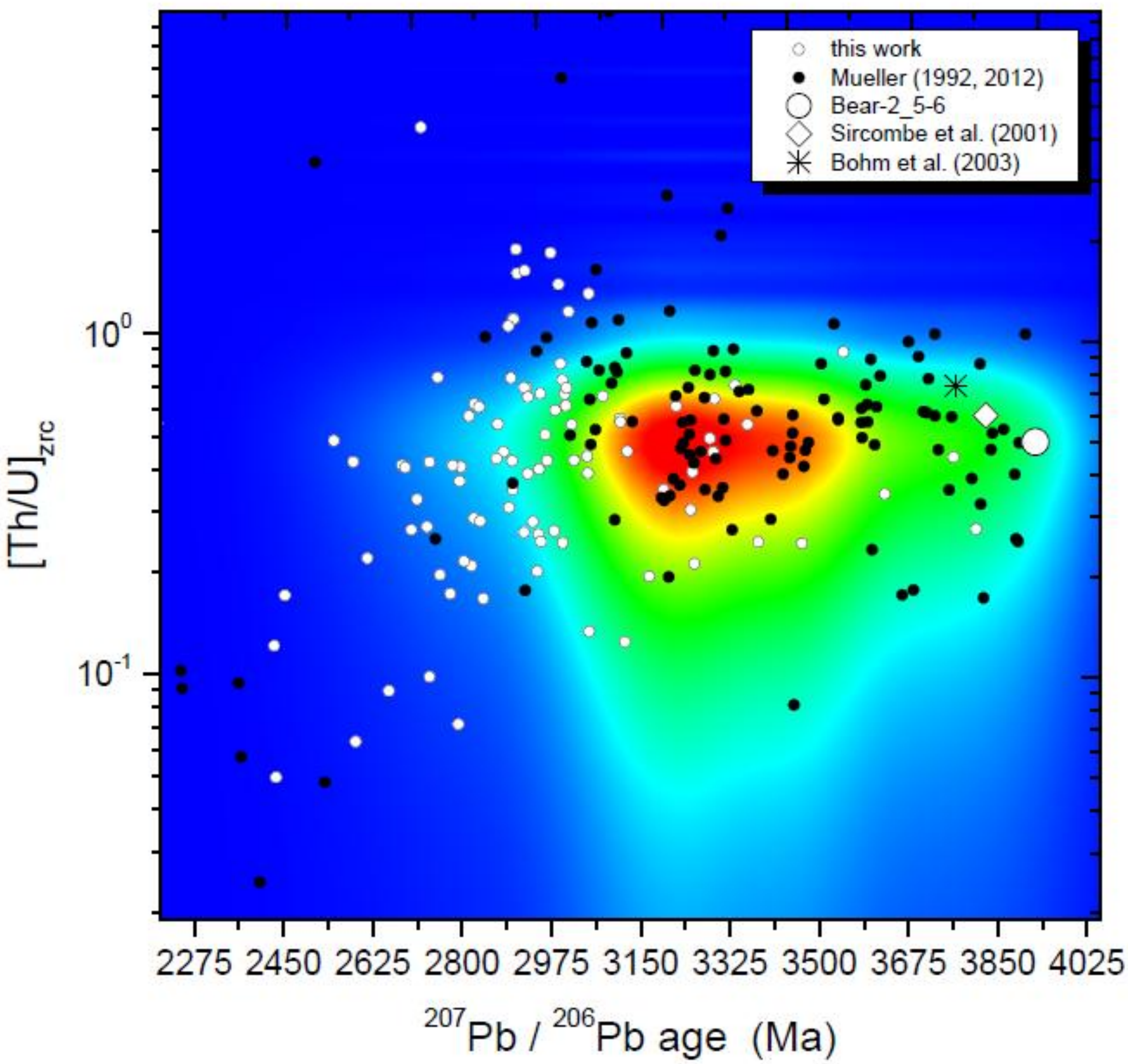
this work
Mueller (1992, 2012)
Bear-2_5-6
Sircombe et al. (2001)
Bohm et al. (2003)
[Th/U]zrc
10^0
10^-1
2275 2450 2625 2800 2975 3150 3325 3500 3675 3850 4025
207Pb / 206Pb age (Ma)

Figure 6

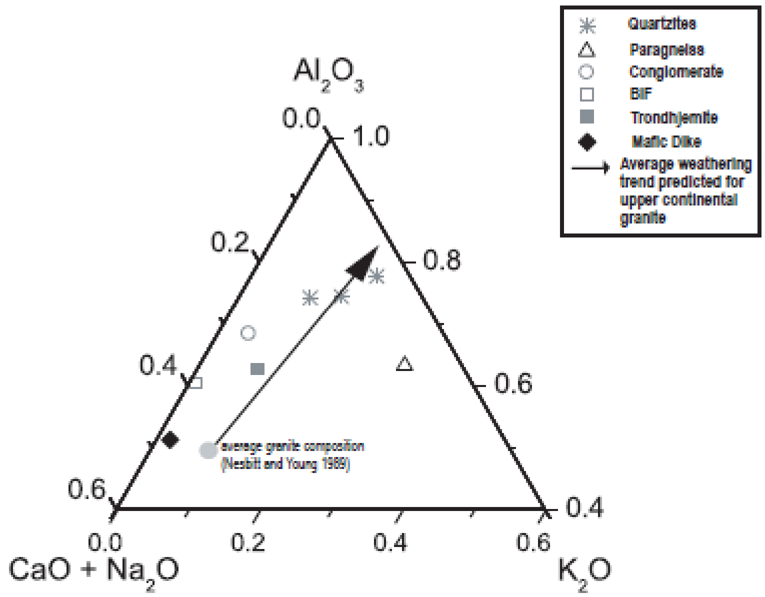
Al2O3
0.0
1.0
0.2
0.8
0.4
0.6
0.6
0.4
0.0
0.2
0.4
0.6
CaO + Na2O
K2O
average granite composition
(Nesbitt and Young 1989)
Quartzites
Paragneiss
Conglomerate
BIF
Trondhjemite
Mafic Dike
Average weathering
trend predicted for
upper continental
granite

Figure 7

Highlights

Maier et al. Geology and geochemistry of Hadean zircon bearing supracrustal rocks from Quad Creek, eastern Beartooth Mountains (Montana, USA)

> The oldest crust tapped by the Quad Creek quartzites (Montana) is comparable in age to the ca. 3960 Ma Acasta Gneiss Complex. > Similarity is suggestive of a linkage between the geology of the Wyoming Craton and the Western Slave Province. > Pre-3900 Ma zircons may be present in similarly-aged basins elsewhere in North America.

ACCEPTED MANUSCRIPT