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SHRIMP U-Pb and REE data pertaining to the origins of xenotime in Belt Supergroup rocks:
Evidence for ages of deposition, hydrothermal alteration, and metamorphism

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ABSTRACT

The Belt-Purcell Supergroup, northern Idaho, western Montana, and southern British Columbia, is a thick succession of Mesoproterozoic sedimentary rocks with an age range of about 1470-1400 Ma. Stratigraphic layers within several sedimentary units were sampled to apply the new technique of U-Pb dating of xenotime that sometimes forms as rims on detrital zircon during burial diagenesis; xenotime also can form epitaxial overgrowths on zircon during hydrothermal and metamorphic events. Belt Supergroup units sampled are the Prichard and Revett Formations in the lower Belt, and the McNamara and Garnet Range Formations, and Pilcher Quartzite in the upper Belt. Additionally, all samples that yielded xenotime were also processed for detrital zircon to provide maximum age constraints for the time of deposition and information about provenances; the sample of Prichard Formation yielded monazite that was also analyzed.

Ten xenotime overgrowths from the Prichard Formation yielded a U-Pb age of 1458 ± 4 Ma. However, because SEM-BSE imagery suggests complications due to possible analysis of multiple age zones, we prefer a slightly older age of 1462 ± 6 Ma derived from the three oldest samples, within error of a previous U-Pb zircon age on the syn-sedimentary Plains sill. We interpret the Prichard xenotime as diagenetic in origin. Monazite from the Prichard Formation, originally thought to be detrital, yielded Cretaceous metamorphic ages. Xenotime from the McNamara and Garnet Range Formations, and Pilcher Quartzite formed at about 1160-1050 Ma, several hundred m.y. after deposition, and probably also experienced Early Cretaceous growth. These xenotime overgrowths are interpreted as metamorphic/diagenetic in origin (i.e., derived during greenschist facies metamorphism elsewhere in the basin, but deposited in sub-greenschist facies rocks). Several xenotime grains are older detrital grains of igneous derivation. A previous

study on the Revett Formation at the Spar Lake Ag-Cu deposit provides data for xenotime overgrowths in several ore zones formed by hydrothermal processes; herein, those results are compared to data from newly analyzed diagenetic, metamorphic, and magmatic xenotime overgrowths.

The origin of a xenotime overgrowth is reflected in its REE pattern. Detrital (i.e., igneous) xenotime has a large negative Eu anomaly and is HREE-enriched (similar to REE in igneous zircon). Diagenetic xenotime has a small negative Eu anomaly and flat HREE (Tb to Lu). Hydrothermal xenotime is depleted in LREE, has a small negative Eu anomaly, and decreasing HREE. Metamorphic xenotime is very LREE-depleted, has a very small negative Eu anomaly, and is strongly depleted in HREE (from Gd to Lu). Because these characteristics seem to be process related, they may be useful for interpretation of xenotime of unknown origin.

The occurrence of 1.16-1.05 Ga metamorphic xenotime, in the apparent absence of pervasive deformation structures, suggests that the heating may be related to poorly understood regional heating due to broad regional underplating of mafic magma. These results may be additional evidence (together with published ages from metamorphic titanite, zircon, monazite, and garnet) for an enigmatic, Grenville-age metamorphic event that is more widely recognized in the southwestern and eastern United States.

KEY WORDS: Belt-Purcell Supergroup, U-Pb SHRIMP, xenotime, zircon

INTRODUCTION

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The determination of deposition ages for sedimentary rocks of the Mesoproterozoic Belt-Purcell Supergroup of northern Idaho, western Montana, and southern British Columbia, was a longstanding problem until Evans et al. (2000) provided U-Pb ages for zircon from three volcanic layers within units of the middle and upper parts of the Belt Supergroup. These data, coupled with a U-Pb zircon age for a mafic rock intruded into wet sediment in the lower part of the Prichard Formation, lower Belt (Sears et al., 1998) and mafic sills in the Aldridge Formation, British Columbia (Anderson and Davis, 1995), establish a time span of about 70 m.y. (about 1470-1400 Ma) for deposition of most of the Belt-Purcell Supergroup. These results require relatively rapid, but not unreasonable, sedimentation rates for accumulation of this very thick (15-20 km) sedimentary package (Evans et al., 2000).

Because very few volcanic layers within the Belt-Purcell Supergroup (henceforth referred to as the Belt Supergroup because all samples were collected in the U.S.) units have been recognized, other geochronologic methods for dating these rocks have been attempted (see detailed summary in Evans et al., 2000). On the basis of the U-Pb zircon ages, most previous studies yielded results that proved to be unsatisfactory, probably because several episodes of post-deposition metamorphism reset, or newly grew, the minerals being dated. The purpose of this contribution is to provide additional age constraints using a relatively new technique that involves U-Pb geochronology of xenotime that forms on detrital zircon during phosphate diagenesis at shallow burial depths; a review of this technique for dating sedimentary rocks is given in Rasmussen (2005). It was anticipated that sedimentary rocks of the Belt Supergroup would be appropriate lithologic units for formation of diagenetic xenotime, obviating the need for extremely rare volcanic layers to provide better age constraints for these non-fossiliferous rocks. To pursue this goal, we sampled sandstone layers from units throughout the Belt

Supergroup, including the Prichard Formation in the lower Belt Supergroup, the Revett Formation in the Ravalli Group, and the McNamara and Garnet Range Formations and Pilcher Quartzite from the upper Belt Supergroup (Missoula Group). Xenotime was obtained from most samples (see description of sample preparation below) and was dated using the sensitive high resolution ion microprobe (SHRIMP).

GEOLOGIC SETTING

The Belt Supergroup of western Montana, and the Purcell Supergroup in southern British Columbia and Alberta, Canada, are successions of Mesoproterozoic sedimentary rocks (Harrison, 1972; Link [et al., et al.](#) 1993, and references therein) of probable rift basin origin). About 15 to 20 km of sediments were deposited along the western margin of Laurentia (Price 1964; McMechan 1981; Cressman 1989; Ross [et al., et al.](#) 1989; Whipple, 1989; Sears [et al., et al.](#) 1998). The Belt Supergroup is subdivided into four parts: lower Belt, Ravalli Group, middle Belt carbonate (also known as Piegan Group), and Missoula Group (Fig. 2). Although formation names change across the geographic distribution of the Belt Supergroup from northern Idaho to central Montana, there is general agreement about correlations (cf. Winston, 1986, for a history of Belt nomenclature).

Depositional ages for the Belt/Purcell succession were determined from interlayered volcanic rocks (Evans [et al., et al.](#) 2000) and from early syn- and post-sedimentation sills (Anderson and Davis 1995; Sears [et al., et al.](#) 1998). Recent studies have dated detrital zircon for the purpose of constraining depositional ages and determining provenance for testing pre-Rodinian paleogeographic reconstructions (Ross [et al., et al.](#) 1991; Ross and Villeneuve 2003; Lewis [et al., et al.](#) 2007, 2010; Link [et al., et al.](#) 2007; Stewart [et al., et al.](#) 2010; this study).

Virtually all Belt Supergroup strata occur within the Late Cretaceous Cordilleran fold-and-thrust belt and are allochthonous with respect to underlying Precambrian basement (Price 1981; Harrison and Cressman, 1993; Harrison and Lidke, 1998). Because of this structural stacking, these strata exhibit burial effects such as weak metamorphism and local structurally induced fabrics such as cleavage. Samples from the fine- to very fine-grained Prichard and Revett Formations are in the biotite zone of lower greenschist metamorphism, exhibiting suturing in quartz grains and small (40µm) biotite grains (Harrison, 1974; Cressman, 1989). Samples from the McNamara and Garnet Range Formations, and Pilcher Quartzite are at sub-greenschist facies. There are clues of pre-Cretaceous tectonic events in the Belt Supergroup rocks, including: (1) compelling evidence for Proterozoic deformation based on an angular unconformity between the Belt Supergroup and Cambrian strata (Harrison, 1974), (2) Mesoproterozoic metamorphism based on 1.3-1.0 Ga dates for garnet in western exposures (Doughty and Chamberlain, 1996; Sha [et al., et al.](#) 2004; Vervoort [et al., et al.](#) 2005; Zirakparvar [et al., et al.](#) 2010; Nesheim [et al., et al.](#) 2012), and (3) 1.41 and 1.30 Ga mineralization and hydrothermal flux in rocks of northwestern exposures (Aleinikoff [et al., et al.](#) 2012b). There is also evidence from the Blackbird mining district in east-central Idaho for 1.38-1.36 Ga magmatism and 1.32-1.05 Ga Mesoproterozoic fluid flux in Mesoproterozoic metasedimentary rocks (Aleinikoff [et al., et al.](#) 2012c). The primarily isotopic evidence used to interpret structural, metamorphic, and hydrothermal events in the Mesoproterozoic strata is fragmentary and isolated; no tectonic drivers for these events are presently identified. Our study adds more isotopic age evidence for cryptic late Mesoproterozoic tectonism of Belt Supergroup rocks.

SAMPLE STRATEGY

Rare earth element (REE)-bearing phosphate minerals, such as crandallite $[\text{CaAl}_3(\text{PO}_4)_2(\text{OH})_5 \cdot \text{H}_2\text{O}]$, florencite $[(\text{La,Ce})\text{Al}_3(\text{PO}_4)_2(\text{OH})_6]$, gorceixite $[\text{BaAl}_3(\text{PO}_4)(\text{PO}_3\text{OH})(\text{OH})]$, monazite $[(\text{La,Ce,Nd,Th})\text{PO}_4]$ and xenotime $[\text{YPO}_4]$, can form during early diagenesis of marine sandstone (Rasmussen, 1996). Phosphorus is probably derived from decaying organic matter, whereas REE probably are primarily sourced from minor dissolution of detrital minerals such as monazite, xenotime, and clays (Rasmussen [et al.](#), 1998; 2011). McNaughton et al. (1999) documented the common occurrence of small (i.e., usually $<50 \mu\text{m}$ across) xenotime overgrowths on detrital zircon in numerous thin sections of clastic rocks. Development of a methodology using SHRIMP (McNaughton [et al.](#), 1999; Fletcher [et al.](#), 2000, 2004) enabled U-Pb dating by high spatial resolution micro-analysis of very small and delicate xenotime overgrowths. In addition, *in situ* U-Pb geochronology by laser ablation-inductively coupled plasma-mass spectrometry has recently been applied to xenotime (Klötzli [et al.](#), 2007; Wall [et al.](#), 2008; Liu [et al.](#), 2011).

SHRIMP U-Pb dating of xenotime overgrowths has been utilized in numerous studies of Precambrian sedimentary and metasedimentary rocks (cf. England [et al.](#), 2001; Rasmussen [et al.](#), 2004; Rasmussen, 2005, and references therein; Vallini [et al.](#), 2002, 2005, 2006). In addition, SHRIMP dating of xenotime overgrowths has been used in studies of metamorphism (Rasmussen, 2005; Rasmussen [et al.](#), 2007a, 2010; Aleinikoff [et al.](#), 2012a) and hydrothermal activity (England [et al.](#), 2001; Kositcin [et al.](#), 2003; Rasmussen [et al.](#), 2007a, 2007b; Aleinikoff [et al.](#), 2012b, c; Muhling [et al.](#), 2012).

The formation of diagenetic xenotime is controlled by the availability of REE and phosphate, degree of porosity in the sediment, and the presence of a suitable substrate for precipitation. Because xenotime and zircon are isostructural, diagenetic xenotime can form as epitaxial

overgrowths on detrital zircon. However, due to different compositions of zircon (ZrSiO_4) and xenotime (YPO_4), the contact between detrital zircon and diagenetic xenotime is delicate, and made more fragile by metamictization due to the presence of substantial concentrations of U and Th in both minerals. Thus, xenotime overgrowths do not remain intact during routine crushing and pulverizing of the mineral separation process. To overcome the fragility of xenotime overgrowths, SHRIMP geochronology of xenotime overgrowing detrital zircon is conducted *in situ* using polished thin sections.

In addition to U-Pb analysis of Belt Supergroup xenotime, two other complementary aspects of this study are: (1) U-Pb ages of detrital zircon extracted from each sample of Belt strata, and (2) U-Pb ages of monazite from the Prichard Formation. The ages of the youngest detrital zircon populations provide constraints on the maximum age of deposition of these units. Furthermore, the age distributions of detrital zircon populations yield information about provenance and possible variations in source regions among samples. Although we anticipated that monazite in the Prichard Formation would be detrital (i.e., >1.47 Ga), in fact most monazite grains yield Cretaceous ages, and thus are useful for understanding regional tectonic events that affected these low-grade rocks.

METHODS

Sampling for xenotime in Belt Supergroup rocks consisted of: (1) collecting about 10 hand samples of medium- to coarse-grained, well-sorted, non-ferruginous quartzite, (2) determination of Y (as an indicator of the presence of xenotime) and Zr (as an indicator of the presence of zircon, presumably of detrital origin in a quartzite) by X-ray fluorescence (XRF) analysis of a small piece of each hand sample, (3) preparation of numerous thin section billets from the

relatively Y-rich sample(s), (4) XRF analysis of Y and Zr on both sides of all billets to determine the surface with the highest likelihood of containing xenotime, (5) fabrication of polished thin sections from the Y-rich billets, (6) scanning electron microscope (SEM) auto-search in backscattered electrons mode (BSE) for xenotime, either as overgrowths on zircon or as individual grains, (7) extraction of xenotime-bearing, 1-2 mm pieces of polished thin section using either a wire saw, micro-core, or ultrasonic cutter, (8) incorporation of xenotime-bearing thin-section pieces with a pre-made block containing xenotime and zircon standards into an epoxy mount for SHRIMP analysis. The mount is not repolished, thereby avoiding possible removal of tiny xenotime overgrowths.

Detrital zircon was collected from all xenotime-bearing samples. The Prichard Formation sample also yielded monazite. Standard mineral separation techniques include crushing, pulverizing, Wilfley table heavy mineral concentration, magnetic separation, and density separation in methylene iodide ($\rho=3.3$). To limit laboratory bias, detrital zircon grains were sprinkled on doubled tape. All grains were mounted in 25-mm diameter epoxy disks, ground to about half-thickness to expose grain interiors, and polished sequentially with 6 μm and 1 μm diamond suspensions.

Xenotime, monazite, and zircon were imaged in reflected and transmitted light on a petrographic microscope. The SEM was used to make BSE images of xenotime and monazite in BSE, whereas cathodoluminescence (CL) images were made of zircon.

Xenotime standard MG-1 (490 Ma; Fletcher [et al., et al. 2004](#)) was used to calibrate $^{206}\text{Pb}/^{238}\text{U}$ ages of xenotime overgrowths. However, due to compositional variability (particularly REE, Th, and U concentrations), $^{206}\text{Pb}/^{238}\text{U}$ ages of xenotime are likely to be impacted by matrix effects due to mismatch of compositions between standard and unknown

(Fletcher [et al., et al.](#) 2004). Thus, arrays of U-Pb data on a Concordia plot may be due to both geologic and analytical complications. For this reason, only $^{207}\text{Pb}/^{206}\text{Pb}$ ages (which are not affected by matrix bias) are used for age determinations. Although a secondary xenotime standard of appropriate age was not available to assess instrument reproducibility for $^{207}\text{Pb}/^{206}\text{Pb}$ age, zircon standard FC-1 (1099 Ma; Paces and Miller, 1993) was run occasionally and always produced the correct $^{207}\text{Pb}/^{206}\text{Pb}$ age, providing confidence to the analytical procedure.

Monazite standard 44069 (424 Ma; Aleinikoff [et al., et al.](#) 2006) was used to calibrate $^{206}\text{Pb}/^{238}\text{U}$ ages of monazite grains from the Prichard Formation sample. Zircon standard R33 (419 Ma; Black [et al., et al.](#) 2004) was used to calibrate $^{206}\text{Pb}/^{238}\text{U}$ ages of detrital zircon from metasedimentary units of the Belt Supergroup.

Xenotime and zircon were analyzed on a SHRIMP-RG (either at the Research School of Earth Sciences (RSES), Australian National University, or at the USGS/Stanford SUMAC facility at Stanford University) following the methods described in Williams (1998). For xenotime, an analytical spot with a diameter of 10-15 μm was used, whereas for zircon the spot was set to about 25-30 μm in diameter. The magnet cycled through the mass stations 6 times for xenotime and 4 times for detrital zircon. Monazite was analyzed on SHRIMP II at RSES using a 20-25 μm spot size. For efficiency and because the monazite was thought to be detrital, the magnet was cycled through the mass stations three times. In order to eliminate an isobaric interference at mass 204 (suspected to be a NdThO^{++} molecule; Ireland [et al., et al.](#) 1999), energy filtering was utilized. By closing the energy filter slits by about 50-65%, the UO peak (mass 254) was decreased by about half, most or all of the counts at mass 204 could be attributed to ^{204}Pb , and these counts could be used to reliably correct for the presence of common Pb when calculating a $^{207}\text{Pb}/^{206}\text{Pb}$ or $^{206}\text{Pb}/^{238}\text{U}$ age.

SHRIMP data are reduced using Squid (Ludwig, 2001) or Squid 2 (Ludwig, 2009) and plotted using Isoplot 3 (Ludwig, 2003). U-Pb data for detrital zircon from the Belt Supergroup are shown on conventional Concordia plots to evaluate discordance. Only data that are less than 10% discordant are considered suitable for inclusion in the calculation of Relative Probability curves that display age distributions. The ages of Mesoproterozoic xenotime are calculated using the weighted average of selected $^{207}\text{Pb}/^{206}\text{Pb}$ ages; age of Cretaceous monazite is calculated using the weighted average of selected $^{206}\text{Pb}/^{238}\text{U}$ ages. All ages are cited with ± 2 sigma age uncertainties.

REE data from xenotime grains were collected using the USGS/Stanford SHRIMP-RG (Mazdab and Wooden, 2006). A primary ion beam, operated at about 0.5 nA and a spot size of about 7-10 μm in diameter, excavated a 0.5 to 1- μm deep crater. Mass resolution was set to about 11,000 in order to separate all heavy REE (HREE) from middle REE (MREE) oxides. Xenotime standard BS-1 (Aleinikoff [et al.](#), 2012a) was used to calibrate REE concentrations (believed to be reproducible to about 2-5%), normalized to the chondritic values of Anders and Grevesse (1989) which were modified by Korotev (1996). In this study, we use REE patterns as fingerprints for distinguishing xenotimes of different origin.

RESULTS

Detrital Zircon

U-Pb age data for xenotime overgrowths in metasedimentary layers of the Belt Supergroup are best understood within the framework of zircon crystallization ages of volcanic layers (Evans [et al.](#), 2000). A total of four formations, including one from the lower Belt Supergroup

(Prichard Formation, member E south of Paradise, Montana) and three from the Missoula Group (McNamara, Garnet Range, and Pilcher from a continuous stratigraphic section south of Philipsburg, Montana), were sampled for U-Pb geochronology (Fig. 1). Representative populations of detrital zircon from each sample were analyzed to obtain information about source of sediments and constraints on the time of deposition (Table 1). Previously determined age data from detrital zircon of the Revett Formation (Aleinikoff [et al., et al.](#) 2012b) are included for comparison.

Concordia plots of U-Pb data from detrital zircon in the four sampled formations are shown in Figure 3C. Isotopic data from zircon of member E of the Prichard Formation (sample BB32) are mostly concordant or slightly discordant; 91% of analyses were <10% discordant and were used to calculate a Relative Probability curve (Fig. 4). Relative Probability plots for ages of detrital zircon from the Prichard Formation (this study, plus Ross and Villeneuve, 2003; Link [et al., et al.](#) 2007; Lewis [et al., et al.](#) 2010) are consistent, showing major peaks at about 1625-1590 Ma and subsidiary peaks at 1800-1700 Ma (Fig. 4). Similar age distribution peaks for detrital zircon occur in the Revett Formation (Ross and Villeneuve, 2003; Aleinikoff [et al., et al.](#) 2012b).

Concordia plots for detrital zircon from the McNamara (sample MC-3-03) and Garnet Range (sample GR-4-03) Formations, and Pilcher Quartzite (sample P-1-03) formations show that significant proportions of the U-Pb data are discordant (Fig. 3C). For these units, the percentages of analyses that are <10% discordant are 65%, 56%, and 80%, respectively. Relative Probability plots of age distributions for these detrital zircon samples have major peaks at about 1700 Ma and subsidiary peaks at about 1450 Ma. In addition, McNamara and Garnet Range samples contain a few older grains with ages of about 2.7-2.5 Ga.

The youngest peaks for each sample (i.e., the maximum age of deposition) are about 1468 Ma (Prichard), 1450 Ma (McNamara), 1444 Ma (Garnet Range), and 1433 Ma (Pilcher) (Fig. 4). These ages are compatible with ages of interlayered volcanic units throughout the Belt Supergroup (Evans [et al., et al.](#) 2000).

Included in the Relative Probability curve for the Prichard Formation are data from 25 handpicked euhedral grains. These pristine grains were considered to possibly be of volcanic origin synchronous with Prichard sedimentation. However, they have a broad range of ages (about 1965-1540 Ma), all of which are significantly older than the accepted deposition age of the Prichard (about 1470 Ma; Sears [et al., et al.](#) 1998). Three tips of euhedral grains yield much younger ages of about 130-119 Ma, suggesting a metamorphic overprint in the Early Cretaceous, which is compatible with monazite data described below.

Monazite

Twenty-three grains of monazite from the Prichard Formation sample were analyzed with the intent of obtaining additional provenance information for determining the history of the sedimentary rocks. In BSE imagery, most grains are composed of oscillatory-zoned cores and dark, unzoned rims (Fig. 5A). SHRIMP analyses reveal that the cores ($n=19$) contain about 4000-7000 ppm U and have Th/U of about 2-8 (Table 1). In contrast, rims ($n=3$) have lesser U (about 1000-2000 ppm U) and greater Th/U (about 15-27) (Fig. 5B). The chemical differences between cores and rims suggest different processes or conditions of formation. These differences are also reflected in the weighted average of $^{206}\text{Pb}/^{238}\text{U}$ ages; cores are 110.8 ± 1.0 Ma, whereas rims are 106.5 ± 2.1 Ma (Fig. 5C-E). Taken together, these data indicate that the monazite grains are metamorphic in origin, and that two metamorphic events occurred in the late

Early Cretaceous. In addition, older concordant ages were obtained from one core (1529 ± 10 Ma) and one rim (1100 ± 17 Ma) (Fig. 5C).

Xenotime

Samples from the Prichard, Revett (Aleinikoff [et al., et al.](#) 2012b), McNamara and Garnet Range Formations, and Pilcher Quartzite were collected for xenotime in an attempt to provide additional evidence for the timing and duration of Belt sedimentation and for information about post-depositional history. After SEM-BSE identification of xenotime overgrowths on detrital zircon, potential targets were extracted from polished thin sections and mounted in epoxy for analysis on the SHRIMP-RG at RSES or Stanford.

Prichard Formation

Although xenotime overgrowths on detrital zircon in the Prichard Formation member E sample are common, most are smaller than the minimum SHRIMP primary spot size of about 7-10 μm . Twenty-two analyses were made on relatively large xenotime overgrowths (maximum width of about 50 microns). When imaged in SEM-BSE under normal conditions of contrast and brightness, faint zoning is visible in light gray detrital zircon, whereas the xenotime overgrowths appear as bright white. If the contrast is maximized and the brightness is diminished, faint zoning can be observed in the xenotime overgrowth (Fig. 6A). It is not known whether the compositional variation revealed by BSE is due to different age components or reflects chemical variation during formation of a single overgrowth. Xenotime was found both as overgrowths on single grains and as cement between several grains (Fig. 6B)

$^{207}\text{Pb}/^{206}\text{Pb}$ ages for xenotime overgrowths range from about 1464 to 1310 Ma; U-Pb data are both reversely and normally discordant (Table 2; Fig. 6C), probably partly due to matrix effects related to compositional mismatch of standard and unknowns and perhaps analysis of multiple age components. The weighted average age of the 10 oldest analyses is 1458 ± 4 Ma (Fig. 6D). However, because of the possibility of multiple ages of xenotime formation, perhaps the best estimate for time of initial growth of diagenetic xenotime during shallow burial is given by the weighted average of the three oldest overgrowths— 1462 ± 6 Ma. This age is within uncertainty of the U-Pb zircon age for the Plains sill (1469 ± 2.5 Ma; Sears [et al., et al.](#) 1998), which is interpreted as having been emplaced into wet sediment of Prichard member E, prior to lithification. Thus, the time of deposition of the Prichard Formation is verified by the $^{207}\text{Pb}/^{206}\text{Pb}$ age of xenotime overgrowths, which are interpreted to be diagenetic in origin. Other ages, some of which have large errors due to high common Pb content (shown by large error ellipses, Fig. 6C; Table 2) were excluded from the age calculation.

Revett Formation

Ages of xenotime overgrowths in the Revett Formation from samples collected at the Spar Lake Cu-Ag deposit, western Montana, are described in detail in Aleinikoff et al. (2012b).

Thirty-two analyses of xenotime from five mineral zones (Hayes [et al., et al.](#) 1989) result in a weighted average age of 1409 ± 8 Ma. This age is about 50 m.y. younger than the depositional age of the Revett (from Evans [et al., et al.](#) 2000). Six other analyses yield a younger age of 1304 ± 19 Ma.

Four observations concerning the occurrence of xenotime overgrowths from the Revett Formation led to the conclusion that this xenotime is of hydrothermal origin: (1) because the

calculated age derived from most of the xenotime overgrowths is about 50 m.y. younger than the stratigraphic age of the Revett, these overgrowths could not have formed during shallow burial diagenesis, (2) xenotime overgrowths were found in mineralized samples of Revett from the Spar Lake Cu-Ag deposit, (3) no overgrowths were found in several unmineralized samples of Revett collected in western Montana outside of the mining district, and (4) relatively enriched concentrations of As occur in xenotime from the Spar Lake Cu-Ag deposit (Aleinikoff [et al., et al.](#) 2012b).

McNamara Formation

Xenotime overgrowths in the McNamara Formation are rare and small. Despite searching several samples, only four suitable overgrowths were found. In one overgrowth, a very narrow, irregular shaped, medium gray (in BSE) inner zone is overgrown by a white 20- μm thick outer rim (Fig. 7A). The weighted average age of slightly discordant data from three outer rims is 1164 ± 51 Ma (Fig. 7B). One other overgrowth yielded extremely discordant age data and is not considered further. On the basis of morphology, the inner zone may have formed during diagenesis; however, the very narrow width of this phase of xenotime precludes analysis by SHRIMP.

Garnet Range Formation

Two types of xenotime were found in the sample of Garnet Range Formation: (1) monomineralic individual grains, and (2) overgrowths on detrital zircon (Table 2, Fig. 8A). Three analyses of monomineralic grains yield $^{207}\text{Pb}/^{206}\text{Pb}$ ages of about 1.65 Ga; these xenotime grains are interpreted as detrital in origin. Of the remaining eight analyses, two are nearly

concordant with ages of 989 ± 59 and 1092 ± 29 Ma (1 sigma errors). The other six analyses are discordant, with $^{206}\text{Pb}/^{238}\text{U}$ ages ranging between about 430 and 685 Ma (Fig. 8B). It is unclear whether the discordance is caused by: (1) analysis of multiple age zones (i.e., is a mixture of two or more ages), (2) Pb loss due to Cretaceous thermal events (see Prichard monazite ages, above), or (3) matrix effects due to compositional mismatch between standard and unknown. The most likely explanation for the data array is the first possibility (above) because complex BSE zoning occurs in many overgrowths. A very thin, dark, irregular inner layer adjacent to the seed zircon can be observed locally (Fig. 8A). In addition, the two oldest analyses have much lower common Pb content than the younger analyses, suggesting separate growth. Given the narrow width of a typical overgrowth from this sample ($\sim 10\text{-}20\text{ }\mu\text{m}$), and the width of the primary ion beam ($\sim 7\text{-}10\text{ }\mu\text{m}$) for SHRIMP analysis, mixtures on the scale of a few microns are mostly unavoidable.

The weighted average of the eight $^{207}\text{Pb}/^{206}\text{Pb}$ ages is 1041 ± 42 Ma (Fig. 8B). However, because of the high degree of discordance, perhaps a more accurate estimate of the Proterozoic age of formation of the overgrowths may be determined by calculating an upper intercept age of a best-fit line anchored at a reasonable lower intercept age of 110 ± 10 Ma (based on data from the Prichard monazite) and calculated through the 8 data points. Using this method, the upper intercept age is 1068 ± 47 Ma. Regardless of the method used, it is clear that these overgrowths are significantly younger than the assumed age of deposition of the Garnet Range Formation.

Pilcher Quartzite

In the Pilcher Quartzite, some xenotime overgrowths have complex zoning in BSE suggestive of multiple age components, whereas others appear to be simpler, composed only of one age component (Fig. 8C). No detrital xenotime grains were found in this sample.

Twenty-seven analyses of xenotime overgrowths from the Pilcher Quartzite (acquired during two analytical sessions; Table 2) yielded a broad array of concordant to about 80% discordant data (Fig. 8D). The weighted average of $^{207}\text{Pb}/^{206}\text{Pb}$ ages of all analyses is 1068 ± 26 Ma. However, this array may contain two age groups: (1) three discordant (25-50%) analyses have a weighted average of $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1161 ± 28 Ma, and (2) eight concordant to 22% discordant data have a weighted average of $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1060 ± 32 Ma. We are unable to determine if the extreme discordance of some analyses is due to matrix effects (i.e., instrumental issues) or is the result of analysis of old and young age components. Regardless of whether this data set is composed of one or two age components, the results clearly show that xenotime overgrowths in the Pilcher Quartzite are significantly younger than its assumed age of deposition. These ages agree with the age determined for overgrowths from the nearby sample of Garnet Range Formation. Similar to the Garnet Range, no diagenetic xenotime was found in Pilcher Quartzite.

Trace Elements

In order to understand the range of ages obtained from xenotime overgrowths, several samples were analyzed for trace element concentrations. Chemical fingerprinting was initiated to provide additional evidence for distinguishing populations of xenotime overgrowths which may reflect their origins. Utilizing the capabilities of the USGS/Stanford SHRIMP-RG (i.e., high mass resolution, high sensitivity, and high spatial resolution) and the analytical protocols

developed for that instrument (Mazdab and Wooden, 2006), we were able to determine complete sets of REE concentrations (La-to-Lu) for each type of xenotime. This work expands on results of England et al. (2001) and Kositcin et al. (2003) for the geochemistry of xenotime of diverse origins from the Witwatersrand basin, South Africa.

Xenotime of detrital (i.e., igneous) origin was determined to be geochemically distinct from other xenotime in this study (Table 3). Detrital/igneous xenotime typically has relatively high U content (Fig. 9A) and greater negative Eu anomaly (lower values of Eu/Eu^* ; Fig. 9B). The Eu anomaly in igneous xenotime is caused by the “plagioclase effect,” i.e., preferential partitioning of Eu into co-genetic and contemporaneous plagioclase. The REE pattern for detrital xenotime is identical to the patterns found in igneous xenotime, showing depletion in light REE (LREE), a large negative Eu anomaly, and enrichment in HREE (cf. Wendell xenotime, 302 ± 2 Ma from a pegmatite in Wendell, MA; P. Holden, personal communication to J. Wooden, 2000; Fig. 9D, and REE patterns for detrital xenotime; Kositcin et al., 2003).

Xenotime overgrowths of interpreted diagenetic, hydrothermal, or metamorphic origin typically have small negative Eu anomalies (Figs. 9D-E). Metamorphic xenotime is distinguished from diagenetic and hydrothermal xenotime because it contains less U (Fig. 9A), and has significantly greater Gd/Lu and Th/U (Figs. 9B and 9C). The REE pattern for metamorphic xenotime shows extreme depletion in LREE, little or no Eu anomaly, enrichment in MREE (maximum values at Gd), and strong depletion in HREE (Fig. 9F). The high values for Gd/Lu from metamorphic xenotime are probably caused by increased MREE and HREE depletion. The REE pattern for hydrothermal xenotime shows depletion in LREE, a small negative Eu anomaly, and a decrease from MREE to HREE (Fig. 9D). The REE pattern for

diagenetic xenotime shows depletion of LREE, a small negative Eu anomaly, and little or no decrease between MREE and HREE (Fig. 9E).

DISCUSSION

Zircon U-Pb Systematics

U-Pb geochronology of detrital zircon from Belt Supergroup samples yields two very different results. Most of the data from the Prichard (Fig. 3C) and the Revett (Fig. 4, Aleinikoff [et al., et al. 2012b](#)) Formations are less than 10% discordant, whereas many analyses of detrital zircon from the McNamara and Garnet Range Formations, and Pilcher Quartzite are quite discordant. On Concordia plots, the trajectories of discordance are toward Cretaceous lower intercept ages (Fig. 3C). CL imaging indicates that most analyzed grains lack overgrowths (Fig. 3A, B). In all cases, the SHRIMP spot was put on oscillatory-zoned cores. Because the primary ion beam only excavates a shallow pit of about 0.5-1 micron, it is unlikely that the analytical spot encountered multiple growth zones during analysis. Thus, it is probable that the pattern of extreme discordance in some U-Pb data from detrital zircon grains of the McNamara and Garnet Range Formations, and Pilcher Quartzite was caused by Pb-loss due to geologic causes such as heating and (or) fluid flow. The discussion of xenotime age data (below) provides additional speculation.

The detrital zircon data provide details on the ages of grains and their histories that can be used for interpretation of the other dated minerals, and the zircon age populations add to the growing volume of provenance data sets for these rocks. Samples from the Prichard and Revett Formations from lower parts of the section in the western edge of the preserved basin yielded numerous ages between about 1500 and 1600 Ma. These ages coincide with the “North

American magmatic gap” of Ross and Villeneuve (2003), and they therefore suggest derivation from non-Laurentian sources that may now be part of northeastern Australia (Link [et al., et al.](#) 2007) or northern Russia (Sears and Price, 2003).

The detrital zircon peaks for the Garnet Range Formation and Pilcher Quartzite do not feature the youngest ages acquired by Ross and Villeneuve (2003) for the Garnet Range Formation despite the significantly larger number of grains analyzed in our study. From our data, and the limited age data for the whole section, there is no evidence that these rocks are younger than, or had a different source than, the rest of the Missoula Group. In contrast to the detrital zircon age distribution in the Prichard sample and for other units in the western Belt basin, data for detrital grains from the McNamara and Garnet Range Formations and Pilcher Quartzite from the upper part of the section in the central part of the depositional basin show a distinct lack of 1600-1500 Ma zircon. Thus, the data confirm that there was a shift in provenance within the Belt basin (as discussed in previous detrital zircon studies, Ross and Villeneuve, 2003; Lewis [et al., et al.](#) 2007, 2010; Link [et al., et al.](#) 2007; Stewart [et al., et al.](#) 2010) that occurred after deposition of the Prichard Formation and Ravalli Group (pre-1454 $\pm$ 9 Ma; Evans [et al., et al.](#) 2000) and before deposition of the uppermost Missoula Group (post-1401 $\pm$ 6 Ma; Evans [et al., et al.](#) 2000) (Fig. 2).

Xenotime and Monazite U-Pb Systematics

U-Pb geochronology of xenotime overgrowths from all samples shows discordant arrays of isotopic data. For diagenetic xenotime from the Prichard Formation, moderately discordant data were obtained from only 10 analyses (Fig. 6C, D). Possible causes for the discordance are: (1) Pb loss or gain, (2) matrix effects related to compositional mismatch between standard and

unknowns, and (3) analysis of multiple age zones (Fig. 6A). Pb-loss or gain (Cause #1) is unlikely because of the very slow diffusion rate of Pb in xenotime (Cherniak, 2006). U-loss, which would cause reverse discordance (i.e., U-Pb data that plot above the Concordia curve) is more unlikely because of the crystallographic substitution of U for Y in xenotime. Also, because the rocks were only heated to sub-greenschist or lower greenschist facies, there was no obvious driver for elemental mobility due to diffusion. Cause #2 possibly explains the reversely discordant age data (Fig. 7C), whereas normally discordant data could have been due to Causes #1, 2 and (or) 3.

Similar degrees of normal discordance were obtained from hydrothermal xenotime from the Revett Formation at the Spar Lake deposit (Aleinikoff [et al.](#), 2012b). Xenotime overgrowths from units in the lower Belt and Ravalli Groups, while somewhat complicated, are relatively simple compared to isotopic systematics of xenotime that formed higher in the stratigraphic section.

The results for xenotime in the upper part of the stratigraphic section are analogous to the U-Pb data for detrital zircon from the same units. On the basis of discordant arrays of data, one possible explanation is that there was a greater impact of Cretaceous disturbance to the isotopic systematics in the younger units than apparently is present in xenotime overgrowths and detrital zircon grains in the lower Belt and Ravalli Groups. However, there may have been different causes for the discordance of data from detrital zircon and xenotime samples. For detrital zircon, CL images show little evidence of metamorphic rims and all analyses were located within oscillatory-zoned cores. Thus, Pb loss is considered to be the most likely cause for discordance in the detrital grains. For xenotime, it is difficult to evaluate the possible cause(s) for discordant arrays of data due to the unknown impact of matrix effects on $^{206}\text{Pb}/^{238}\text{U}$ ages. However, BSE

images suggest the presence of multiple age components in this xenotime (Figs. 7A; 8A, C). It is possible that very fine layering of Proterozoic and Cretaceous age components were within the analyzed volume of SHRIMP analysis, and thus the cause of discordant xenotime data probably was due to mixed analyses, not Pb loss..

Monazite from the Prichard Formation also records evidence of Cretaceous event(s). SHRIMP dating of monazite rims yielded ages of 111 ± 1 and 107 ± 2 Ma, although there is little evidence for Cretaceous xenotime growth in either the Prichard or Revett samples. In contrast, monazite from the Mt. Shields and Bonner formations of the Missoula Group yielded ages of about 1.7 Ga, and must be detrital in origin (Ross [et al.](#), [et al.](#) 1991; 1992). We provide further discussion of Proterozoic and Cretaceous metamorphic events below.

1.0-1.2 Ga Regional Metamorphism

Xenotime overgrowths obtained from units near the top of the Belt Supergroup yielded ages of about 1.16 to 1.05 Ga. More specifically, xenotime overgrowth ages are about: (1) 1.16 Ga (McNamara Formation), (2) 1.07 Ga (Garnet Range Formation), and (3) 1.15 and 1.07 Ga (Pilcher Quartzite). In addition, one xenotime overgrowth from the Blackbird mining district near Salmon, Idaho, yielded an age of about 1.06 Ga (Aleinikoff [et al.](#), [et al.](#) 2012c). One grain of monazite from the Prichard Formation is about 1.03 Ga (Table 1). Thus, there are abundant new geochronologic data from this study that suggest two Proterozoic episodes of xenotime growth at about 1.16 and 1.05 Ga.

Although the xenotime overgrowths in the Garnet Range Formation and Pilcher Quartzite are contemporaneous with biotite-grade metamorphic rocks to the west (Doughty and Chamberlain, 1996; Vervoort [et al.](#), [et al.](#) 2005; Flagg [et al.](#), [et al.](#) 2010; Zirakparvar [et al.](#), [et al.](#) 2010; Nesheim

[et al., et al. 2012](#)), these overgrowths formed at sub-greenschist temperatures. The formation of xenotime overgrowths in units of the upper part of the Belt probably involved conversion of smectite to illite in rocks at depth; this transformation would have caused dehydration of smectite and resulted in the production of diagenetic brines (Gonzalez-Alvarez and Kerrich 2010). These fluids were derived at greenschist facies metamorphic conditions, and then percolated upward through the stratigraphic section, eventually forming xenotime overgrowths at very low (sub-greenschist) temperatures (see Fig. 9F). We consider these overgrowths to be metamorphic/diagenetic in origin. This process differs significantly from the burial diagenesis process responsible for the formation of xenotime overgrowths in the Prichard Formation, where xenotime precipitated from REE- and phosphate-enriched pore waters near the seabed-seawater interface in unlithified sediment (cf. Rasmussen, 2005).

In addition to our xenotime U-Pb ages of 1.16-1.05 Ga, there is isotopic evidence of enigmatic metamorphic events in southern British Columbia and northern Idaho at about 1.1 to 1.0 Ga, including growth of metamorphic titanite, zircon, monazite, and garnet (Doughty and Chamberlain, 1996; Anderson and Parrish, 2000; Vervoort [et al., et al. 2005](#); Flagg [et al., et al. 2010](#); Zirakparvar [et al., et al. 2010](#); Nesheim [et al., et al. 2012](#); McFarlane 2015). Although age data from several minerals using different isotopic systems indicate Proterozoic episodes of formation, the underlying structural and (or) tectonic causes of this mineral growth are not yet understood. Criteria for distinguishing between various tectonic models to explain these events (for example, static heating perhaps supplied by deep mafic magmas vs. heating due to deformation/thrusting/burial) are lacking at local and regional scales.

Cretaceous Metamorphism

Although dated xenotime overgrowths in the Prichard Formation only record Mesoproterozoic events, monazite from the Prichard is mostly Cretaceous in age. Cores and rims of individual grains occur as two geochemically distinct populations (Fig. 5B) and have slightly different weighted average ages of 110.8 ± 1.0 Ma (cores) and 106.5 ± 2.1 Ma (rims) (Fig. 5C- E). Early Cretaceous ages for monazite and xenotime were also found at the Blackbird Co-Cu deposit in central Idaho (Aleinikoff [et al., et al.](#) 2012c). These age data suggest some sort of thermal and (or) hydrothermal activity in the Early Cretaceous that pre-dated emplacement of the 95-65 Ma Idaho batholith (Gaschnig [et al., et al.](#) 2010).

SHRIMP U-Pb age data from xenotime overgrowths in the Garnet Range Formation and Pilcher Quartzite form discordant arrays on Concordia plots (Fig. 8B, D). Although the high degree of discordance may be due to Pb loss, it is also possible that the discordant data result from analyses of more than one age component (Mesoproterozoic and Early Cretaceous). High contrast BSE imagery reveals that xenotime overgrowths from the Garnet Range Formation and Pilcher Quartzite are complexly zoned (Figs. 7A; 8A, C). Unfortunately, sampling of single BSE zones was difficult because these zones are finer than the SHRIMP primary ion beam spot size. In this case, SHRIMP analyses will sample mixtures of age zones, resulting in discordant arrays between the upper and lower intercept ages of ~ 1050 and 110 Ma, respectively. Similar Mesoproterozoic and Cretaceous ages for garnet cores and rims have been reported from paragneisses of northern Idaho (Vervoort [et al., et al.](#) 2005; Zirakparvar [et al., et al.](#) 2010).

Geochemical analysis of xenotime overgrowths from the Pilcher Quartzite shows that they all have relatively high Gd/Lu (Fig. 9B). Eight geochemical analyses of xenotime that yielded the least discordant ages (shown as a square with “x”; Fig. 9B, C) plot within the field of all geochemical data from Pilcher xenotime overgrowths. We suggest that this distribution of data,

plus the irregular contact between zones displayed by BSE imagery, implies that the Cretaceous components of the overgrowths probably formed by dissolution and reprecipitation of the older overgrowths.

Xenotime Trace Element Geochemistry

SHRIMP-RG determination of REE abundances in xenotime overgrowths and individual grains is helpful in distinguishing xenotime of different origins. Detrital (presumably igneous) xenotime is enriched in HREE, and has large negative Eu anomalies (Fig. 9D; Fig. 9A, Aleinikoff [et al., et al.](#) 2012b). These REE distributions are similar to patterns from known igneous xenotime (cf. Förster, 1998; Kositsin [et al., et al.](#) 2003). In contrast, REE patterns for xenotime of metamorphic origin show extreme depletion in LREE, enrichment in MREE, modest depletion in HREE (resulting in high Gd/Lu values), small negative Eu anomalies, and relatively low U concentrations (and therefore relatively high Th/U; Fig. 9A, B). The distribution for REE in Belt Supergroup metamorphic xenotime overgrowths is similar to xenotime grains of known metamorphic origin (Cabella [et al., et al.](#) 2001). Diagenetic xenotime from the Belt Supergroup has relatively low Th, small negative Eu anomalies, and relatively low Gd/Lu (Fig. 9A, B, E). Xenotime of hydrothermal origin (Aleinikoff [et al., et al.](#) 2012b) has slight depletion in HREE, a small Eu anomaly, and relatively high Th content. The distinguishing characteristics of diagenetic and hydrothermal xenotime are also evident in known diagenetic and hydrothermal xenotime from the Witwatersrand basin (Figs. 9D, E; Kositsin [et al., et al.](#) 2003).

The depositional ages of the Garnet Range Formation and Pilcher Quartzite are not well established but are constrained to be younger than the ~1.4 Ga youngest detrital zircons (Ross and Villeneuve 2003) and older than the overlying Middle Cambrian units. Although numerous

xenotime overgrowths in the Garnet Range Formation and Pilcher Quartzite yielded ages of about 1.16 and 1.05 Ga, these dates are not considered to be depositional ages because the xenotime overgrowths have distinctive REE patterns that are dissimilar to REE patterns in diagenetic xenotime from the Prichard.

The depletion in HREE and the high Gd/Lu for Pilcher xenotime clearly distinguish these overgrowths. In medium- to high-grade metamorphic rocks, HREE depletion in xenotime is usually considered to be caused by cogenetic formation of garnet (the “garnet effect,” i.e., preferential partitioning of HREE into garnet; Spear and Pyle, 2002; Pyle and Spear, 2003; Hetherington *et al.*, 2008; Rubatto *et al.*, 2009; Chen *et al.*, 2010, and references therein). However, our samples of Garnet Range Formation and Pilcher Quartzite are from localities in the eastern part of the Belt Supergroup, far from the higher grade, garnet-bearing units to the west. Because the Garnet Range and Pilcher were only metamorphosed to sub-greenschist facies, they do not contain metamorphic garnet. A possible alternative source for the relatively HREE-depleted, 1.16-1.05 Ga xenotime overgrowths is oxidized alkaline brines (see green field of data, Fig. 9F; Schieber, 1988; Gonzalez-Alvarez and Kerrich, 2010;).

Structural and Tectonic Implications

Samples of the Missoula Group from southwestern Montana, lower Belt from southern British Columbia, and Lemhi Group from east-central Idaho contain metamorphic or hydrothermal xenotime and sphene that are dated at 1.2-1.0 Ga (Anderson and Davis, 1995; Aleinikoff *et al.*, 2012c; this study). Garnet in the Wallace Formation from north-central Idaho has a more extended age span of 1.39-1.1 Ga (Zirakparvar *et al.*, 2010; Nesheim *et al.*, 2012). None of these data sets discriminates discrete events within that age range.

Instead, samples for the Missoula Group, which were all collected in the same structural setting and from a continuous stratigraphic section, result in ages that span the entire age range and young upward in the section. Paradoxically, xenotime of the 1.2-1.0 Ga age is not present in the sample of Prichard Formation (lower Belt) from northwestern Montana, although McFarlane (2015) reports 1.2-1.0 monazite, zircon, and titanite ages in the Lower Aldridge (Prichard equivalent) in southeastern British Columbia. To date, none of the studies reporting 1.2-1.0 Ga xenotime has identified associated rock fabrics, structures, or regional metamorphic belt(s), and thus, the nature of any causal event remains undetermined; perhaps the entire section was affected only by circulating hydrothermal brines at this time.

Much of the xenotime and monazite analyzed from these rocks provide ages of Cretaceous low-grade metamorphism. Monazite in the Prichard Formation from northwestern Montana formed at 111 and 107 Ma, and xenotime overgrowths in the Garnet Range Formation are about 110 Ma. In the Lemhi Group, monazite yields ages of about 110 and 92 Ma (Aleinikoff [et al., et al.](#) 2012c). The onset of Cretaceous orogeny is poorly established in the central parts of the Idaho-Montana fold and thrust belt because most rocks of the hinterland were buried deeply, and not cooled until after culminating magmatic events (Lund [et al., et al.](#) 1986). These monazite and xenotime ages provide the best presently available documentation that deformation, heating, and fluid flow related to Cretaceous compressional orogeny in the northern Cordillera began by about 111 Ma, ages that correspond well to terrane accretion along the Salmon River suture to the west (Lund, 1995, and references therein).

CONCLUSIONS

SHRIMP U-Pb geochronology of xenotime overgrowths on detrital zircon obtained from samples of the Belt Supergroup confirm details of depositional history and provide additional evidence on tectonic history. Xenotime overgrowths on zircon from the Prichard Formation confirm its age of deposition is about 1462 ± 6 Ma. Xenotime overgrowths document weak metamorphism (or diagenesis) of undetermined origin within the McNamara and Garnet Range Formations, and Pilcher Quartzite in the southern part of the Belt basin at about 1.16 and 1.05 Ga. Younger xenotime overgrowths in these formations and monazite in the Prichard Formation grew during the Cretaceous orogeny at about 112-105 Ma.

SHRIMP U-Pb geochronology of xenotime overgrowths on detrital zircon also reveals that the xenotime formed by a number of processes including: (1) diagenesis (Prichard Formation age of deposition is about 1462 ± 6 Ma), (2) metamorphism/diagenesis (McNamara and Garnet Range Formations, and Pilcher Quartzite ages of metamorphism are about 1.16 and 1.05 Ga), (3) hydrothermal activity (xenotime overgrowths in the Revett Formation formed locally at the Spar Lake Cu-Ag deposit), and (4) magmatism (origin of detrital xenotime grains in several samples). Because of the possible occurrence of multiple age components of xenotime overgrowths, high contrast/low brightness BSE imagery was necessary to interpret discordant arrays of U-Pb data, particularly for xenotime of metamorphic origin.

Xenotime overgrowths of each origin yield distinctive REE patterns. The REE distributions in xenotime overgrowths are similar to data from xenotime of known origin from other studies. Thus, the combination of SHRIMP U-Pb dating and trace element analysis is a powerful tool for understanding ages of deposition and subsequent events within sedimentary successions.

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FIGURE CAPTIONS

Fig. 1 Simplified geologic map (modified from Winston and Link, 1993; Evans et al., 2000). H, Helena, M, Missoula, S, Salmon, Sp, Spokane.

Fig. 2 Stratigraphic column for the Belt Supergroup (modified from Evans et al., 2000).

Fig. 3 Images and age data for samples of detrital zircon. A. CL image of representative detrital zircon from the Pilcher Quartzite. B. CL image of representative detrital zircon from the Prichard Formation. C. Concordia plots of U-Pb data from detrital zircon Belt Supergroup samples.

Fig. 4 Relative Probability plots for detrital zircon data. Bold curves show data from this study; shaded curves show previously published data. For clarity, two curves of Prichard Formation U-Pb data (Lewis et al., 2010) are shown below Prichard data from this study.

Fig. 5 Prichard Formation monazite images and plots. A. BSE images of monazite grains, showing zoned cores and unzoned rims. White ellipses indicate size and location of SHRIMP spot. Values indicate ages in Ma with 1-sigma errors. B. Plot showing geochemical differences between monazite cores and rims, plus two analyses of grains interpreted as detrital in origin. C. Concordia plot showing all analyses of Prichard monazite. D. Inset from C, showing two groupings of Cretaceous age data. White-filled ellipses are data from cores; gray-filled ellipses are data from rims. E. Weighted average plot of $^{206}\text{Pb}/^{238}\text{U}$ ages of cores (white-filled 2-sigma error bars). Gray-filled error bars are $^{206}\text{Pb}/^{238}\text{U}$ ages of rims.

Fig. 6 Images and plots of age data from xenotime of the Prichard Formation. A. BSE images of the same grain. Above, normal BSE settings showing faint zoning in light gray zircon and white xenotime overgrowth. Below, image adjusted to high contrast-low brightness to display heterogeneous zoning in rim xenotime. B. Representative zircon grains with xenotime overgrowths. Above, xenotime overgrowths (white) that have become a cement between closely spaced detrital zircon grains. Below, relatively large xenotime overgrowth. Ellipses indicate size and location of SHRIMP spots. Values indicate ages in Ma with 1-sigma errors. C. Concordia plot of U-Pb data from xenotime overgrowths. White-filled ellipses are data used for age calculation; gray-filled ellipses excluded from age calculation because the errors are large and (or) the data are discordant or young (see D). D. Weighted average plot of $^{207}\text{Pb}/^{206}\text{Pb}$ ages. Only white-filled 2-sigma error bars used for age calculation. Horizontal gray line represents the weighted average of all 10 $^{207}\text{Pb}/^{206}\text{Pb}$ ages. However, because the xenotime overgrowths may contain multiple age components, the weighted average of the 3 oldest ages is considered to be the minimum age of deposition.

Fig. 7 Images and plots of age data from xenotime of the McNamara Formation. A. BSE image of detrital zircon grain with xenotime overgrowth. Although most of the overgrowth is

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white, a discontinuous innermost area is darker gray, suggestive of an older component (perhaps the original diagenetic overgrowth). Ellipse indicates size and location of SHRIMP spot. Value indicates age in Ma with 1-sigma error. B. Concordia plot of U-Pb data from xenotime overgrowths. Inset shows weighted average of three $^{207}\text{Pb}/^{206}\text{Pb}$ ages (white error ellipses only).

Fig. 8 Images and plots of age data from xenotime of the Garnet Range Formation and Pilcher Quartzite. A. BSE images of xenotime from Garnet Range Formation. Left, individual grain of detrital xenotime (lacking a zircon core). Right, xenotime overgrowths showing faint zoning. Grain farthest right has darker gray, irregular, discontinuous inner zone perhaps representing an earlier episode of xenotime formation. Ellipses indicate size and location of SHRIMP spots. Values indicate ages in Ma with 1-sigma errors. B. Concordia plot of U-Pb data from Garnet Range xenotime. Gray-filled error ellipses represent analyses of detrital xenotime. White-filled ellipses represent xenotime of metamorphic origin. Dispersed array of data is suggestive of mixing of two (or more) age components. Inset shows the weighted average of eight $^{207}\text{Pb}/^{206}\text{Pb}$ ages. C. BSE images of xenotime from Pilcher Quartzite. Upper left, xenotime overgrowth on detrital zircon. Lower left, magnified view of overgrowth with contrast and brightness adjusted to maximize heterogeneous zoning. Location of SHRIMP spot indicates overlap of inner and outer zones, suggesting a mixed age. Right, xenotime overgrowth with homogeneous zoning. D. Concordia plot of U-Pb data from Pilcher xenotime. Black error ellipses have similar, older $^{207}\text{Pb}/^{206}\text{Pb}$ ages. Inset shows weighted average age of $^{207}\text{Pb}/^{206}\text{Pb}$ ages of eight least discordant analyses (white-filled error ellipses). See text for further explanation.

Fig. 9 Trace element data for xenotime from the Belt Supergroup. A-C — Binary plots of trace element data for 4 types of xenotime—diagenetic (Prichard), hydrothermal (Revett; Aleinikoff et al., 2012b), metamorphic (Pilcher), and detrital (Revett; Aleinikoff et al., 2012b). Square symbols with “x” (Pilcher) from xenotime samples that yielded the least discordant U-Pb data, i.e., white-filled error ellipses in Fig. 8D. D-F — REE patterns for xenotime. D — Hydrothermal xenotime (gray field); detrital xenotime (individual curves). All data from Revett (Aleinikoff et al., 2012b). Green dashed curve shows REE pattern for igneous xenotime from Wendell pegmatite. Red field shows data array for hydrothermal xenotime from the Witwatersrand Basin, South Africa. E — Diagenetic xenotime (Prichard). Note flattening of HREE part of curves. Red field shows data array for diagenetic xenotime from the Witwatersrand basin, South Africa. F — Metamorphic xenotime (Pilcher). Individual curves from 8 least discordant xenotime analyses; gray field is all other Pilcher xenotime samples. Note extremely low LREE and decreasing HREE. Red field shows data array for metamorphic xenotime from Sestri-Voltaggio Zone, Italy. Green field shows normalized REE abundances in upper Belt sandstones (calculated from data in Gonzalez-Alvarez and Kerrich, 2010).

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Prichard Formation monazite images and plots. A. BSE images of monazite grains, showing zoned cores and unzoned rims. White ellipses indicate size and location of SHRIMP spot. Values indicate ages in Ma with 1-sigma errors. B. Plot showing geochemical differences between monazite cores and rims, plus two analyses of grains interpreted as detrital in origin. C. Concordia plot showing all analyses of Prichard monazite. D. Inset from C, showing two groupings of Cretaceous age data. White-filled ellipses are data from cores; gray-filled ellipses are data from rims. E. Weighted average plot of $^{206}\text{Pb}/^{238}\text{U}$ ages of cores (white-filled 2-sigma error bars). Gray-filled error bars are $^{206}\text{Pb}/^{238}\text{U}$ ages of rims.

Figure 6

Images and plots of age data from xenotime of the Prichard Formation. A. BSE images of the same grain. Above, normal BSE settings showing faint zoning in light gray zircon and white xenotime overgrowth. Below, image adjusted to high contrast-low brightness to display heterogeneous zoning in rim xenotime. B. Representative zircon grains with xenotime overgrowths. Above, xenotime overgrowths (white) that have become cement between closely spaced detrital zircon grains. Below, relatively large xenotime overgrowth. Ellipses indicate size and locations of SHRIMP spots. Values indicate ages in Ma with 1-sigma errors. C. Concordia plot of U-Pb data from xenotime overgrowths. White-filled ellipses are data used for age calculation; gray-filled ellipses excluded from age calculation because the errors are large and (or) the data are discordant or young (see D). D. Weighted average plot of $^{207}\text{Pb}/^{206}\text{Pb}$ ages. Only white-filled 2-sigma error bars used for age calculation. Horizontal gray line represents the weighted average of all 10 $^{207}\text{Pb}/^{206}\text{Pb}$ ages. However, because the xenotime overgrowths may contain multiple age components, the weighted average of the 3 oldest ages is considered to be the minimum age of deposition.

279x361mm (300 x 300 DPI)

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Figure 7

Images and plots of age data from xenotime of the McNamara Formation. A. BSE image of detrital zircon grain with xenotime overgrowth. Although most of the overgrowth is white, a discontinuous innermost area is darker gray, suggestive of an older component (perhaps the original diagenetic overgrowth). Ellipse indicates size and location of SHRIMP spot. Value indicates age in Ma with 1-sigma error. B. Concordia plot of U-Pb data from xenotime overgrowths. Inset shows weighted average of three $^{207}\text{Pb}/^{206}\text{Pb}$ ages (white error ellipses only).

279x361mm (300 x 300 DPI)

Figure 8

Images and plots of age data from xenotime of the Garnet Range Formation and Pilcher Quartzite. A. BSE images of xenotime from Garnet Range Formation. Left, individual grain of detrital xenotime (lacking a zircon core). Right, xenotime overgrowths showing faint zoning. Grain farthest right has darker gray, irregular, discontinuous inner zone perhaps representing an earlier episode of xenotime formation. Ellipses indicate size and locations of SHRIMP spots. Values indicate ages in Ma with 1-sigma errors. B. Concordia plot of U-Pb data from Garnet Range xenotime. Gray-filled error ellipses represent analyses of detrital xenotime. White-filled ellipses represent xenotime of metamorphic origin. Dispersed array of data is suggestive of mixing of two (or more) age components. Inset shows weighted average of eight $^{207}\text{Pb}/^{206}\text{Pb}$ ages. C. BSE images of xenotime from Pilcher Quartzite. Upper left, xenotime overgrowth on detrital zircon. Lower left, magnified view of overgrowth with contrast and brightness adjusted to maximize heterogeneous zoning. Location of SHRIMP spot indicates overlap of inner and outer zones, suggesting a mixed age. Right, xenotime overgrowth with homogeneous zoning. D. Concordia plot of U-Pb data from Pilcher xenotime. Black error ellipses have similar, older $^{207}\text{Pb}/^{206}\text{Pb}$ ages. Inset shows weighted average age of $^{207}\text{Pb}/^{206}\text{Pb}$ ages of eight least discordant analyses (white-filled error ellipses). See text for further explanation.

215x166mm (300 x 300 DPI)

Figure 9

Trace element data for xenotime from the Belt Supergroup. A-C. Binary plots of trace element data for 4 types of xenotime—diagenetic (Prichard), hydrothermal (Revett; Aleinikoff et al. 2012b), metamorphic (Pilcher), and detrital (Revett; Aleinikoff et al. 2012b). Square symbols with "x" (Pilcher) from xenotime samples that yielded the least discordant U-Pb data, i.e., white-filled error ellipses in Fig. 8D. D-F. REE patterns for xenotime. D. Hydrothermal xenotime (gray field); detrital xenotime (individual curves). All data from Revett (Aleinikoff et al., 2012b). Green dashed curve shows REE pattern for igneous xenotime from Wendell pegmatite. Red field shows data array for hydrothermal xenotime from the Witwatersrand Basin, South Africa. E. Diagenetic xenotime (Prichard). Note flattening of HREE part of curves. Red field shows data array for diagenetic xenotime from the Witwatersrand basin, South Africa. F. Metamorphic xenotime (Pilcher). Individual curves from 8 least discordant xenotime analyses; gray field is all other Pilcher xenotime samples. Note extremely low LREE and decreasing HREE. Red field shows data array for metamorphic xenotime from Sestri-Voltaggio Zone, Italy. Green field shows normalized REE abundances in upper Belt sandstones (calculated from data in Gonzalez-Alvarez and Kerrich 2010).

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Table 1. SHRIMP U-Th-Pb data for detrital zircon from Mesoproterozoic Belt Supergroup, western Montana.

sample ¹	measured $\frac{^{204}\text{Pb}}{^{206}\text{Pb}}$	measured $\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	% common ^{206}Pb	U (ppm)	Th/U	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$ ² (Ma)	err ³ (Ma)	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$ ^{2,3} (Ma)	err ⁴ (Ma)	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$ ⁵	err ⁴ (%)	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$ ⁵	err ⁴ (%)	□
BB-32 (Prichard Formation) location: 47.3175°, -114.8042°														
BB32-1.1	-0.000006	0.0945	-0.01	278	0.75	1668.5	16.8	1520	17	3.81	1.4	0.2924	1.0	0.743
BB32-2.1	0.000068	0.0982	0.12	395	0.29	1638.4	15.6	1572	16	3.86	1.3	0.2880	1.0	0.755
BB32-3.1	0.000070	0.0923	0.13	257	0.77	1497.8	16.0	1454	22	3.29	1.6	0.2608	1.1	0.688
BB32-4.1	0.000174	0.1027	0.31	131	0.60	1717.2	26.3	1631	30	4.20	2.2	0.3033	1.5	0.694
BB32-5.1	0.000097	0.1079	0.18	276	0.51	1617.5	17.0	1741	20	4.23	1.5	0.2878	1.1	0.688
BB32-6.1	0.000760	0.1005	1.37	55	1.21	1292.5	25.1	1422	96	2.77	5.4	0.2237	2.0	0.371
BB32-7.1	0.000172	0.0935	0.31	264	1.25	1360.4	14.8	1449	31	2.97	2.0	0.2362	1.1	0.563
BB32-8.1	0.000026	0.1031	0.05	1278	0.59	1590.7	14.2	1674	9	3.99	1.0	0.2815	0.9	0.887
BB32-9.1	0.000135	0.1049	0.24	144	0.73	1578.6	18.6	1680	32	3.97	2.1	0.2795	1.2	0.565
BB32-10.1	0.000117	0.1060	0.21	198	0.86	1689.8	17.9	1703	22	4.32	1.6	0.3000	1.1	0.662
BB32-11.1	0.000057	0.1014	0.10	518	0.69	1593.9	14.8	1636	15	3.90	1.2	0.2813	0.9	0.765
BB32-12.1	0.000375	0.1018	0.68	241	2.05	1582.3	17.0	1560	35	3.70	2.2	0.2778	1.1	0.501
BB32-13.1	0.000121	0.1001	0.22	201	0.63	1556.8	17.2	1595	27	3.72	1.8	0.2739	1.1	0.608
BB32-14.1	0.000168	0.0994	0.30	405	0.13	1649.0	18.1	1568	21	3.88	1.6	0.2899	1.1	0.712
BB32-15.1	0.000056	0.0953	0.10	728	0.14	1499.9	13.8	1519	13	3.42	1.2	0.2623	0.9	0.811
BB32-16.1	0.000291	0.0993	0.53	128	0.46	1558.2	18.3	1533	39	3.59	2.4	0.2730	1.2	0.497
BB32-17.1	0.000453	0.0972	0.82	42	1.18	1470.5	24.8	1444	76	3.21	4.4	0.2558	1.7	0.397
BB32-18.1	0.000219	0.0954	0.40	154	0.36	1609.3	18.0	1475	33	3.58	2.1	0.2811	1.1	0.542
BB32-19.1	0.000245	0.1062	0.44	144	0.86	1690.1	21.3	1676	35	4.25	2.3	0.2994	1.3	0.555
BB32-20.1	0.000409	0.1023	0.74	147	1.74	1547.4	18.0	1560	52	3.62	3.0	0.2715	1.2	0.397
BB32-21.1	0.000101	0.1109	0.18	540	0.16	1813.2	17.0	1791	13	4.89	1.2	0.3242	0.9	0.790
BB32-22.1	0.000348	0.1034	0.63	151	0.74	1675.3	19.3	1598	44	4.01	2.6	0.2952	1.2	0.447
BB32-23.1	0.000066	0.1011	0.12	416	0.11	1616.5	15.6	1628	15	3.94	1.3	0.2852	1.0	0.773
BB32-24.1	0.000128	0.1043	0.23	193	0.37	1702.3	17.8	1670	21	4.26	1.6	0.3015	1.1	0.678
BB32-25.1	0.000030	0.1581	0.05	558	0.02	2501.9	30.6	2432	22	10.22	1.6	0.4697	1.0	0.609
BB32-26.1	0.000833	0.1035	1.50	115	1.20	1471.0	18.3	1466	72	3.25	4.0	0.2562	1.3	0.323
BB32-27.1	0.000345	0.1023	0.62	297	0.48	1643.9	16.8	1577	46	3.89	2.6	0.2891	1.0	0.388
BB32-28.1	0.000777	0.1109	1.40	121	0.57	1574.1	36.6	1628	68	3.84	4.4	0.2776	2.4	0.546
BB32-29.1	0.000412	0.1038	0.74	153	0.61	1674.0	18.7	1588	34	3.99	2.2	0.2947	1.1	0.525
BB32-30.1	0.000015	0.1000	0.03	541	0.21	1620.0	15.4	1621	13	3.93	1.2	0.2857	1.0	0.820
BB32-31.1	0.000117	0.1100	0.21	938	0.56	1968.0	18.4	1773	11	5.25	1.1	0.3512	0.9	0.841
BB32-32.1	0.000080	0.1114	0.15	482	0.50	1828.5	17.2	1805	12	4.98	1.1	0.3273	0.9	0.815
BB32-33.1	0.000137	0.1105	0.25	277	0.19	1858.7	18.9	1776	18	4.97	1.4	0.3320	1.0	0.718
BB32-34.1	0.000170	0.1050	0.31	218	0.79	1726.8	18.0	1673	24	4.33	1.7	0.3059	1.1	0.636
BB32-35.1	0.000383	0.1012	0.69	287	0.36	1614.8	16.2	1545	34	3.74	2.1	0.2833	1.0	0.494
BB32-36.1	0.000547	0.1027	0.99	256	0.40	1675.3	17.0	1529	37	3.85	2.2	0.2938	1.0	0.468
BB32-37.1	0.000623	0.1095	1.12	142	0.79	1722.5	21.1	1641	46	4.24	2.8	0.3045	1.2	0.448

BB32-38.1	0.000087	0.1016	0.16	318	1.03	1686.0	16.6	1632	21	4.12	1.5	0.2978	1.0	0.659
BB32-39.1	0.000159	0.1005	0.29	722	0.52	1635.2	15.3	1592	16	3.90	1.3	0.2879	0.9	0.744
BB32-40.1	0.000639	0.1085	1.15	140	0.74	1614.5	19.3	1619	50	3.91	2.9	0.2847	1.2	0.414
BB32-41.1	0.001023	0.1369	1.85	107	1.43	1953.9	26.0	2003	58	6.04	3.5	0.3556	1.2	0.357
BB32-42.1	0.000404	0.1203	0.73	215	1.21	1882.0	21.2	1878	27	5.37	1.9	0.3389	1.1	0.596
BB32-43.1	0.000079	0.0929	0.14	823	0.91	1614.1	14.5	1464	12	3.57	1.1	0.2817	0.9	0.811
BB32-44.1	0.000324	0.1045	0.58	262	0.90	1699.7	17.1	1625	27	4.14	1.8	0.3001	1.0	0.579
BB32-45.1	0.000271	0.0989	0.49	119	2.04	1679.0	21.5	1531	47	3.86	2.8	0.2945	1.3	0.467
BB32-46.1	0.000321	0.0964	0.58	343	0.74	1738.1	17.6	1466	28	3.85	1.8	0.3037	1.0	0.570
BB32-47.1	0.000049	0.0981	0.09	762	0.04	1683.2	15.2	1574	11	3.98	1.1	0.2961	0.9	0.841
BB32-48.1	0.000172	0.1093	0.31	486	0.26	1780.1	16.8	1749	16	4.68	1.3	0.3173	0.9	0.743
BB32-49.1	0.000388	0.1033	0.70	101	0.57	1601.9	19.5	1586	43	3.81	2.6	0.2818	1.2	0.473
BB32-50.1	0.000065	0.1103	0.12	285	0.15	1871.0	19.8	1789	16	5.05	1.4	0.3345	1.0	0.763
BB32-1.1el	0.000064	0.0990	0.10	144	0.59	1673.0	18.1	1588	19	3.99	1.5	0.2947	1.1	0.737
BB32-2.1el	0.000048	0.0967	0.08	219	0.99	1600.6	14.4	1548	13	3.72	1.1	0.2809	0.9	0.810
BB32-3.1el	0.000033	0.1007	0.05	116	1.19	1609.4	16.7	1629	19	3.93	1.5	0.2839	1.1	0.727
BB32-4.1el	0.000474	0.0815	0.80	450	0.06	259.6	2.6	1061	55	0.44	2.9	0.0422	1.0	0.354
BB32-5.1el	-0.000032	0.1024	-0.05	83	0.62	1621.1	18.7	1675	19	4.07	1.6	0.2869	1.2	0.760
BB32-6.1el	-0.000016	0.0993	-0.02	100	1.05	1641.6	17.9	1616	16	3.97	1.4	0.2896	1.1	0.793
BB32-7.1el	0.000094	0.1000	0.15	204	0.31	1617.8	14.6	1600	14	3.88	1.2	0.2849	0.9	0.773
BB32-7.2el	0.000019	0.0991	0.03	1049	0.13	1782.5	13.0	1602	6	4.29	0.8	0.3148	0.7	0.926
BB32-8.1el	0.000065	0.0987	0.10	95	0.58	1672.8	18.8	1582	18	3.97	1.5	0.2946	1.1	0.761
BB32-9.1el	0.000034	0.1008	0.05	340	4.36	1680.5	13.8	1630	9	4.11	1.0	0.2969	0.8	0.855
BB32-10.1el	0.000028	0.0987	0.05	534	0.01	1707.4	13.2	1592	8	4.08	0.9	0.3010	0.8	0.878
BB32-11.1el	0.000035	0.1099	0.06	247	0.37	1831.5	16.1	1789	10	4.94	1.0	0.3276	0.9	0.854
BB32-12.1el	-0.000001	0.0993	0.00	187	0.76	1610.0	15.8	1611	14	3.88	1.2	0.2837	1.0	0.809
BB32-13.1el	0.000021	0.0962	0.03	381	1.40	1565.6	12.4	1547	14	3.63	1.1	0.2746	0.8	0.729
BB32-14.1el	0.000435	0.0555	0.80	276	0.02	170.3	4.0			0.18	12.6	0.0268	2.5	0.197
BB32-15.1el	0.000012	0.0985	0.02	132	0.58	1616.6	16.3	1593	14	3.86	1.3	0.2846	1.0	0.801
BB32-16.1el	0.000073	0.1013	0.12	187	2.61	1672.2	15.6	1630	13	4.08	1.2	0.2954	1.0	0.799
BB32-17.1el	0.000165	0.0992	0.26	93	0.75	1583.9	18.2	1566	26	3.72	1.8	0.2782	1.2	0.655
BB32-18.1el	0.000204	0.0486	0.38	500	0.00	122.0	1.4			0.12	4.5	0.0190	1.2	0.257
BB32-19.1el	-0.000006	0.0957	-0.01	96	0.50	1546.3	17.4	1543	17	3.58	1.5	0.2710	1.2	0.788
BB32-20.1el	-0.000012	0.1007	-0.02	168	0.65	1617.6	15.5	1639	18	3.97	1.4	0.2856	1.0	0.715
BB32-21.1el	0.000079	0.0484	0.15	539	0.00	129.6	1.4			0.13	5.8	0.0203	1.1	0.197
BB32-22.1el	0.000156	0.0997	0.25	166	0.94	1672.9	17.7	1578	23	3.96	1.6	0.2945	1.1	0.660
BB32-23.1el	0.000043	0.1213	0.07	66	1.20	1894.8	24.2	1966	17	5.72	1.6	0.3435	1.3	0.803
BB32-24.1el	-0.000026	0.0958	-0.04	365	0.17	1598.4	14.0	1551	9	3.72	1.0	0.2806	0.9	0.875
BB32-25.1el	0.000040	0.0985	0.06	433	0.03	1640.8	13.9	1585	9	3.90	1.0	0.2888	0.9	0.875
BB32-25.2el	-0.000004	0.0999	-0.01	135	1.02	1697.5	17.6	1624	15	4.13	1.3	0.2998	1.1	0.805
BB32-26.1el	0.000214	0.0923	0.35	51	1.22	1531.8	22.3	1411	51	3.28	3.1	0.2664	1.5	0.495
BB32-27.1el	0.000020	0.0998	0.03	163	0.82	1574.7	15.1	1615	14	3.81	1.2	0.2774	1.0	0.803
BB32-28.1el	-0.000022	0.0921	-0.04	1030	0.08	306.8	2.4	1477	13	0.65	1.0	0.0510	0.8	0.752
BB32-28.2el	-0.000006	0.0500	-0.01	628	0.01	118.7	1.6			0.13	1.8	0.0186	1.3	0.738

mBB32-1.1	0.000199	0.0499	0.21	4034	5.1	112.4	1.6			0.11	2.9	0.0176	1.5	0.511
mBB32-2.1	0.000296	0.0518	0.45	4465	7.0	109.5	1.6			0.11	2.9	0.0171	1.5	0.508
mBB32-3.1	0.000212	0.0506	0.28	3252	10.7	114.6	1.9			0.12	3.3	0.0179	1.6	0.499
mBB32-4.1	0.000277	0.0503	0.26	4085	5.3	111.7	1.7			0.11	3.3	0.0174	1.5	0.466
mBB32-5.1	0.000239	0.0504	0.27	6771	4.9	111.1	1.6			0.11	2.8	0.0174	1.5	0.537
mBB32-6.1	0.000117	0.0507	0.31	3965	5.3	111.9	1.7			0.12	2.9	0.0175	1.5	0.531
mBB32-7.1	0.000249	0.0490	0.09	3680	4.6	113.9	1.7			0.11	3.5	0.0178	1.5	0.435
mBB32-8.1	0.000072	0.0960	0.07	1361	30.6	1536.6	29.0	1529	10	3.53	2.0	0.2690	2.0	0.966
mBB32-9.1	0.000214	0.0513	0.38	5057	6.2	114.3	1.7			0.12	2.6	0.0179	1.5	0.573
mBB32-9.2	0.001301	0.0579	1.23	936	26.3	105.5	2.0			0.09	17.7	0.0163	2.1	0.116
mBB32-10.1	0.000021	0.0740	-0.26	1666	14.4	1099.8	17.0	1032	11	1.88	1.7	0.1855	1.6	0.945
mBB32-11.1	0.000201	0.0508	0.32	4341	5.0	110.7	1.7			0.11	3.7	0.0173	1.5	0.413
mBB32-12.1	0.000215	0.0513	0.39	5171	5.1	109.3	1.6			0.11	2.9	0.0171	1.5	0.520
mBB32-13.1	0.000742	0.0511	0.37	2124	17.0	107.1	1.8			0.09	8.8	0.0166	1.7	0.195
mBB32-14.1	0.000107	0.0506	0.30	7283	4.2	109.6	1.6			0.12	2.3	0.0172	1.5	0.644
mBB32-15.1	0.000314	0.0508	0.32	4399	5.4	111.5	1.7			0.11	3.1	0.0174	1.6	0.516
mBB32-16.1	0.000275	0.0508	0.32	6171	6.3	111.4	1.7			0.11	2.9	0.0174	1.5	0.513
mBB32-17.1	0.000460	0.0505	0.29	2009	14.1	106.6	1.8			0.10	6.8	0.0166	1.7	0.250
mBB32-18.1	0.000189	0.0513	0.39	5448	5.0	107.9	1.6			0.11	2.8	0.0169	1.5	0.534
mBB32-19.1	0.000268	0.0503	0.27	4239	7.5	110.4	1.7			0.11	3.6	0.0172	1.6	0.432
mBB32-20.1	0.000118	0.0502	0.26	5437	4.8	107.4	1.6			0.11	2.8	0.0168	1.5	0.547
mBB32-21.1	0.000259	0.0504	0.27	6692	2.5	110.6	1.6			0.11	2.8	0.0173	1.5	0.531
mBB32-22.1	0.000222	0.0503	0.27	6162	4.5	107.9	1.6			0.11	3.2	0.0169	1.5	0.486
mBB32-23.1	0.000229	0.0510	0.34	4555	6.9	112.0	1.8			0.11	3.1	0.0175	1.6	0.509

MC-3-03 (McNamara Formation) location: 46.2442°, -113.3228°														
MC-1.1	-0.000026	0.1042	-0.04	123	0.56	1571.0	26.1	1707	23	4.01	2.1	0.2783	1.7	0.810
MC-2.1	0.000569	0.1104	0.90	912	0.67	736.0	10.6	1672	22	1.79	1.9	0.1264	1.5	0.780
MC-3.1	0.000020	0.1838	0.03	113	0.94	2843.2	58.4	2685	12	13.74	1.9	0.5428	1.7	0.917
MC-4.1	-0.000032	0.0904	-0.05	182	0.28	1460.1	22.8	1444	22	3.18	2.0	0.2540	1.6	0.817
MC-5.1	0.000786	0.1136	1.24	856	0.68	672.8	9.7	1676	26	1.63	2.1	0.1152	1.5	0.723
MC-6.1	0.000700	0.1122	1.11	1255	0.44	595.1	8.5	1672	23	1.44	1.9	0.1015	1.5	0.756
MC-7.1	0.000477	0.1140	0.75	350	0.79	1206.5	17.7	1757	23	3.15	2.0	0.2122	1.5	0.773
MC-8.1	0.000148	0.1866	0.20	261	0.74	2144.4	33.2	2696	9	10.63	1.6	0.4174	1.5	0.938
MC-9.1	0.000820	0.1136	1.30	946	1.11	714.0	10.2	1667	41	1.73	2.7	0.1224	1.5	0.561
MC-10.1	0.000045	0.1089	0.07	181	0.40	1795.4	28.3	1771	18	4.79	1.9	0.3206	1.6	0.859
MC-11.1	0.000012	0.0914	0.02	322	0.50	1488.3	22.1	1450	16	3.26	1.7	0.2591	1.5	0.880
MC-12.1	0.000000	0.0908	0.00	180	0.46	1495.5	23.5	1443	20	3.26	1.9	0.2603	1.6	0.834
MC-13.1	0.000182	0.0918	0.30	350	0.84	1245.5	18.3	1411	24	2.65	2.0	0.2150	1.5	0.778
MC-14.1	0.000021	0.1082	0.03	243	0.33	1774.1	27.2	1764	15	4.71	1.8	0.3166	1.6	0.891
MC-15.1	0.000409	0.1082	0.65	598	0.69	957.9	13.8	1672	21	2.35	1.9	0.1660	1.5	0.793
MC-16.1	0.000018	0.1621	0.03	155	0.37	2433.1	41.7	2476	11	10.28	1.8	0.4606	1.6	0.922
MC-17.1	-0.000003	0.0972	0.00	216	0.45	1421.1	21.7	1572	18	3.34	1.9	0.2488	1.6	0.854
MC-18.1	0.000035	0.1043	0.06	190	0.48	1705.9	26.6	1693	17	4.33	1.9	0.3027	1.6	0.863
MC-19.1	0.000000	0.1078	0.00	431	0.20	1763.0	25.9	1762	11	4.67	1.6	0.3145	1.5	0.933

MC-20.1	0.000005	0.1043	0.01	287	0.28	1752.0	26.4	1701	13	4.47	1.7	0.3112	1.5	0.903
MC-21.1	0.000443	0.1098	0.70	728	0.32	1007.3	14.3	1691	18	2.50	1.8	0.1752	1.5	0.833
MC-22.1	0.000012	0.1861	0.02	160	1.02	2699.9	49.3	2707	10	13.35	1.7	0.5206	1.6	0.937
MC-23.1	0.000065	0.1043	0.10	413	0.76	1691.6	24.8	1686	13	4.28	1.7	0.2999	1.5	0.907
MC-24.1	0.000156	0.1060	0.25	707	0.66	1091.2	15.5	1694	13	2.73	1.6	0.1904	1.5	0.901
MC-25.1	0.000212	0.1104	0.33	596	0.61	1322.2	18.9	1758	14	3.46	1.7	0.2335	1.5	0.887
MC-26.1	0.000008	0.1871	0.01	209	0.82	2357.8	38.2	2716	9	11.85	1.7	0.4594	1.6	0.942
MC-27.1	0.000034	0.1140	0.05	379	0.46	1666.2	24.4	1857	13	4.68	1.7	0.2987	1.5	0.904
MC-28.1	0.000446	0.1118	0.70	748	0.59	812.9	11.6	1728	23	2.05	1.9	0.1405	1.5	0.769
MC-29.1	0.000059	0.1057	0.09	321	0.28	1644.3	24.4	1712	15	4.22	1.7	0.2918	1.5	0.888
MC-30.1	0.000547	0.1310	0.83	1384	0.56	662.4	9.4	2010	14	1.98	1.7	0.1159	1.5	0.873
MC-31.1	0.000030	0.1067	0.05	223	0.39	1661.5	25.4	1737	16	4.33	1.8	0.2954	1.6	0.875
MC-32.1	0.000170	0.1053	0.27	655	0.21	1284.8	18.3	1678	13	3.20	1.6	0.2255	1.5	0.898
MC-33.1	0.000052	0.1085	0.08	189	0.35	1795.6	28.3	1762	18	4.76	1.9	0.3205	1.6	0.852
MC-34.1	0.000000	0.1060	0.00	252	0.23	1720.3	26.3	1731	15	4.47	1.8	0.3061	1.6	0.890
MC-35.1	0.000030	0.0915	0.05	138	0.57	1435.8	23.3	1449	25	3.14	2.1	0.2497	1.7	0.790
MC-36.1	0.000063	0.1058	0.10	291	0.92	1710.2	25.8	1713	15	4.40	1.7	0.3039	1.5	0.887
MC-37.1	0.000042	0.1068	0.07	211	0.36	1748.4	26.9	1735	17	4.56	1.8	0.3113	1.6	0.862
MC-38.1	0.000087	0.0913	0.14	155	0.41	1481.9	23.6	1427	26	3.20	2.1	0.2577	1.6	0.775
MC-39.1	0.000021	0.1087	0.03	180	0.42	1797.0	28.2	1773	16	4.80	1.8	0.3210	1.6	0.876
MC-40.1	-0.000024	0.1043	-0.04	293	0.47	1652.6	24.8	1708	14	4.23	1.7	0.2932	1.5	0.899
MC-41.1	0.000048	0.1038	0.08	167	0.47	1617.9	25.5	1681	19	4.07	1.9	0.2864	1.6	0.838
MC-42.1	-0.000084	0.0906	-0.14	88	0.79	1467.0	25.5	1462	32	3.23	2.5	0.2555	1.8	0.731
MC-43.1	0.000168	0.1818	0.23	434	0.66	1965.3	28.9	2651	9	9.42	1.6	0.3801	1.5	0.937
MC-44.1	-0.000026	0.0906	-0.04	210	0.40	1469.5	22.5	1447	20	3.21	1.9	0.2557	1.6	0.833
MC-45.1	0.000063	0.1068	0.10	196	0.56	1566.2	24.2	1731	19	4.06	1.9	0.2779	1.6	0.837
MC-46.1	0.000048	0.1068	0.07	329	0.36	1705.6	25.3	1734	14	4.44	1.7	0.3034	1.5	0.900
MC-47.1	-0.000083	0.1049	-0.13	111	0.51	1790.8	30.2	1733	24	4.66	2.2	0.3190	1.7	0.797
MC-48.1	0.000741	0.1144	1.17	932	0.98	693.6	9.9	1702	23	1.71	1.9	0.1191	1.5	0.769
MC-49.1	0.000195	0.1074	0.31	463	0.74	1570.7	22.7	1710	14	4.02	1.7	0.2783	1.5	0.888
MC-50.1	0.000166	0.1067	0.26	623	0.54	1244.9	17.7	1705	13	3.15	1.6	0.2185	1.5	0.902
MC-51.1	0.000000	0.1119	0.00	121	0.41	1714.7	26.3	1830	22	4.74	2.0	0.3075	1.5	0.781
MC-52.1	0.000054	0.1718	0.10	313	0.71	1899.1	11.5	2569	10	8.72	0.8	0.3697	0.6	0.684
MC-53.1	-0.000062	0.1061	-0.11	84	0.57	1762.1	39.1	1748	28	4.63	2.7	0.3140	2.2	0.822
MC-54.1	-0.000013	0.1045	-0.02	96	0.48	1661.8	3.8	1709	26	4.26	1.4	0.2951	0.1	0.082
MC-55.1	0.000000	0.0904	0.00	147	0.36	1356.6	13.6	1434	27	2.93	1.8	0.2353	1.0	0.580
MC-56.1	0.000021	0.0921	0.04	128	0.57	1402.8	22.2	1463	28	3.09	2.2	0.2440	1.6	0.736
MC-57.1	0.000341	0.1181	0.62	178	1.86	1040.8	10.6	1856	45	2.89	2.7	0.1844	1.1	0.398
MC-58.1	0.000019	0.1270	0.03	186	0.92	1837.8	6.5	2054	16	5.88	0.9	0.3363	0.3	0.336
MC-59.1	0.000061	0.1052	0.11	86	0.67	1753.8	3.6	1703	29	4.48	1.6	0.3115	0.1	0.045
MC-60.1	0.000019	0.1064	0.03	207	0.63	1695.5	18.9	1734	18	4.41	1.5	0.3017	1.1	0.751
MC-61.1	0.000035	0.1048	0.06	361	0.84	1661.4	4.5	1702	15	4.24	0.9	0.2949	0.3	0.291
MC-62.1	0.000000	0.1090	0.00	81	0.16	1769.0	24.3	1783	28	4.75	2.0	0.3161	1.4	0.670
MC-63.1	-0.000087	0.1126	-0.16	63	0.44	1820.2	19.2	1861	33	5.14	2.1	0.3274	1.0	0.492
MC-64.1	-0.000019	0.0887	-0.03	84	0.78	1402.2	31.1	1403	35	2.98	2.9	0.2430	2.3	0.780

MC-65.1	0.000104	0.1521	0.19	71	1.77	2228.6	40.5	2355	23	8.71	2.1	0.4192	1.7	0.781
GR-4-03 (Garnet Range Formation) location: 46.2451°, -113.3297°														
GR-1.1	0.000083	0.1060	0.13	623	0.44	958.7	13.8	1713	14	2.41	1.7	0.1666	1.5	0.892
GR-2.1	0.000065	0.1044	0.10	163	0.30	1762.1	28.3	1688	20	4.46	2.0	0.3128	1.6	0.828
GR-3.1	0.000151	0.1042	0.24	574	0.97	765.8	11.1	1663	18	1.85	1.8	0.1316	1.5	0.840
GR-4.1	-0.000016	0.1065	-0.03	324	0.21	1659.0	24.8	1744	14	4.34	1.7	0.2951	1.5	0.896
GR-5.1	0.000030	0.1059	0.05	111	0.27	1684.2	28.4	1722	22	4.35	2.1	0.2993	1.7	0.817
GR-6.1	0.000050	0.1060	0.08	156	0.51	1667.8	26.8	1720	20	4.30	2.0	0.2963	1.6	0.839
GR-7.1	0.000051	0.1051	0.08	232	0.35	1682.9	25.9	1704	17	4.30	1.8	0.2987	1.6	0.863
GR-8.1	0.000000	0.1110	0.00	118	0.42	1737.3	29.1	1816	21	4.76	2.1	0.3110	1.7	0.834
GR-9.1	0.000551	0.1125	0.87	432	1.46	1407.9	20.5	1714	22	3.60	1.9	0.2485	1.5	0.784
GR-10.1	0.000045	0.1028	0.07	577	0.45	1345.3	19.3	1664	12	3.33	1.6	0.2363	1.5	0.914
GR-11.1	0.001659	0.1034	2.77	310	1.04	1837.9	32.7	1196	157	3.50	8.2	0.3172	1.9	0.236
GR-12.1	0.000040	0.1049	0.06	167	0.61	1688.9	26.9	1702	19	4.31	1.9	0.2998	1.6	0.844
GR-13.1	0.000452	0.1067	0.72	962	0.78	621.7	9.0	1633	23	1.47	1.9	0.1059	1.5	0.762
GR-14.1	0.000047	0.1054	0.07	100	0.56	1732.5	30.0	1711	25	4.45	2.2	0.3079	1.8	0.791
GR-15.1	0.000519	0.0905	0.86	1726	0.16	310.6	4.5	1275	29	0.59	2.1	0.0511	1.5	0.701
GR-16.1	0.000044	0.1036	0.07	578	0.49	1294.9	18.6	1678	12	3.23	1.6	0.2273	1.5	0.914
GR-17.1	0.000358	0.1058	0.57	628	0.84	734.9	10.7	1640	21	1.75	1.9	0.1259	1.5	0.795
GR-18.1	0.000038	0.0914	0.06	238	0.50	1342.3	20.5	1444	21	2.92	1.9	0.2328	1.6	0.826
GR-19.1	0.000000	0.1060	0.00	79	0.40	1609.9	29.0	1732	26	4.18	2.3	0.2859	1.9	0.789
GR-20.1	0.000577	0.1006	0.93	1059	0.38	334.7	4.9	1480	32	0.71	2.3	0.0557	1.5	0.662
GR-21.1	0.001127	0.0951	1.89	2394	0.24	198.8	2.9	1175	61	0.35	3.4	0.0324	1.5	0.435
GR-22.1	0.000000	0.1608	0.00	169	0.42	2362.9	39.9	2464	13	9.92	1.8	0.4473	1.6	0.898
GR-23.1	0.000035	0.1847	0.05	118	1.04	2516.2	45.7	2692	12	12.38	1.8	0.4873	1.7	0.915
GR-24.1	0.000102	0.1033	0.16	136	0.81	1486.9	24.2	1659	26	3.68	2.2	0.2621	1.7	0.765
GR-25.1	0.000028	0.1053	0.04	434	0.47	1558.2	22.7	1714	12	4.00	1.6	0.2761	1.5	0.917
GR-26.1	-0.000059	0.1088	-0.09	89	1.04	1594.2	27.9	1793	27	4.30	2.3	0.2842	1.8	0.768
GR-27.1	0.000889	0.1064	1.43	1501	1.30	437.5	6.3	1510	31	0.95	2.2	0.0734	1.5	0.673
GR-28.1	-0.000012	0.1051	-0.02	139	0.52	1691.2	27.6	1719	20	4.36	2.0	0.3005	1.7	0.837
GR-29.1	0.001404	0.0939	2.39	2725	0.30	171.5	2.5	1039	67	0.28	3.6	0.0278	1.5	0.412
GR-30.1	0.000140	0.1039	0.22	725	0.74	1018.5	14.5	1660	14	2.49	1.7	0.1768	1.5	0.886
GR-31.1	0.000111	0.1058	0.17	472	0.40	1371.2	19.8	1701	14	3.47	1.7	0.2416	1.5	0.891
GR-32.1	0.000167	0.1068	0.26	260	0.44	1617.7	24.5	1706	18	4.13	1.8	0.2868	1.6	0.847
GR-33.1	0.000100	0.0915	0.16	98	0.56	1372.0	23.8	1428	45	2.96	3.0	0.2379	1.8	0.604
GR-34.1	0.000115	0.1060	0.18	348	0.75	1466.3	21.7	1704	17	3.73	1.8	0.2591	1.5	0.861
GR-35.1	0.000235	0.1033	0.37	732	0.75	695.2	10.0	1625	19	1.64	1.8	0.1188	1.5	0.822
GR-36.1	0.000046	0.1054	0.07	499	0.46	1280.8	18.5	1710	13	3.25	1.7	0.2252	1.5	0.906
GR-37.1	0.000444	0.1133	0.70	382	1.37	889.2	13.2	1753	25	2.28	2.1	0.1545	1.5	0.741
GR-38.1	0.000048	0.1055	0.08	378	0.58	1699.4	25.2	1712	13	4.36	1.7	0.3019	1.5	0.904
GR-39.1	0.000164	0.0920	0.27	734	0.55	1030.4	14.7	1420	16	2.18	1.7	0.1766	1.5	0.865
GR-40.1	0.000027	0.1056	0.04	418	0.33	1673.3	24.6	1719	12	4.31	1.6	0.2972	1.5	0.919
GR-41.1	0.000466	0.1053	0.74	1259	0.92	513.8	7.4	1603	21	1.19	1.9	0.0869	1.5	0.793

GR-42.1	0.000474	0.1072	0.75	276	1.27	985.5	14.8	1637	32	2.37	2.3	0.1707	1.6	0.678
GR-42.1	-0.000013	0.0894	-0.02	152	0.73	1418.2	22.7	1416	24	3.04	2.1	0.2461	1.7	0.803
GR-43.1	-0.000058	0.1042	-0.09	169	0.40	1717.6	27.3	1715	20	4.42	2.0	0.3053	1.6	0.836
GR-44.1	0.000000	0.1091	0.00	216	0.64	1782.9	27.7	1784	15	4.79	1.8	0.3186	1.6	0.889
GR-46.1	0.000077	0.1070	0.12	726	0.73	1075.8	15.3	1731	12	2.75	1.6	0.1880	1.5	0.911
GR-47.1	0.000005	0.1043	0.01	287	0.28	1752.0	26.4	1701	13	4.47	1.7	0.3112	1.5	0.903
GR-48.1	0.000062	0.1035	0.10	213	0.51	1583.4	24.4	1673	18	3.96	1.9	0.2800	1.6	0.850
GR-49.1	-0.000041	0.1038	-0.06	181	1.05	1634.6	25.6	1702	19	4.17	1.9	0.2899	1.6	0.847
GR-50.1	0.000040	0.1054	0.06	176	0.84	1980.2	33.0	1712	22	5.10	2.0	0.3527	1.7	0.817
GR-51.1	0.000046	0.1055	0.08	175	0.19	1759.5	3.5	1711	20	4.52	1.1	0.3127	0.1	0.139
GR-52.1	0.000097	0.1054	0.18	116	0.54	1699.9	22.0	1698	27	4.33	2.0	0.3017	1.3	0.661
GR-53.1	0.000075	0.1073	0.14	166	0.55	1376.2	15.5	1737	24	3.57	1.7	0.2438	1.1	0.656
GR-54.1	0.000077	0.1052	0.14	46	0.61	1697.6	20.8	1699	38	4.33	2.4	0.3013	1.2	0.512
GR-55.1	0.000070	0.0932	0.13	106	0.68	1426.3	39.0	1472	36	3.16	3.4	0.2483	2.8	0.830
GR-56.1	0.000033	0.1039	0.06	105	0.54	1764.5	33.4	1687	24	4.46	2.3	0.3130	1.9	0.827
GR-57.1	-0.000015	0.0993	-0.03	42	0.64	1457.4	40.5	1616	41	3.52	3.6	0.2563	2.8	0.789
GR-58.1	0.000063	0.1099	0.11	187	1.17	1419.3	7.2	1783	20	3.80	1.2	0.2526	0.5	0.413
GR-59.1	0.000220	0.0912	0.40	182	0.67	1256.8	2.0	1386	40	2.64	2.1	0.2168	0.2	0.089
GR-60.1	0.000000	0.0875	0.00	207	0.95	1240.1	18.0	1372	23	2.58	1.9	0.2137	1.5	0.784
GR-61.1	-0.000051	0.1055	-0.09	106	0.41	1655.5	37.7	1735	25	4.31	2.7	0.2945	2.3	0.858
GR-62.1	0.000129	0.1558	0.23	168	1.45	1193.3	4.8	2392	21	4.77	1.3	0.2246	0.3	0.262
GR-63.1	0.000089	0.1060	0.16	151	0.47	1728.6	32.2	1710	22	4.44	2.2	0.3071	1.9	0.846
GR-64.1	0.000056	0.1037	0.10	195	0.88	1688.9	15.4	1678	20	4.25	1.4	0.2993	0.9	0.653
GR-65.1	0.000310	0.1045	0.56	69	0.22	1752.0	54.6	1629	47	4.28	4.0	0.3095	3.1	0.777
GR-66.1	0.000086	0.1036	0.16	354	1.35	747.2	1.4	1669	25	1.82	1.4	0.1291	0.1	0.107
GR-67.1	-0.000091	0.0554	-0.16	119	0.38	444.6	6.2			0.56	9.0	0.0715	1.5	0.170
GR-68.1	-0.000168	0.1028	-0.30	64	0.60	1747.4	22.7	1716	38	4.50	2.4	0.3106	1.3	0.531
GR-69.1	0.000029	0.1850	0.05	203	0.48	2631.3	87.4	2695	18	12.97	2.9	0.5093	2.7	0.924
GR-70.1	0.000000	0.0910	0.00	104	1.25	1422.2	5.0	1447	29	3.10	1.5	0.2472	0.3	0.203
GR-71.1	0.000068	0.1053	0.12	120	0.51	1728.6	11.2	1704	25	4.42	1.5	0.3070	0.6	0.431
GR-72.1	0.000437	0.1116	0.79	163	1.06	1190.0	19.3	1724	37	3.05	2.6	0.2096	1.7	0.636
GR-73.1	0.000097	0.0993	0.18	68	0.47	1696.6	8.7	1586	34	4.04	1.9	0.2987	0.5	0.258

P-1-03 (Pilcher Quartzite) location: 46.2462°, -113.3323°

Pil-1.1	0.000057	0.1046	0.09	161	0.63	1549.6	17.0	1693	24	3.92	1.7	0.2742	1.1	0.658
Pil-2.1	0.000257	0.1008	0.46	1037	0.66	546.5	6.1	1572	24	1.25	1.6	0.0929	0.9	0.592
Pil-3.1	0.000000	0.1053	0.00	298	0.18	1596.8	16.6	1720	16	4.11	1.4	0.2833	1.1	0.771
Pil-4.1	0.000045	0.0891	0.07	117	0.93	1429.4	17.5	1392	32	3.02	2.1	0.2477	1.3	0.601
Pil-5.1	0.000000	0.1055	0.00	215	0.27	1665.4	17.3	1723	18	4.30	1.5	0.2959	1.1	0.728
Pil-6.1	0.000000	0.1047	0.00	392	0.23	1656.0	15.8	1710	14	4.24	1.2	0.2939	1.0	0.785
Pil-7.1	0.000047	0.1080	0.07	241	0.34	1743.8	18.8	1755	18	4.60	1.5	0.3108	1.1	0.747
Pil-8.1	0.000116	0.0926	0.19	250	0.59	1232.5	12.7	1446	27	2.67	1.8	0.2131	1.1	0.594
Pil-9.1	0.000049	0.1049	0.08	468	0.63	1067.0	11.1	1700	18	2.68	1.4	0.1865	1.0	0.710
Pil-10.1	0.000069	0.1053	0.11	170	0.39	1590.1	17.8	1702	23	4.05	1.7	0.2817	1.1	0.678

Pil-11.1	0.000058	0.1037	0.09	241	0.15	1675.7	21.2	1677	19	4.21	1.6	0.2969	1.3	0.790
Pil-12.1	0.000000	0.1037	0.00	177	0.39	1646.3	18.9	1692	23	4.17	1.7	0.2918	1.2	0.682
Pil-13.1	0.000000	0.1067	0.00	218	0.52	1704.5	18.8	1743	18	4.46	1.5	0.3034	1.1	0.753
Pil-14.1	0.000026	0.0906	0.04	278	0.75	1425.1	14.3	1431	21	3.08	1.5	0.2475	1.0	0.687
Pil-15.1	0.000009	0.1081	0.01	428	0.45	1698.2	16.3	1766	12	4.51	1.2	0.3028	1.0	0.830
Pil-16.1	0.000032	0.1039	0.05	128	0.50	1675.5	19.4	1686	24	4.24	1.8	0.2970	1.2	0.671
Pil-17.1	0.000000	0.1014	0.00	201	0.54	1669.5	18.1	1650	21	4.13	1.6	0.2952	1.1	0.696
Pil-18.1	0.000000	0.1034	0.00	162	0.30	1590.2	19.4	1686	23	4.01	1.8	0.2815	1.2	0.708
Pil-19.1	0.000000	0.1035	0.00	131	0.46	1566.3	20.7	1688	27	3.96	2.0	0.2771	1.4	0.683
Pil-20.1	0.000124	0.1033	0.22	267	1.11	685.1	8.8	1653	33	1.65	2.1	0.1177	1.1	0.543
Pil-21.1	0.000016	0.0895	0.03	312	0.48	1427.8	13.9	1410	19	3.05	1.4	0.2477	1.0	0.716
Pil-22.1	0.000020	0.1038	0.03	253	0.45	1709.0	17.8	1687	19	4.33	1.5	0.3032	1.1	0.722
Pil-23.1	0.000072	0.1065	0.12	219	0.55	1376.9	14.9	1724	20	3.54	1.5	0.2432	1.1	0.698
Pil-24.1	0.000000	0.1015	0.00	136	0.28	1717.3	20.5	1652	25	4.25	1.8	0.3040	1.2	0.662
Pil-25.1	0.000168	0.0960	0.27	189	0.61	1500.7	17.0	1502	29	3.39	1.9	0.2622	1.2	0.606
Pil-26.1	0.000054	0.1040	0.09	209	0.51	1609.0	16.8	1684	19	4.06	1.5	0.2849	1.1	0.712
Pil-27.1	0.000099	0.1063	0.15	89	0.42	1755.8	22.3	1714	32	4.52	2.1	0.3122	1.3	0.601
Pil-28.1	0.000049	0.1051	0.08	246	0.50	1654.6	17.7	1705	19	4.23	1.5	0.2936	1.1	0.725
Pil-29.1	0.000000	0.0907	0.00	262	0.69	1462.5	14.8	1441	20	3.18	1.5	0.2544	1.0	0.701
Pil-30.1	0.000091	0.1067	0.14	160	0.29	1663.4	19.7	1722	24	4.30	1.8	0.2955	1.2	0.677
Pil-31.1	0.000026	0.1052	0.04	174	0.36	1682.4	18.5	1712	25	4.32	1.8	0.2988	1.1	0.632
Pil-32.1	0.000033	0.1046	0.05	498	0.64	1603.2	15.0	1700	14	4.08	1.2	0.2841	1.0	0.793
Pil-33.1	0.000042	0.1054	0.07	198	0.40	1729.3	18.4	1711	20	4.44	1.5	0.3073	1.1	0.706
Pil-34.1	0.000021	0.0897	0.03	229	0.56	1452.5	14.9	1414	22	3.11	1.5	0.2522	1.1	0.683
Pil-35.1	0.000075	0.1049	0.12	177	0.35	1660.6	19.2	1695	22	4.22	1.7	0.2945	1.2	0.712
Pil-36.1	0.000000	0.1047	0.00	221	0.65	1743.5	18.0	1709	18	4.47	1.4	0.3099	1.1	0.737
Pil-37.1	0.000048	0.1050	0.08	183	0.35	1667.4	19.1	1703	20	4.26	1.6	0.2959	1.2	0.730
Pil-38.1	0.000132	0.1075	0.23	640	0.15	947.7	10.0	1726	18	2.41	1.4	0.1653	0.9	0.686
Pil-39.1	0.000249	0.1057	0.43	579	1.25	746.2	8.3	1666	26	1.81	1.7	0.1287	1.0	0.565
Pil-40.1	0.000058	0.0913	0.09	223	0.66	1442.9	14.8	1437	22	3.13	1.6	0.2508	1.1	0.674
Pil-41.1	0.000049	0.1068	0.08	169	0.73	1724.5	19.3	1734	24	4.49	1.7	0.3069	1.1	0.653
Pil-42.1	0.000133	0.1058	0.21	153	0.39	1777.3	20.7	1696	28	4.53	1.9	0.3158	1.2	0.613
Pil-43.1	-0.000078	0.1030	-0.12	130	0.60	1724.2	20.8	1697	28	4.39	2.0	0.3061	1.2	0.623
Pil-44.1	0.000000	0.1042	0.00	254	0.72	1553.2	16.0	1701	19	3.95	1.5	0.2750	1.1	0.714
Pil-45.1	0.000176	0.1596	0.30	570	0.68	990.8	16.2	2427	14	4.01	1.3	0.1848	1.0	0.772
Pil-46.1	0.000012	0.1065	0.02	408	0.13	1672.7	16.0	1737	14	4.36	1.2	0.2975	1.0	0.788
Pil-47.1	0.000122	0.1055	0.21	586	0.45	836.0	9.2	1694	19	2.08	1.4	0.1449	1.0	0.681
Pil-48.1	0.000145	0.1060	0.26	1059	0.36	666.1	7.4	1696	16	1.64	1.3	0.1147	0.9	0.715
Pil-49.1	0.000032	0.1036	0.05	121	0.74	1675.1	19.4	1682	24	4.22	1.8	0.2969	1.2	0.674
Pil-50.1	0.000000	0.0903	0.00	237	0.63	1348.8	14.6	1433	21	2.91	1.6	0.2338	1.1	0.708

1 Prefix “m” for monazite, analyzed on SHRIMP II, Research School of Earth Sciences, Australian National University. All zircon samples analyzed on USGS/Stanford SHRIMP-RG, Stanford University.

2 ²⁰⁶Pb/²³⁸U and ²⁰⁷Pb/²⁰⁶Pb ages corrected for common Pb using the ²⁰⁴Pb-correction method. Decay constants from Steiger and Jäger (1977).

3 Not listed for ages <1.0 Ga

4 1-sigma errors.

5 Radiogenic ratios, corrected for common Pb using the ^{204}Pb -correction method, based on the Stacey and Kramers (1975) model.

Draft

Table 2. SHRIMP U-Th-Pb data for xenotime from Mesoproterozoic Belt Supergroup, western Montana.

sample	measured $\frac{^{204}\text{Pb}}{^{206}\text{Pb}}$	measured $\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	% common ^{206}Pb	U (ppm)	Th/U	$\frac{^{206}\text{Pb}^{1,2}}{^{238}\text{U}}$ (Ma)	err ³ (Ma)	$\frac{^{207}\text{Pb}^2}{^{206}\text{Pb}}$ (Ma)	err ³ (Ma)	$\frac{^{207}\text{Pb}^4}{^{235}\text{U}}$	err ³ (%)	$\frac{^{206}\text{Pb}^4}{^{238}\text{U}}$	err ³ (%)	ρ
BB-32 (Prichard Formation)														
session 1														
BB32-E1-1.1	0.000341	0.0955	0.55	6046	0.41	1474.5	52.6	1441	42	3.21	4.3	0.2565	3.7	0.857
BB32-E1-1.2	0.000170	0.0910	0.28	4373	1.86	1550.1	18.6	1395	13	3.29	1.4	0.2694	1.2	0.883
BB32-E1-1.3	0.000534	0.0974	0.87	5348	0.56	1516.5	18.1	1425	27	3.27	1.9	0.2638	1.2	0.661
BB32-E14-1.1	0.000156	0.0924	0.25	4677	1.39	1511.4	22.2	1431	16	3.27	1.7	0.2630	1.5	0.877
BB32-A7-1.1	0.000052	0.0922	0.08	10310	0.10	1695.5	21.2	1457	5	3.74	1.3	0.2965	1.3	0.979
BB32-A7-1.2	0.000073	0.0912	0.12	4742	1.05	1557.3	22.0	1429	8	3.37	1.5	0.2712	1.5	0.959
BB32-A7-1.3	0.000009	0.0916	0.01	4258	0.55	1494.1	17.8	1456	6	3.28	1.3	0.2603	1.2	0.971
BB32-A7-1.4	0.000086	0.0868	0.14	4896	0.79	1355.2	16.2	1328	8	2.76	1.3	0.2336	1.2	0.944
BB32-A7-1.5	0.000008	0.0919	0.01	3955	0.57	1524.8	18.3	1464	6	3.37	1.3	0.2659	1.2	0.971
BB32-A7-1.6	0.000070	0.0927	0.11	4158	0.85	1530.0	18.3	1462	7	3.37	1.3	0.2668	1.2	0.955
BB32-A7-1.8	0.001018	0.1077	1.64	7288	0.92	1049.3	28.8	1501	66	2.33	4.5	0.1807	2.8	0.625
BB32-E11-1.1	0.000157	0.0934	0.25	5151	0.93	1600.7	19.4	1451	14	3.51	1.5	0.2794	1.2	0.854
BB32-A7-1.7B	0.000123	0.0928	0.20	7294	0.23	1769.0	23.3	1448	8	3.89	1.4	0.3095	1.3	0.951
session 2														
BB32C-3.1	0.000495	0.0968	0.81	6759	1.62	1656.2	38.2	1423	47	3.58	3.4	0.2889	2.4	0.690
BB32C-4.1	0.000087	0.0914	0.14	5850	1.46	1615.4	26.7	1429	15	3.50	1.9	0.2817	1.7	0.907
BB32C-4.2	0.000262	0.0950	0.42	5032	1.29	1585.8	25.8	1454	40	3.49	2.7	0.2767	1.7	0.628
BB32C-1.1	0.000168	0.0933	0.27	4769	3.13	1456.7	22.5	1446	9	3.18	1.7	0.2534	1.6	0.957
BB32C-1.2	0.001005	0.1055	1.63	4121	1.98	1331.1	22.1	1458	45	2.91	2.9	0.2309	1.7	0.591
BB32C-1.3	0.000016	0.0919	0.03	4978	1.18	1515.6	23.4	1461	5	3.34	1.6	0.2642	1.6	0.989
BB32B-3.1	0.000251	0.0883	0.41	4635	0.68	1314.7	20.9	1310	27	2.64	2.2	0.2262	1.7	0.765
BB32B-3.2	0.000010	0.0889	0.02	4732	1.53	1397.4	22.6	1400	10	2.96	1.8	0.2421	1.7	0.956
BB32B-4.1	0.003319	0.1372	5.40	4500	1.96	1405.0	30.7	1446	377	3.06	19.9	0.2441	2.2	0.111
BB32B-4.2	0.001244	0.1067	2.03	6606	1.71	1437.5	22.9	1412	90	3.07	5.0	0.2495	1.7	0.333
BB32B-2.1	-0.000001	0.0909	0.00	6090	2.50	1565.2	25.2	1446	4	3.42	1.7	0.2729	1.7	0.991
BB32B-2.2	0.000012	0.0911	0.02	4805	3.59	1480.9	23.3	1444	5	3.23	1.6	0.2577	1.6	0.988
MC-3-03 (McNamara Formation)														
MC5A-1.1	0.000413	0.0851	1.10	1202	5.02	1091.9	24.0	1179	30	2.03	2.7	0.1853	2.3	0.836
MC5G-1.1	0.000909	0.0899	1.93	844	6.46	1032.9	22.2	1121	70	1.85	4.2	0.1745	2.2	0.538
MC5E-1.1	0.001435	0.0961	2.84	1498	12.79	994.6	19.7	1086	93	1.75	5.1	0.1675	2.1	0.409
MC5H-1.1	0.000400	0.0991	4.56	5186	4.91	662.3	11.9	1499	22	1.45	2.2	0.1126	1.9	0.852
GR-4-03 (Garnet Range Formation)														
GR22A-1.1	0.000612	0.0793	2.95	2923	8.12	428.2	8.0	944	50	0.68	3.1	0.0700	1.9	0.607
GR21F-1.1	0.003688	0.1181	6.94	2281	8.78	647.2	13.3	771	439	0.95	21.0	0.1061	2.4	0.112

GR21D-1.1	0.000015	0.1030	-1.66	7969	1.29	1919.9	27.8	1676	4	4.84	1.5	0.3412	1.5	0.988
GR21E-1.1	0.001657	0.0955	4.65	3000	7.54	519.0	9.9	981	212	0.84	10.6	0.0853	1.8	0.175
GR18H-1.1	0.003612	0.1234	7.98	3313	7.39	545.1	13.5	980	278	0.89	13.8	0.0897	2.4	0.172
GR18G-1.1	0.000194	0.1040	0.64	1314	11.81	1594.8	22.5	1648	14	3.93	1.6	0.2816	1.5	0.886
GR18G-1.2	0.000223	0.1025	2.81	1534	12.13	1165.4	22.9	1613	19	2.78	2.2	0.2031	2.0	0.896
GR9C-1.1	0.000619	0.0809	0.76	2505	9.50	1057.1	17.4	989	59	1.77	3.4	0.1777	1.7	0.510
GR18A-1.1	0.000352	0.0809	0.58	5162	1.77	1095.9	15.4	1092	29	1.94	2.0	0.1853	1.5	0.714
GR18D-1.1	0.000647	0.0825	2.45	2338	9.21	685.0	10.0	1020	69	1.15	3.7	0.1136	1.5	0.401
GR18F-1.1	0.002497	0.1070	6.34	6019	18.92	438.8	14.3	966	349	0.71	17.4	0.0718	3.2	0.182

P-1-03 (Pilcher Quartzite)

session 1

P1L1A-1.1	0.001555	0.0887	2.70	9020	3.26	203.3	7.7	817	119	0.30	6.9	0.0327	3.8	0.560
P1L1B	0.000431	0.0777	0.74	569	6.77	881.1	16.5	973	63	1.45	3.7	0.1470	2.0	0.534
P1L1F-1.1	0.001084	0.0852	1.87	611	7.41	1036.9	21.0	919	123	1.67	6.4	0.1736	2.1	0.335
P1L2E-1.2	0.000632	0.0790	1.09	1461	4.64	454.2	16.5	927	64	0.72	4.9	0.0742	3.7	0.764
P1L2B-1.1	0.005149	0.1271	9.42	144993	1.53	254.1	17.9	268	1233	0.29	54.3	0.0402	7.4	0.136
P1A1G-1.2	0.000150	0.0712	0.26	1643	3.93	266.1	4.3	899	39	0.41	2.5	0.0430	1.6	0.655
P1A2C-1.1	0.000171	0.0757	0.29	1617	12.26	935.6	12.4	1023	21	1.58	1.7	0.1568	1.4	0.800
P1A2F-1.1	0.000352	0.0791	0.60	2002	6.10	501.6	6.8	1043	39	0.84	2.4	0.0825	1.4	0.581
P1A2F-1.2	0.000352	0.0764	0.60	1434	7.02	661.6	12.6	968	32	1.08	2.5	0.1093	2.0	0.785
P1A1E-1.1	0.000597	0.0838	1.01	837	6.09	610.1	13.5	1078	57	1.05	3.6	0.1011	2.3	0.626
P1A1E-1.2	0.001072	0.0841	1.85	9080	2.33	180.4	4.8	891	68	0.28	4.3	0.0290	2.7	0.630

session 2

P1A1-15-1.1	0.000062	0.0750	0.11	486	8.44	950.9	8.2	1045	25	1.63	1.5	0.1596	0.9	0.584
P1A1-7-1.1	0.000081	0.0768	0.14	2181	6.12	635.0	7.8	1086	19	1.10	1.6	0.1053	1.3	0.798
P1A1-6-1.1	0.000423	0.0791	0.72	1481	8.37	536.8	4.0	1017	42	0.89	2.2	0.0884	0.8	0.348
P1A1-4-1.1	0.000113	0.0799	0.19	1517	17.30	879.4	5.9	1155	20	1.60	1.2	0.1479	0.7	0.572
P1A1-4-1.2	0.000141	0.0810	0.24	1546	11.22	654.2	13.2	1173	24	1.19	2.4	0.1090	2.1	0.868
P1A1-4-1.3	0.000145	0.0779	0.24	1138	17.95	959.6	8.0	1092	25	1.69	1.5	0.1614	0.9	0.578
P1A1-1-1.1	0.000132	0.0754	0.22	1847	7.06	767.1	5.6	1028	26	1.29	1.5	0.1277	0.8	0.497
P1A1-13-1.1	0.000710	0.0883	1.19	1472	10.94	587.1	4.6	1154	48	1.05	2.6	0.0975	0.8	0.320
P1L1-3-1.1	0.000993	0.0874	1.69	1024	9.11	953.2	15.3	1021	68	1.61	3.8	0.1598	1.7	0.447
P1L1-2-1.1	0.000325	0.0793	0.55	2091	10.87	363.4	2.4	1060	43	0.61	2.2	0.0594	0.7	0.306
P1L1-1-1.1	0.001737	0.1007	2.94	1158	10.45	678.8	6.5	1095	102	1.18	5.2	0.1129	1.1	0.204
P1A2-5-1.1	0.001243	0.0918	2.11	996	7.75	887.0	7.6	1043	72	1.52	3.7	0.1485	0.9	0.249
P1A2-6-1.1	0.000563	0.0801	0.96	2628	5.90	692.0	5.5	987	49	1.14	2.6	0.1146	0.8	0.325
P1A2-7-1.1	0.000623	0.0825	1.06	1492	10.43	672.8	5.3	1031	45	1.13	2.4	0.1115	0.8	0.347
P1A2-7-1.2	0.000139	0.0774	0.24	1567	6.59	734.9	9.5	1078	22	1.27	1.7	0.1224	1.3	0.773
P1A2-8-1.1	0.000074	0.0769	0.12	1631	15.53	847.7	5.5	1092	18	1.49	1.1	0.1420	0.7	0.601

1 $^{206}\text{Pb}/^{238}\text{U}$ ages possibly affected by matrix mismatch with standard.2 $^{206}\text{Pb}/^{238}\text{U}$ ages corrected for common Pb using the ^{207}Pb -correction method; $^{207}\text{Pb}/^{206}\text{Pb}$ ages corrected for common Pb using the ^{204}Pb -correction method.

Decay constants from Steiger and Jäger (1977).

3 1-sigma errors.

4 Radiogenic ratios, corrected for common Pb using the ^{204}Pb -correction method, based on the Stacey and Kramers (1975) model.

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Table 3. Trace element data of xenotime overgrowths, Belt Supergroup, western Montana.

sample	La ¹	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	total REE ²	Th	U
BB-32 (Prichard Formation)																	
BB32-E15-1.149		227	84	1710	6804	4037	30705	7828	53137	11697	31792	4651	27739	3914	18.4	15458	5080
BB32-E14-1.135		186	75	1378	5433	3012	29110	8014	53037	11524	28001	4386	21589	3832	17.0	10145	6659
BB32-E3-1.1 25		188	83	1436	5190	2546	28622	8031	60677	14987	41640	6794	39856	6960	21.7	16193	8166
BB32-E11-1.126		262	133	2193	7257	3798	32202	8557	57014	12306	31628	4900	27482	4622	19.2	7333	8007
BB32-A7-1.1 20		356	151	2115	6279	3012	30789	8561	59784	13264	35465	5562	34985	5576	20.6	4914	9801
BB32-A7-2.1 24		199	116	1216	4667	2525	25114	6335	44565	10099	27211	4333	24868	4358	15.6	11037	5615
BB32-A7-3.1 36		774	386	5095	12842	7225	47608	11412	67223	13254	33432	5073	34278	5080	24.4	4792	11730
BB32-A7-4.1 21		361	205	3331	10586	5144	45707	11298	66459	13040	31154	4279	22749	3134	21.7	10392	7501
BB32-A7-4.2 3		93	71	1430	6603	3547	34398	9299	58524	11994	29253	4113	21645	2969	18.4	3699	6357
BB32-A7-5.1 5		121	90	1681	6297	3396	30580	8426	55782	11980	31058	4459	24387	3295	18.2	2905	6000
BB32-E1-1.1 24		313	159	2744	9161	5107	37901	9576	59614	12168	30157	4235	23898	3621	19.9	7959	7733
BB32-E1-2.1 49		857	386	4689	9290	4012	32597	8873	60215	12682	31328	4587	26647	3834	20.0	1111	7503
BB32-E1-3.1 41		796	385	4818	10621	4852	39956	10698	73909	16160	42615	6554	38213	6076	25.6	6361	11482
P-1-03 (Pilcher Quartzite)																	
P1A1D-1.1	1	25	18	550	10372	6960	55674	9223	43565	8021	17762	2166	10867	1477	16.7	17151	6246
P1A1F-1.1	1	37	57	2069	25808	16905	127480	18847	83561	14768	33378	4182	21713	2580	35.1	6344	1111
P1A1F-1.2	0	14	24	932	15205	9492	76438	12616	60547	11172	25111	3087	15727	1958	23.2	20267	2531
P1A1G-1.2	0	13	20	770	15957	11103	85168	13175	60647	10771	23941	2884	14941	1840	24.1	12549	2381
P1A2C-1.1	3	49	27	811	14260	10692	80984	12435	59730	11056	25668	3312	17023	2307	23.8	18926	7942
P1L1B-1.2	0	6	13	555	12355	9055	85277	13781	64342	11878	26729	3334	17617	2194	24.7	15057	1904
P1L1F-1.1	1	8	9	437	11826	8815	75510	12115	62363	12583	31143	4027	21268	2808	24.3	6317	1011
P1L1H-1.1	1	34	23	715	11583	7705	65485	11019	52077	9327	20802	2675	13527	1842	19.7	20002	6547
P1L2A-1.1	2	50	20	740	14898	10527	82664	12653	56874	10258	22918	2844	14238	1981	23.1	18888	4625
P1L2B-1.2	1	114	16	531	10465	7385	58350	9517	45325	8086	18603	2341	12010	1648	17.4	13019	5124
P1L2C-1.2	0	8	15	574	12275	8842	82634	13601	63727	11289	24759	3001	15637	1999	23.8	15953	2779
P1L2E-1.1	0	5	9	409	10114	8100	72421	11209	50659	9208	21223	2656	14175	1855	20.2	9013	1669
P1L2E-1.2	0	4	7	325	8944	7939	75203	11836	55825	10806	25441	3294	17488	2263	21.9	8665	1427
P1A1-13-1.1	1	9	11	507	12220	8793	72082	10897	50873	9564	22917	2986	15507	2055	20.8	9204	1785
P1A1-15-1.1	0	10	20	888	17186	10547	99710	16136	74939	13291	29704	3672	19150	2356	28.8	12902	1714
P1A1-4-1.1	1	37	45	1608	21475	10485	87023	13355	60285	10664	22811	2720	13854	1688	24.6	29011	1575
P1A1-4-1.3	1	43	67	2125	28423	14405	122074	18773	86734	15276	32936	3946	20026	2460	34.7	36384	2612
P1A1-7-1.1	0	6	11	445	8246	4838	48391	8286	39674	7267	16540	2061	11027	1407	14.8	21147	1158
P1A2-6-1.1	1	7	14	636	17880	14631	122181	18755	86023	15565	35190	4282	22364	2833	34.0	23567	3520
P1A2-7-1.1	2	46	25	841	13635	8283	73044	12219	58308	10456	24218	3092	16103	2255	22.3	27726	5796
P1A2-7-1.2	1	7	14	602	15003	12230	122059	18843	86639	16140	37724	4704	25323	3119	34.2	11949	1558
P1A2-8-1.1	0	14	23	980	15320	7799	72477	12458	59420	10843	24544	3006	15759	2019	22.5	22128	1912
P1L1-1-1.1	0	11	15	649	12124	7971	70364	10834	48188	8669	19887	2474	12966	1570	19.6	17500	1572

P1L1-2-1.1	0	12	16	646	11987	8193	64188	10749	52027	9573	21261	2572	12761	1634	19.6	25357	2537
P1L1-2-1.2	0	9	12	443	10731	8270	64344	11228	54591	9876	21374	2515	12523	1565	19.7	28651	2795
P1L1-3-1.1	0	8	9	444	10879	8170	61120	9352	43856	8354	19648	2457	12701	1722	17.9	6938	999

1 Values of all elements in parts per million.
2 Total REE in weight %.

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Table 2. SHRIMP U-Th-Pb data for xenotime from Mesoproterozoic Belt Supergroup, western Montana.

sample	measured $\frac{^{204}\text{Pb}}{^{206}\text{Pb}}$	measured $\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	% common ^{206}Pb	U (ppm)	Th/U	$\frac{^{206}\text{Pb}^{1,2}}{^{238}\text{U}}$ (Ma)	err ³ (Ma)	$\frac{^{207}\text{Pb}^2}{^{206}\text{Pb}}$ (Ma)	err ³ (Ma)	$\frac{^{207}\text{Pb}^4}{^{235}\text{U}}$	err ³ (%)	$\frac{^{206}\text{Pb}^4}{^{238}\text{U}}$	err ³ (%)	ρ
BB-32 (Prichard Formation)														
session 1														
BB32-E1-1.1	0.000341	0.0955	0.55	6046	0.41	1474.5	52.6	1441	42	3.21	4.3	0.2565	3.7	0.857
BB32-E1-1.2	0.000170	0.0910	0.28	4373	1.86	1550.1	18.6	1395	13	3.29	1.4	0.2694	1.2	0.883
BB32-E1-1.3	0.000534	0.0974	0.87	5348	0.56	1516.5	18.1	1425	27	3.27	1.9	0.2638	1.2	0.661
BB32-E14-1.1	0.000156	0.0924	0.25	4677	1.39	1511.4	22.2	1431	16	3.27	1.7	0.2630	1.5	0.877
BB32-A7-1.1	0.000052	0.0922	0.08	10310	0.10	1695.5	21.2	1457	5	3.74	1.3	0.2965	1.3	0.979
BB32-A7-1.2	0.000073	0.0912	0.12	4742	1.05	1557.3	22.0	1429	8	3.37	1.5	0.2712	1.5	0.959
BB32-A7-1.3	0.000009	0.0916	0.01	4258	0.55	1494.1	17.8	1456	6	3.28	1.3	0.2603	1.2	0.971
BB32-A7-1.4	0.000086	0.0868	0.14	4896	0.79	1355.2	16.2	1328	8	2.76	1.3	0.2336	1.2	0.944
BB32-A7-1.5	0.000008	0.0919	0.01	3955	0.57	1524.8	18.3	1464	6	3.37	1.3	0.2659	1.2	0.971
BB32-A7-1.6	0.000070	0.0927	0.11	4158	0.85	1530.0	18.3	1462	7	3.37	1.3	0.2668	1.2	0.955
BB32-A7-1.8	0.001018	0.1077	1.64	7288	0.92	1049.3	28.8	1501	66	2.33	4.5	0.1807	2.8	0.625
BB32-E11-1.1	0.000157	0.0934	0.25	5151	0.93	1600.7	19.4	1451	14	3.51	1.5	0.2794	1.2	0.854
BB32-A7-1.7B	0.000123	0.0928	0.20	7294	0.23	1769.0	23.3	1448	8	3.89	1.4	0.3095	1.3	0.951
session 2														
BB32C-3.1	0.000495	0.0968	0.81	6759	1.62	1656.2	38.2	1423	47	3.58	3.4	0.2889	2.4	0.690
BB32C-4.1	0.000087	0.0914	0.14	5850	1.46	1615.4	26.7	1429	15	3.50	1.9	0.2817	1.7	0.907
BB32C-4.2	0.000262	0.0950	0.42	5032	1.29	1585.8	25.8	1454	40	3.49	2.7	0.2767	1.7	0.628
BB32C-1.1	0.000168	0.0933	0.27	4769	3.13	1456.7	22.5	1446	9	3.18	1.7	0.2534	1.6	0.957
BB32C-1.2	0.001005	0.1055	1.63	4121	1.98	1331.1	22.1	1458	45	2.91	2.9	0.2309	1.7	0.591
BB32C-1.3	0.000016	0.0919	0.03	4978	1.18	1515.6	23.4	1461	5	3.34	1.6	0.2642	1.6	0.989
BB32B-3.1	0.000251	0.0883	0.41	4635	0.68	1314.7	20.9	1310	27	2.64	2.2	0.2262	1.7	0.765
BB32B-3.2	0.000010	0.0889	0.02	4732	1.53	1397.4	22.6	1400	10	2.96	1.8	0.2421	1.7	0.956
BB32B-4.1	0.003319	0.1372	5.40	4500	1.96	1405.0	30.7	1446	377	3.06	19.9	0.2441	2.2	0.111
BB32B-4.2	0.001244	0.1067	2.03	6606	1.71	1437.5	22.9	1412	90	3.07	5.0	0.2495	1.7	0.333
BB32B-2.1	-0.000001	0.0909	0.00	6090	2.50	1565.2	25.2	1446	4	3.42	1.7	0.2729	1.7	0.991
BB32B-2.2	0.000012	0.0911	0.02	4805	3.59	1480.9	23.3	1444	5	3.23	1.6	0.2577	1.6	0.988
MC-3-03 (McNamara Formation)														
MC5A-1.1	0.000413	0.0851	1.10	1202	5.02	1091.9	24.0	1179	30	2.03	2.7	0.1853	2.3	0.836
MC5G-1.1	0.000909	0.0899	1.93	844	6.46	1032.9	22.2	1121	70	1.85	4.2	0.1745	2.2	0.538
MC5E-1.1	0.001435	0.0961	2.84	1498	12.79	994.6	19.7	1086	93	1.75	5.1	0.1675	2.1	0.409
MC5H-1.1	0.000400	0.0991	4.56	5186	4.91	662.3	11.9	1499	22	1.45	2.2	0.1126	1.9	0.852
GR-4-03 (Garnet Range Formation)														
GR22A-1.1	0.000612	0.0793	2.95	2923	8.12	428.2	8.0	944	50	0.68	3.1	0.0700	1.9	0.607
GR21F-1.1	0.003688	0.1181	6.94	2281	8.78	647.2	13.3	771	439	0.95	21.0	0.1061	2.4	0.112
GR21D-1.1	0.000015	0.1030	-1.66	7969	1.29	1919.9	27.8	1676	4	4.84	1.5	0.3412	1.5	0.988
GR21E-1.1	0.001657	0.0955	4.65	3000	7.54	519.0	9.9	981	212	0.84	10.6	0.0853	1.8	0.175

GR18H-1.1	0.003612	0.1234	7.98	3313	7.39	545.1	13.5	980	278	0.89	13.8	0.0897	2.4	0.172
GR18G-1.1	0.000194	0.1040	0.64	1314	11.81	1594.8	22.5	1648	14	3.93	1.6	0.2816	1.5	0.886
GR18G-1.2	0.000223	0.1025	2.81	1534	12.13	1165.4	22.9	1613	19	2.78	2.2	0.2031	2.0	0.896
GR9C-1.1	0.000619	0.0809	0.76	2505	9.50	1057.1	17.4	989	59	1.77	3.4	0.1777	1.7	0.510
GR18A-1.1	0.000352	0.0809	0.58	5162	1.77	1095.9	15.4	1092	29	1.94	2.0	0.1853	1.5	0.714
GR18D-1.1	0.000647	0.0825	2.45	2338	9.21	685.0	10.0	1020	69	1.15	3.7	0.1136	1.5	0.401
GR18F-1.1	0.002497	0.1070	6.34	6019	18.92	438.8	14.3	966	349	0.71	17.4	0.0718	3.2	0.182

P-1-03 (Pilcher Formation)

session 1														
P1L1A-1.1	0.001555	0.0887	2.70	9020	3.26	203.3	7.7	817	119	0.30	6.9	0.0327	3.8	0.560
P1L1B	0.000431	0.0777	0.74	569	6.77	881.1	16.5	973	63	1.45	3.7	0.1470	2.0	0.534
P1L1F-1.1	0.001084	0.0852	1.87	611	7.41	1036.9	21.0	919	123	1.67	6.4	0.1736	2.1	0.335
P1L2E-1.2	0.000632	0.0790	1.09	1461	4.64	454.2	16.5	927	64	0.72	4.9	0.0742	3.7	0.764
P1L2B-1.1	0.005149	0.1271	9.42	144993	1.53	254.1	17.9	268	1233	0.29	54.3	0.0402	7.4	0.136
P1A1G-1.2	0.000150	0.0712	0.26	1643	3.93	266.1	4.3	899	39	0.41	2.5	0.0430	1.6	0.655
P1A2C-1.1	0.000171	0.0757	0.29	1617	12.26	935.6	12.4	1023	21	1.58	1.7	0.1568	1.4	0.800
P1A2F-1.1	0.000352	0.0791	0.60	2002	6.10	501.6	6.8	1043	39	0.84	2.4	0.0825	1.4	0.581
P1A2F-1.2	0.000352	0.0764	0.60	1434	7.02	661.6	12.6	968	32	1.08	2.5	0.1093	2.0	0.785
P1A1E-1.1	0.000597	0.0838	1.01	837	6.09	610.1	13.5	1078	57	1.05	3.6	0.1011	2.3	0.626
P1A1E-1.2	0.001072	0.0841	1.85	9080	2.33	180.4	4.8	891	68	0.28	4.3	0.0290	2.7	0.630
session 2														
P1A1-15-1.1	0.000062	0.0750	0.11	486	8.44	950.9	8.2	1045	25	1.63	1.5	0.1596	0.9	0.584
P1A1-7-1.1	0.000081	0.0768	0.14	2181	6.12	635.0	7.8	1086	19	1.10	1.6	0.1053	1.3	0.798
P1A1-6-1.1	0.000423	0.0791	0.72	1481	8.37	536.8	4.0	1017	42	0.89	2.2	0.0884	0.8	0.348
P1A1-4-1.1	0.000113	0.0799	0.19	1517	17.30	879.4	5.9	1155	20	1.60	1.2	0.1479	0.7	0.572
P1A1-4-1.2	0.000141	0.0810	0.24	1546	11.22	654.2	13.2	1173	24	1.19	2.4	0.1090	2.1	0.868
P1A1-4-1.3	0.000145	0.0779	0.24	1138	17.95	959.6	8.0	1092	25	1.69	1.5	0.1614	0.9	0.578
P1A1-1-1.1	0.000132	0.0754	0.22	1847	7.06	767.1	5.6	1028	26	1.29	1.5	0.1277	0.8	0.497
P1A1-13-1.1	0.000710	0.0883	1.19	1472	10.94	587.1	4.6	1154	48	1.05	2.6	0.0975	0.8	0.320
P1L1-3-1.1	0.000993	0.0874	1.69	1024	9.11	953.2	15.3	1021	68	1.61	3.8	0.1598	1.7	0.447
P1L1-2-1.1	0.000325	0.0793	0.55	2091	10.87	363.4	2.4	1060	43	0.61	2.2	0.0594	0.7	0.306
P1L1-1-1.1	0.001737	0.1007	2.94	1158	10.45	678.8	6.5	1095	102	1.18	5.2	0.1129	1.1	0.204
P1A2-5-1.1	0.001243	0.0918	2.11	996	7.75	887.0	7.6	1043	72	1.52	3.7	0.1485	0.9	0.249
P1A2-6-1.1	0.000563	0.0801	0.96	2628	5.90	692.0	5.5	987	49	1.14	2.6	0.1146	0.8	0.325
P1A2-7-1.1	0.000623	0.0825	1.06	1492	10.43	672.8	5.3	1031	45	1.13	2.4	0.1115	0.8	0.347
P1A2-7-1.2	0.000139	0.0774	0.24	1567	6.59	734.9	9.5	1078	22	1.27	1.7	0.1224	1.3	0.773
P1A2-8-1.1	0.000074	0.0769	0.12	1631	15.53	847.7	5.5	1092	18	1.49	1.1	0.1420	0.7	0.601

1 ²⁰⁶Pb/²³⁸U ages possibly affected by matrix mismatch with standard.
2 ²⁰⁶Pb/²³⁸U ages corrected for common Pb using the ²⁰⁷Pb-correction method; ²⁰⁷Pb/²⁰⁶Pb ages corrected for common Pb using the ²⁰⁴Pb-correction method.
Decay constants from Steiger and Jäger (1977).
3 1-sigma errors.
4 Radiogenic ratios, corrected for common Pb using the ²⁰⁴Pb-correction method, based on the Stacey and Kramers (1975) model.

Table 3. Trace element data of xenotime overgrowths, Belt Supergroup, western Montana.

sample	La ¹	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	total REE ²	Th	U
Pilcher Formation (P-1-03)																	
P1A1D-1.1	1	25	18	550	10372	6960	55674	9223	43565	8021	17762	2166	10867	1477	16.7	17151	6246
P1A1F-1.1	1	37	57	2069	25808	16905	127480	18847	83561	14768	33378	4182	21713	2580	35.1	6344	1111
P1A1F-1.2	0	14	24	932	15205	9492	76438	12616	60547	11172	25111	3087	15727	1958	23.2	20267	2531
P1A1G-1.2	0	13	20	770	15957	11103	85168	13175	60647	10771	23941	2884	14941	1840	24.1	12549	2381
P1A2C-1.1	3	49	27	811	14260	10692	80984	12435	59730	11056	25668	3312	17023	2307	23.8	18926	7942
P1L1B-1.2	0	6	13	555	12355	9055	85277	13781	64342	11878	26729	3334	17617	2194	24.7	15057	1904
P1L1F-1.1	1	8	9	437	11826	8815	75510	12115	62363	12583	31143	4027	21268	2808	24.3	6317	1011
P1L1H-1.1	1	34	23	715	11583	7705	65485	11019	52077	9327	20802	2675	13527	1842	19.7	20002	6547
P1L2A-1.1	2	50	20	740	14898	10527	82664	12653	56874	10258	22918	2844	14238	1981	23.1	18888	4625
P1L2B-1.2	1	114	16	531	10465	7385	58350	9517	45325	8086	18603	2341	12010	1648	17.4	13019	5124
P1L2C-1.2	0	8	15	574	12275	8842	82634	13601	63727	11289	24759	3001	15637	1999	23.8	15953	2779
P1L2E-1.1	0	5	9	409	10114	8100	72421	11209	50659	9208	21223	2656	14175	1855	20.2	9013	1669
P1L2E-1.2	0	4	7	325	8944	7939	75203	11836	55825	10806	25441	3294	17488	2263	21.9	8665	1427
P1A1-13-1.1	1	9	11	507	12220	8793	72082	10897	50873	9564	22917	2986	15507	2055	20.8	9204	1785
P1A1-15-1.1	0	10	20	888	17186	10547	99710	16136	74939	13291	29704	3672	19150	2356	28.8	12902	1714
P1A1-4-1.1	1	37	45	1608	21475	10485	87023	13355	60285	10664	22811	2720	13854	1688	24.6	29011	1575
P1A1-4-1.3	1	43	67	2125	28423	14405	122074	18773	86734	15276	32936	3946	20026	2460	34.7	36384	2612
P1A1-7-1.1	0	6	11	445	8246	4838	48391	8286	39674	7267	16540	2061	11027	1407	14.8	21147	1158
P1A2-6-1.1	1	7	14	636	17880	14631	122181	18755	86023	15565	35190	4282	22364	2833	34.0	23567	3520
P1A2-7-1.1	2	46	25	841	13635	8283	73044	12219	58308	10456	24218	3092	16103	2255	22.3	27726	5796
P1A2-7-1.2	1	7	14	602	15003	12230	122059	18843	86639	16140	37724	4704	25323	3119	34.2	11949	1558
P1A2-8-1.1	0	14	23	980	15320	7799	72477	12458	59420	10843	24544	3006	15759	2019	22.5	22128	1912
P1L1-1-1.1	0	11	15	649	12124	7971	70364	10834	48188	8669	19887	2474	12966	1570	19.6	17500	1572
P1L1-2-1.1	0	12	16	646	11987	8193	64188	10749	52027	9573	21261	2572	12761	1634	19.6	25357	2537
P1L1-2-1.2	0	9	12	443	10731	8270	64344	11228	54591	9876	21374	2515	12523	1565	19.7	28651	2795
P1L1-3-1.1	0	8	9	444	10879	8170	61120	9352	43856	8354	19648	2457	12701	1722	17.9	6938	999
Prichard Formation (BB32)																	
BB32-E15-1.149	227	84	1710	6804	4037	30705	7828	53137	11697	31792	4651	27739	3914	18.4	15458	5080	
BB32-E14-1.135	186	75	1378	5433	3012	29110	8014	53037	11524	28001	4386	21589	3832	17.0	10145	6659	
BB32-E3-1.1 25	188	83	1436	5190	2546	28622	8031	60677	14987	41640	6794	39856	6960	21.7	16193	8166	
BB32-E11-1.126	262	133	2193	7257	3798	32202	8557	57014	12306	31628	4900	27482	4622	19.2	7333	8007	
BB32-A7-1.1 20	356	151	2115	6279	3012	30789	8561	59784	13264	35465	5562	34985	5576	20.6	4914	9801	
BB32-A7-2.1 24	199	116	1216	4667	2525	25114	6335	44565	10099	27211	4333	24868	4358	15.6	11037	5615	
BB32-A7-3.1 36	774	386	5095	12842	7225	47608	11412	67223	13254	33432	5073	34278	5080	24.4	4792	11730	
BB32-A7-4.1 21	361	205	3331	10586	5144	45707	11298	66459	13040	31154	4279	22749	3134	21.7	10392	7501	
BB32-A7-4.2 3	93	71	1430	6603	3547	34398	9299	58524	11994	29253	4113	21645	2969	18.4	3699	6357	
BB32-A7-5.1 5	121	90	1681	6297	3396	30580	8426	55782	11980	31058	4459	24387	3295	18.2	2905	6000	
BB32-E1-1.1 24	313	159	2744	9161	5107	37901	9576	59614	12168	30157	4235	23898	3621	19.9	7959	7733	

BB32-E1-2.1	49	857	386	4689	9290	4012	32597	8873	60215	12682	31328	4587	26647	3834	20.0	1111	7503
BB32-E1-3.1	41	796	385	4818	10621	4852	39956	10698	73909	16160	42615	6554	38213	6076	25.6	6361	11482

- 1 Values of all elements in parts per million.
2 Total REE in weight %.

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