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Prolonged high relief in the northern Cordilleran orogenic front during middle and late Eocene extension based on stable isotope paleoaltimetry

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ABSTRACT

The paleoelevation and size of the North America Cordilleran orogen during the late Cretaceous–Paleogene contractional and subsequent extensional tectonics remain enigmatic. We present new estimates of paleorelief of the northern Cordilleran orogenic front during the middle and late Eocene using oxygen isotope compositions of unaltered molluscan fossils and paleosol carbonates in the Kishenehn basin. Bounded by several mountains ranges to the east, the Kishenehn basin was a half graben developed during middle Eocene to early Miocene collapse of the Cordilleran orogen. These mollusk taxa include three sympatric groups with affinities to wet tropical, semi-arid subtropical, and temperate environments. Our reconstructed surface water $\delta^{18}O$ values vary between $-19.8‰$ and $-6.3‰$ (VSMOW) during the middle and late Eocene. The large differences in paleoenvironments and surface water $\delta^{18}O$ values suggest that the catchment of the Kishenehn basin was at variable elevation. The estimated paleorelief between the basin and the surrounding mountains, based on both Rayleigh condensation model and predictions of Eocene precipitation isotope values using an isotope-enabled global climate model, is ∼4 km, and the basin floor was <1.5 km high. This high topography and high relief paleogeography suggest that the Cordilleran orogenic front reached an elevation of at least 4 km, and the crust thickness may have reached more than 55 km before Eocene gravitational collapse. We attribute the maintenance of high Eocene topography to the combination of an inherited thick crust, thermal uplift caused by mantle upwelling, and isostatic uplift caused by removing lower lithosphere or oceanic slab.

1. Introduction

The construction and collapse of the North America Cordilleran orogen reflect changes of lithosphere structure, plate tectonics, and mantle dynamic process. Although the tectonic history of the orogen has been extensively studied, little is known about the paleoelevation and size of the Cordilleran orogenic plateau during the Late Cretaceous–early Paleogene contractional and subsequent late Paleogene–recent extensional tectonics (e.g., Wernicke et al., 1987; Constenius, 1996; Sonder and Jones, 1999; DeCelles, 2004; Fuentes et al., 2011; Chamberlain et al., 2012; Fuentes et al., 2012; Lechler et al., 2013). In northwestern Montana and adjacent parts of Canada, crustal shortening during the Late Cretaceous and early Eocene associated with eastward progressive displacements of multiple thrust sheets, including the immense Lewis thrust, constructed an edifice of highly deformed Proterozoic–Mesozoic strata (e.g., Fuentes et al., 2011, 2012). After large-magnitude post-early Eocene extension, modern crustal thickness in the area remains high (∼40 km, Constenius, 1996; Perry et al., 2002), suggesting that the pre-extensional crustal thickness was very high (>50 km). If limited addition of high-density material occurred to the lithosphere during the compressional tectonics, isostatic compensation of such thick crust would have resulted in high pre-extensional paleoelevation (>3 km) in the Cordilleran orogen (Lachenbruch and Morgan, 1990). Currently, the lack of accurate quantitative paleoelevation estimates for the Cordilleran orogenic front limits our ability to understand the geodynamic process that changed lithosphere structure.

Extensional collapse of the Cordilleran orogen in British Columbia and northwestern Montana initiated during the early middle Eocene (ca. 53–48 Ma; e.g., Constenius, 1996; Mulch et al., 2004, 2007; Foster et al., 2007), associated with the rapid drop in North

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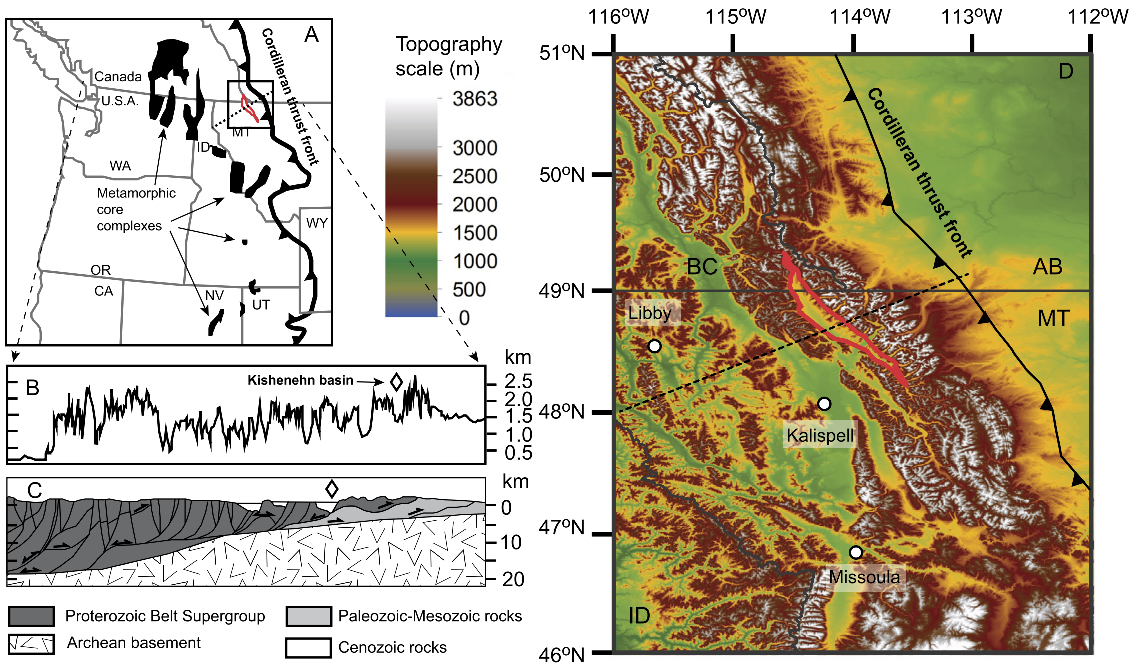

Fig. 1. A. Location of the Kishenehn basin (red polygon) with respect to the Cordillera thrust front and Eocene extensional metamorphic core complex in the western United States (modified from Constenius, 1996, and Foster et al., 2007). B. W–E elevation profile along the U.S. and Canada border. C. Cross section along the dashed line in A (modified from Fuentes et al., 2012). D. Relief map of the Kishenehn basin in relation to the nearby mountain ranges. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

America–Pacific plate convergence rate (Engebretson et al., 1985). The extension formed a network of half grabens (Constenius, 1996), and metamorphic core complexes (Wernicke et al., 1987; Sonder and Jones, 1999). The mechanism of extension has been attributed to the relaxation of horizontal stresses on the Cordillera that had high gravitation potential following a protracted episode of crustal shortening (e.g., Wernicke et al., 1987). Weakening of lithosphere by asthenosphere upwelling induced by lower crust delamination (e.g., Sonder and Jones, 1999; Liu, 2001), or removal of Farallon slab (Dewey, 1988; Humphreys, 1995), or a slab window (e.g., Breitsprecher et al., 2003; Haeussler et al., 2003) are other elements that potentially facilitated crustal spreading. Crustal extensional was partly concurrent with the southward migration of arc magmatism in the Cordillera hinterland (Humphreys, 1995), in particular the Absoroka–Challis–Kamloops volcanic field (Schmandt and Humphreys, 2011), thus may be associated with the southward removal of the subducting Farallon plate (Mix et al., 2011; Chamberlain et al., 2012). However, in the Cordillera foreland, it is suggested that magmatism occurred during the early and middle Eocene following a westward trend, in association with westward rollback of the Farallon plate (Coney and Reynolds, 1977; Constenius, 1996). In northwestern North America, extensional tectonics were associated with mafic magmatism in the Coast Mountains and Cascades, which was attributed to slab window opening related to the breakup of the Resurrection plate, or the Kula–Farallon slab window (e.g., Breitsprecher et al., 2003; Haeussler et al., 2003). Accurate quantitative paleoelevation histories during the extensional collapse of this orogen are critical to evaluate the geodynamic models of the extension.

Recent stable isotope paleoaltimetry studies have brought new understanding to the development of topography in the northern Cordillera during the latest Cretaceous and early Eocene, yet a clear picture of the paleotopography of the entire northern Cordillera during the Late Cretaceous–Paleogene contractional and subsequent extensional tectonics can not be depicted from a few scattered sites over a broad region. In Alberta, oxygen isotope compositions of freshwater invertebrate fossils suggest that the front of the Canadian Cordillera may have been as high as 4.5 km during the latest Cretaceous (Dettman and Lohmann, 2000; Fan and Dettman, 2009). In British Columbia, hydrogen isotope compositions of muscovite formed in detachment faults of metamorphic core complexes suggest a paleoelevation of ∼4 km soon after the initiation of extensional tectonism during the early middle Eocene (Mulch et al., 2004, 2007). This reconstruction is consistent with the high late early Eocene elevation estimated by a fossil floral physiognomy study in northern Washington (Wolfe et al., 1998). The attainment of high elevation in northern Cordillera during the early middle Eocene may represent the initiation of a renewed topographic gain in the North America Cordillera, which migrated southward and reached southern Idaho during the latest Eocene, and Nevada during the Oligocene (Mix et al., 2011; Chamberlain et al., 2012; McFadden et al., 2015). Nevertheless, most of the studies focus on the Cordilleran hinterland, and no study has constrained the paleotopography of the Cordilleran front during the late Paleogene.

Here we present new oxygen isotope data from middle and late Eocene terrestrial and aquatic mollusk fossils and paleosol carbonates in the Kishenehn basin in northwestern Montana and southeastern British Columbia, in combination with previously published stable isotope results, to reconstruct the elevation history of the Cordilleran orogenic front in that region (Fig. 1). The coexistence of three disparate types of fossil mollusks possessing distinct paleoenvironmental affinities, wet tropical, semi-arid subtropical and temperate, suggests a broad range of paleoclimate and paleoelevation existed in the catchment of the Kishenehn basin during the Eocene. The differences of $\delta^{18}O$ values between the alpine snowmelt and basinal precipitation further show that relief of the Cordilleran orogenic front was more than 4 km during the middle and late Eocene extension. We suggest that the persistence of high elevation and high relief during this episode of extension in the Cordilleran orogenic front was the result of mantle upwelling combined with the support of an inherited thick crust and associated isostatic uplift concomitant with changes in the geometry of the subducted Farallon plate.

2. Geologic background

The Lewis thrust, the predominant thrust structure in the Cordilleran thrust front of NW Montana, SE British Columbia, and SW Alberta, places 6 to 7 km of Proterozoic and Lower Paleozoic rocks onto a complexly deformed footwall of Paleozoic and Mesozoic strata (e.g., Constenius, 1996; Osadetz et al., 2004; Fuentes et al., 2012). The youngest rocks cut by the thrust are Campanian in age and geochronologic and stratigraphic evidence suggests final motions on the thrust occurred in the latest Paleocene and earliest Eocene (ca. 52 Ma; Fuentes et al., 2011). Reconstructions of the thickness of the Lewis thrust sheet at the time of emplacement suggest that 4.0 to 5.5 km of Upper Cretaceous strata were removed prior to the initiation of normal faulting, and that the thrust sheet was ∼12–13.5 km thick at the time of initiation (Feinstein et al., 2007).

The Kishenehn basin is situated southwest of the Lewis thrust salient in northwestern Montana and southeastern British Columbia. It is a narrow, asymmetric graben containing up to 3300 m of middle Eocene–early Miocene synextensional basin fill (Fig. 2; Constenius, 1988). Basin subsidence was controlled by faults of the Flathead listric normal fault system, which includes the Flathead, Blacktail and Roosevelt faults that bound the basin to the northeast (McMechan and Price, 1980; Constenius, 1982, 1996). Antithetic faults, such as the Nyack and Shepp faults, were formed along the southwest margin of the basin (McMechan and Price, 1980; Constenius, 1982, 1996). Basin fills in the Kishenehn basin display synextensional growth, that is, a gradual flattening of dip in successively younger units and thickening toward faults of the Flathead system (McMechan and Price, 1980). Importantly, this combination of tectonic subsidence and related sedimentation has resulted in a near continuous sedimentary record of the paleoenvironment and paleoclimate for a period of more than 20 Myr.

Presently, the Kishenehn basin is at 1.2–1.5 km asl, and the basin-bounding mountains are 2.4–3.1 km high (Fig. 1). Modern drainage, including the three forks of the Flathead River, flows west and merges into the Columbia River to the west of the Continental Divide. East of the Continental Divide, drainages are to the east into the Missouri River or northeast into Hudson Bay. The climate in the study area is influenced by Continental Polar air masses during winter time and Maritime Polar air masses from the Northern Pacific during the rest of the year, thus it is characterized by mild winters and cool summers. The Kishenehn basin has ∼400 cm of mean annual precipitation and the mean monthly temperature varies between −11 °C and 15 °C.

Our molluscan fossil samples were collected from two widely spaced localities in the southernmost and northern parts of the Kishenehn basin. The first groups are from the middle Eocene Coal Creek Member of the Kishenehn Formation exposed along the bank of the Middle Fork of the Flathead River (Fig. 2). The Coal Creek Member is about 1120 m thick, and contains predominantly interbedded sandstone, siltstone, coal, oil shale, marlstone, and sandy pebble–cobble conglomerate (Constenius, 1982). The member is further subdivided into three sequences bounded by gradational contacts. The lower sequence consists primarily of open lake (profundal) lacustrine and lacustrine-deltaic deposits; the middle sequence consists of alternating profundal lacustrine, lacustrine delta and fan-delta, and paludal deposits, and the upper sequence comprised of lake-margin, paludal, and fan-delta deposits (Pierce and Constenius, 2014). Paleosol carbonate nodules were only found in the upper sequence. Paleocurrent directions measured in the overlying alluvial fan unit, the Pinchot Conglomerate Member, are all westward suggesting the creeks and rivers discharging into the basin mainly drained the Lewis thrust front during this phase of extension (Constenius, 1982). Vertebrate fossils present in the Coal Creek Member are of the late Bridgerian or early Uintan land mammal stages (ca. 47–45 Ma) (e.g., Smith et al., 2003). An ash bed from the middle sequence of the Coal Creek Member yielded a biotite $^{40}Ar/^{39}Ar$ age of 46.2 ± 0.4 Ma and a zircon fission-track age of 43.5 ± 4.9 Ma (Constenius, 1996). By assuming a sedimentation rate of ∼500 m/Myr (McMechan, 1981), We estimate the age of the upper sequence of the member as ca. 45 Ma.

The second group of mollusks was collected from the lower member of the Kishenehn Formation along the North Fork of the Flathead River in southeastern British Columbia (McMechan, 1981) and northwest Montana (Pierce and Constenius, 2001). Fossil mammals found in association with these mollusks are of the Chadronian land mammal stage (ca. 38–33.9 Ma; e.g., Russell, 1964; Pierce and Constenius, 2001). The member contains mudstone, lignite, siltstone, sandstone, and conglomerate that were deposited in lacustrine, paludal, and fluvial environments (McMechan and Price, 1980). Proximal to the Clark Range in the footwall of the Flathead fault, the upper member of the Kishenehn Formation contains deposits of debris flows and landslide megabreccias (McMechan, 1981), indicating that there was significant topographic relief associated with the ancestral Clark Range.

3. Mollusks samples and their living habits

The molluscan fauna found in the Coal Creek Member and the lower member along the Middle Fork and North Fork of the Flathead River and their tributaries are described in Pierce and Constenius (2001, 2014). The taxa, location and estimated ages of the molluscan fossils we studied are summarized in supplementary data table. The mollusks used in this study are from the families *Planorbidae*, *Lymnaeidae*, *Sphaeriidae*, *Unionidae*, *Valvatidae*, *Vertiginidae*. Mollusks are ideal for analysis of past climates and environments because they have limited mobility, and genera/families tend to live in characteristic habitats through geologic history. The mollusk fossils in the study area were divided into three sympatric groups based on their interpreted habitats and environmental preferences (Pierce and Constenius, 2001, 2014): Group I – tropical wet environment; Group II – semi-arid subtropical environment; and Group III – temperate environment. The modern analogs of the Group I are found in the Caribbean, Central America, and South America with a mean annual temperature of 25–27 °C, an annual temperature range of 3–10 °C, and precipitation >100 cm. The modern analogs of the Group II are found in the region from northern Gulf of Mexico to Baja California, Central America, and South America with a mean annual temperature of 11–22 °C, an annual temperature range of 10–22 °C, and precipitation of 24–61 cm. Gastropods representatives of the Group III have their modern analogue residing within the United States and southern Canada, with a mean annual temperature of 7–18 °C, an annual temperature range of 25–30 °C, and precipitation of ∼100 cm.

4. Methods

We conducted X-ray diffraction (XRD) analysis to representative paleosol carbonates, large specimens of the freshwater Unionidae bivalve, *Elliptio salissiensis*, and aquatic gastropod, *Biomphalaria kishenehnsis*, to determine carbonate type. Samples were powdered using ceramic mortar and pestle. Diffraction patterns were obtained using a Bruker D8 Advance Diffractometer equipped with Cu(Kα) radiation at 40 keV and 40 mA. Samples were scanned from 25° to 55° 2θ at 0.02° steps. Carbonate mineralogy was determined based on the position of the d(104) peak. Polished thin sections were produced from representative samples. We examined the thin sections utilizing both polarizing and cathodoluminescence microscopes to characterize their primary and diagenetic fabrics. A Reliotron cold cathodoluminoscope was operated at an

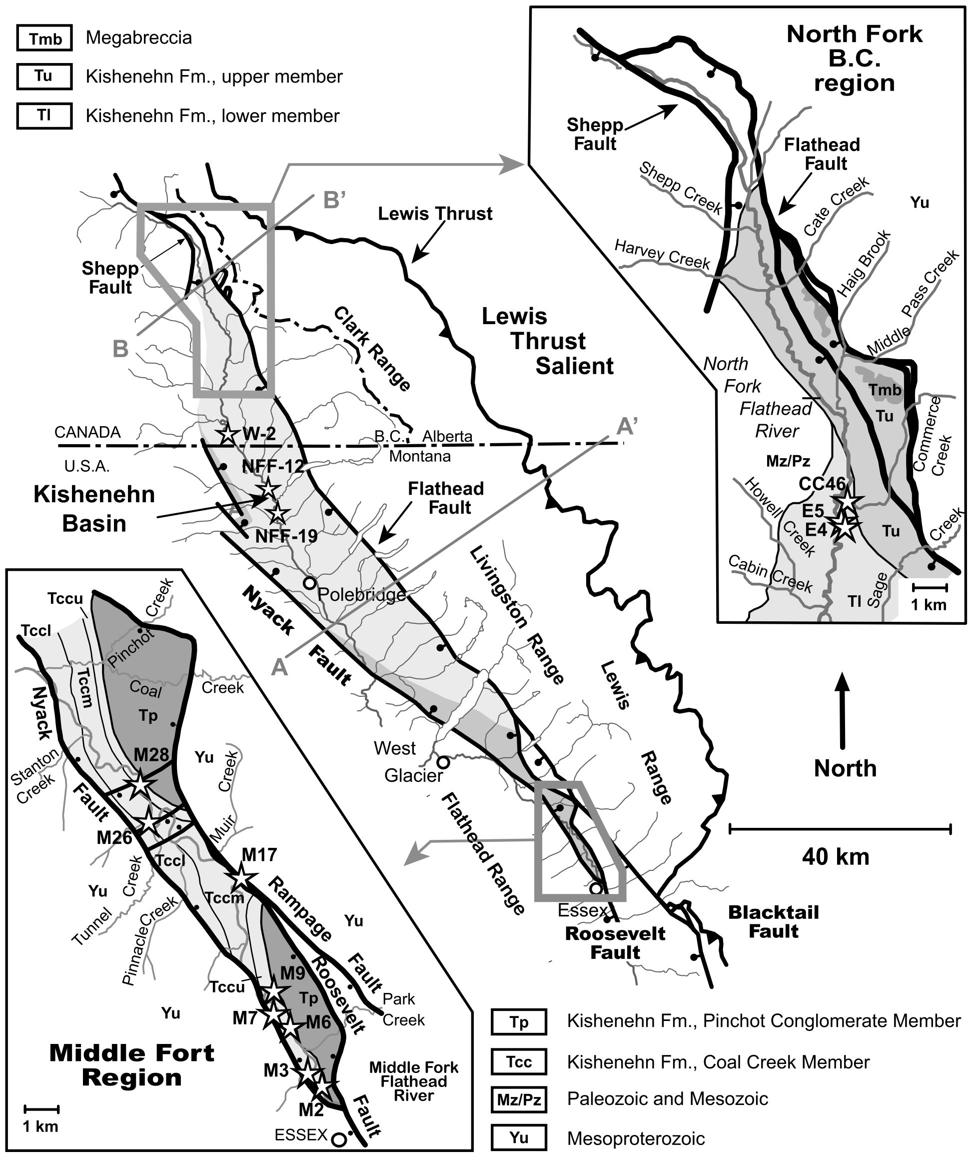

Fig. 2. Geologic index map of the Lewis thrust salient and Kishenehn basin with detailed insets showing the study areas at the northern and southern parts of the basin. Sample sites are designated with stars. Grey lines represent drainage of the Flathead River and its tributaries. Profiles A–A′ and B–B′ are lines of cross-sections where reconstructions of the pre-erosional thickness of the Lewis thrust was estimated in Constenius (1996) and Feinstein et al. (2007), respectively. Figures are modified from McMechan (1981), Osadetz et al. (2004), and Pierce and Constenius (2014).

acceleration voltage of 8–9 kV and a beam current intensity of 0.4–0.5 mA to examine the luminescence of carbonate cement.

We drilled carbonate from the shells using a handheld Dremel drill at low speed under a microscope. We avoided the matrix in the host rocks to ensure minimum contamination. Enough material was collected for a measurement using the entire shell of very small (<2 mm in diameter) mollusks. For unionids, when possible, we drilled through the shell body in order to integrate isotopic variation and derive growth amount-weighted average isotope values. We also drilled carbonate nodules under the microscope to avoid sparry calcite. We measured bulk shell isotope composition for most of the mollusk samples, and sampled along shell growth bands using fragments of large (>2 cm) mollusks of *Elliptio* and *Biomphalaria*. All the carbonate samples were measured using a Gasbench II connected to a Delta V Advantage Mass Spectrometer at the University of Texas at Arlington or a Kiel connected to a MAT 252 Mass Spectrometer at the University of Arizona. The isotope values were corrected using two international standards (NBS 18 and NBS 19). All the isotope values were reported relative to VPDB. The standard deviations of both carbon and oxygen isotope values, based on repeated analysis of in-house standards, are less than 0.15‰.

5. Results

The studied unionid and gastropod fossils all display good nacreous luster, suggesting aragonite composition. XRD results verify that the *Elliptio* and *Biomphalaria* fossils with this appearance are composed of aragonite, while the carbonate nodules consist of calcite (Fig. 3). Under a polarizing microscope, the carbonate nodules are observed to be micritic, and the shells display annual growth bands (Fig. 4). Under a cathodoluminescence microscope, the shells have visible nacreous plates and green-gold luminescence characteristic of aragonite, and the carbonate nodules display dense, homogeneous, and dull luminescence (Fig. 4).

The $\delta^{18}O$ values of the Group I (tropical) aquatic mollusks vary between −18.6‰ and −5.2‰, and the values of the Group I terrestrial gastropods vary between −15.5‰ and −6.5‰ (Fig. 5). The $\delta^{18}O$ values of the Group II (subtropical) terrestrial gastropods vary between −18.6‰ and −7.0‰. The $\delta^{18}O$ values of the Group III

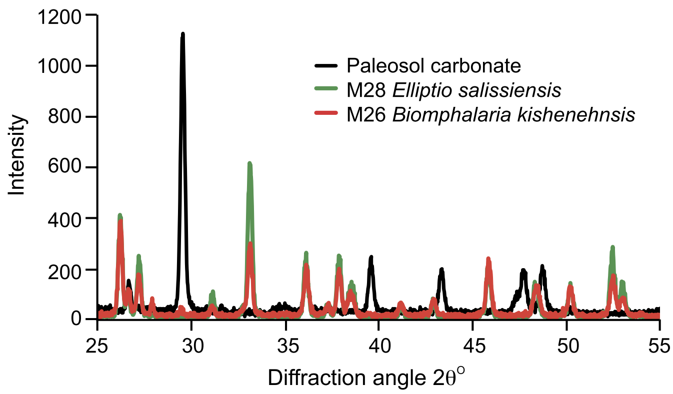

Fig. 3. XRD patterns show that the representative *Elliptio* bivalve, and *Biomphalaria* gastropod are in aragonite, and paleosol carbonate in calcite.

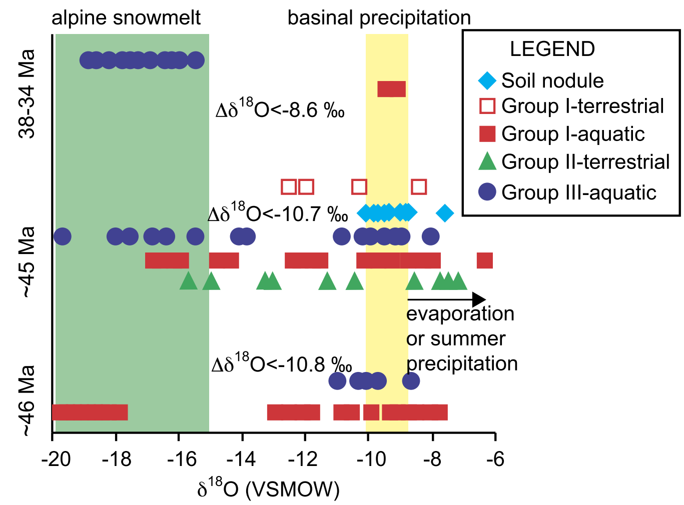

Fig. 5. Stable isotope data of the studied mollusks and paleosol carbonates in the Kishenehn basin.

(temperate) aquatic mollusks vary between −18.8‰ and −7.0‰. The $\delta^{18}O$ values of paleosol carbonate vary between −13.5‰ and −10.9‰. Ancient surface water $\delta^{18}O$ values were calculated from the $\delta^{18}O$ values of *Elliptio* based on the regression relationship between modern river water and shell aragonite $\delta^{18}O$ values (Kohn and Dettman, 2007). The surface water $\delta^{18}O$ values were calculated from the $\delta^{18}O$ values of other families of mollusks based on the mean annual temperature estimated from their modern living relatives and oxygen isotope fractionation between aragonite and water (Kim et al., 2007). Note that even though the uncertainty in these estimated temperatures may be large, the corollary uncertainty in the calculated $\delta^{18}O$ value of surface water is relatively small. A 5 °C uncertainty leads to only a 1‰ uncertainty in water $\delta^{18}O$. We also assume that the *Valvata* and *Lymnaea* shells are aragonite, like the vast majority of freshwater mollusks and species within those genera, although we were unable to X-ray these very small shells to determine their mineralogy. An error in this assumption makes a small difference in the calculated $\delta^{18}O$ value of surface water, ∼0.8‰ (Kim and O'Neil, 1997; Kim et al., 2007). This difference is very small compared to the

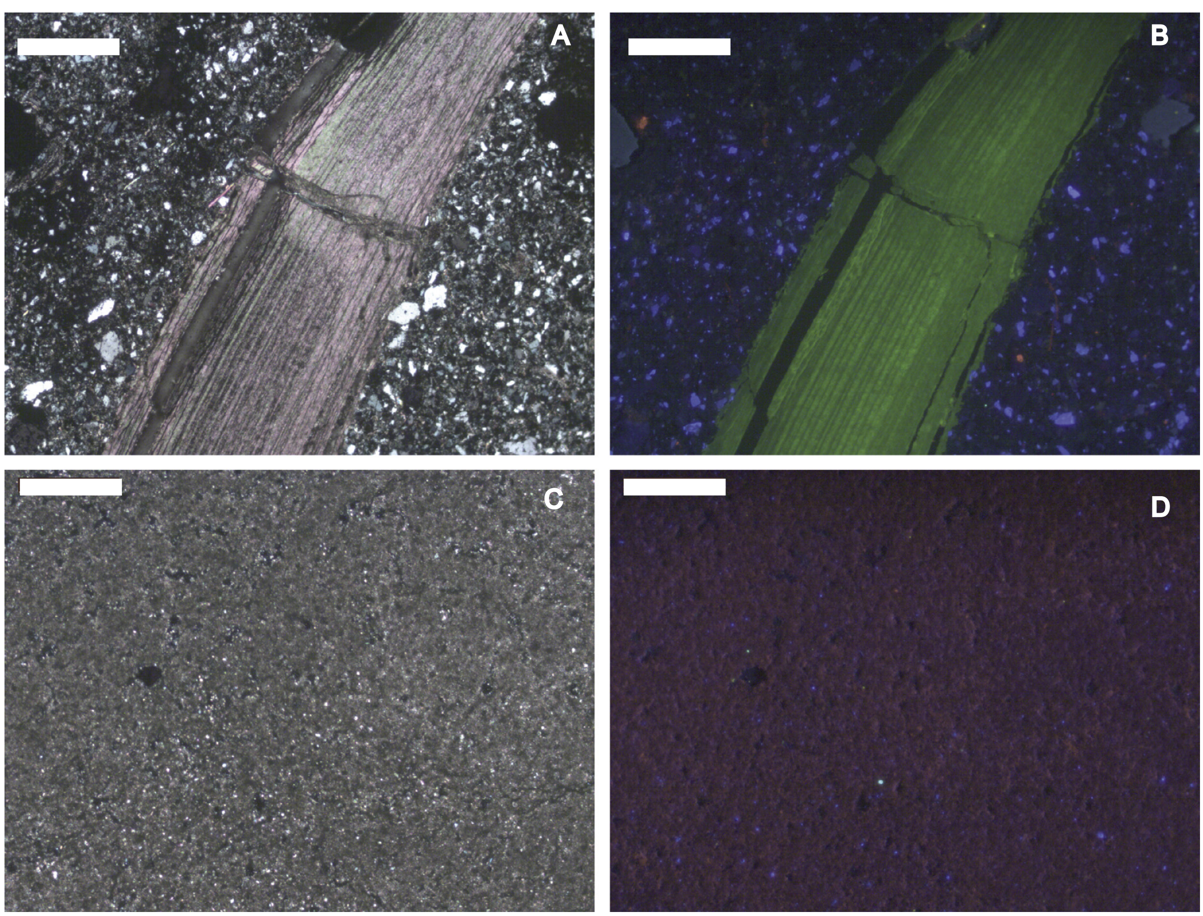

Fig. 4. Paired polarized light (left) and CL images (right) of the studied *Elliptio* bivalve (A, B), and paleosol nodules (C, D). Note the nacreous plates and green-gold luminescence of shell aragonite, and dense, homogeneous and dull luminescence of paleosol carbonate nodule. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

large variation of mollusks and paleosol carbonate $\delta^{18}O$ values, thus does not influence our interpretation of the oxygen isotope compositions of surface waters.

Ancient basinal precipitation $\delta^{18}O$ values were calculated from the $\delta^{18}O$ values of carbonate nodules based on oxygen isotope fractionation between calcite and water (Kim and O'Neil, 1997). The formation temperature of the paleosol carbonate was estimated to be 30 °C, which is 5 °C lower than the formation temperature of the early Eocene paleosol carbonates in the Bighorn basin ~5° south of the study area (Snell et al., 2012). The 5 °C difference can be attributed to slight global cooling following the early Eocene, and latitude difference. The calculated surface water $\delta^{18}O$ values vary between −19.8‰ and −6.3‰. The minimum and maximum surface water $\delta^{18}O$ values remain nearly the same for the entire study period (Fig. 5).

6. Discussions

6.1. Evaluation of diagenesis

Based on the physical appearance, XRD analysis, and petrographic observations of representative samples, and the large variations of isotope values, the shells and micritic paleosol carbonate nodules appeared unaltered. Aragonite is metastable, and typically alters into calcite during diagenesis. Our XRD results show that the carbonate shells of *Elliptio* and *Biomphalaria* fossils remain aragonite, ruling out influence of diagenesis. Petrographic observations show that shells have well-preserved growth bands and contain no sparry calcite, and the carbonate nodules are mostly micritic (Fig. 4), suggesting diagenesis was unlikely (e.g., Machel and Burton, 1992). Significant amounts of diagenesis would tend to homogenize the isotopic composition of shells or soil nodules. The large degree of isotopic variability in the same stratigraphic interval and within single shells suggest that diagenesis did not occur or is very minor in the Kishenehn Formation, and the isotope values reflect surface climate conditions.

6.2. Significance of the co-existing mollusks for paleoclimate and paleogeography

Modern analogs of the three climatic associations of mollusks are found in tropical, semi-arid subtropical, and temporal regions with a wide range of MAT and MAP (Pierce and Constenius, 2001). The unusual coexistence of these climatically disparate groups of mollusks during the middle and late Eocene probably reflects large variations in paleoclimate and paleotopographic relief between the basin floor and the surrounding mountains in the Kishenehn basin. Modern calibration studies of oxygen isotope fractionation in aquatic mollusks show that gastropod shell $\delta^{18}O$ values may be offset from the $\delta^{18}O$ values predicted by calcite–water equilibrium fractionation by ~1‰ (Shanahan et al., 2005). Unionid shell $\delta^{18}O$ values seem to reflect equilibrium fractionation within a restricted temperature range of shell growth (Dettman et al., 1999). Therefore, mollusk $\delta^{18}O$ values respond strongly and understandably to surface water $\delta^{18}O$ values and water temperatures during mollusk shell growth.

As in our earlier work (Dettman and Lohmann, 2000; Fan and Dettman, 2009), we interpret very low $\delta^{18}O$ values in Group I and III aquatic mollusk shell as reflecting rivers and lakes recharged by alpine snowmelt, and the snowmelt $\delta^{18}O$ values are less than −15‰. Higher $\delta^{18}O$ values are associated with animals that lived in rivers and lakes recharged by low-elevation basinal precipitation, with precipitation $\delta^{18}O$ values in the −9 to −10‰ range. The aquatic mollusks with the highest $\delta^{18}O$ values most likely lived in ephemeral streams or ponds that are recharged by low elevation summer precipitation, or influenced by evaporation, or both.

We use the $\delta^{18}O$ values of paleosol carbonates in the upper sequence of the Coal Creek Member to estimate the oxygen isotope composition of basinal precipitation. The calculated value, −10.1 to −9.0‰ is in agreement with estimates based on *Biomphalaria* fossils presented in black lacustrine shale in the middle sequence of the Coal Creek Member. It is generally agreed that paleosol carbonates are formed during the warm and dry season following the dominant wet season of the year, and their $\delta^{18}O$ values reflect mean annual or summer precipitation $\delta^{18}O$ values, with perhaps some degree of evaporation (e.g., Breecker et al., 2009; Hough et al., 2014). Our reconstructed water $\delta^{18}O$ values from the paleosol $\delta^{18}O$ values vary between −10.1‰ and −7.6‰, and we associate the lower end of this range with precipitation $\delta^{18}O$ values that are biased toward the mean annual rainfall and lack of evaporation. The reconstructed lake water $\delta^{18}O$ values from the *Biomphalaria* shell $\delta^{18}O$ values are in the range of −13.7 to −8.2‰, reflecting a balance between alpine snowmelt, basinal precipitation, and evaporation. Aquatic mollusks with intermediate $\delta^{18}O$ values lived in rivers and lakes that were recharged by both basinal precipitation and alpine snowmelt and the variation in $\delta^{18}O$ values reflect the relative abundances of the two sources of water.

Group I and II terrestrial gastropods have reconstructed water $\delta^{18}O$ values varying between −15.1‰ and −7.3. Studies of modern land snail shell $\delta^{18}O$ values suggest that although many factors, such as diet, evaporation, and temperature, can influence shell $\delta^{18}O$ values, precipitation $\delta^{18}O$ value is the dominant factor controlling oxygen isotope ratios, and that the taxonomy dependency of $\delta^{18}O$ values is very small (e.g., Balakrishnan and Yapp, 2004). The living habit of the Group II terrestrial snails and the variation of isotope values suggest that they lived in interfluvial areas at a range of elevations in a semiarid climate, most likely in the rain shadow west of the Lewis thrust front because of stronger Eocene summer monsoon with vapors transported from the east (e.g., Chamberlain et al., 2012). This interpretation is supported by the general westward paleoflow direction in the Kishenehn Formation (Constenius, 1982). The Group II land snails must have been washed into the basin by surface runoff. The Group I land snails lived in a tropical environment, which must have been present in low elevation riparian areas adjacent to drainages on the basin floor. The coexistence of the three groups of mollusks in the Kishenehn Formation suggests that the basin catchments had variable elevations and climate regimes through time and spatially.

6.3. Paleoelevation of the Cordilleran orogenic front during extension

Because studies of modern aquatic mollusks suggest their shell $\delta^{18}O$ values are formed in or nearly in equilibrium with surface water $\delta^{18}O$ values, we can use shell $\delta^{18}O$ values to calculate surface water $\delta^{18}O$ values in and around the basin. From these water $\delta^{18}O$ values we can reconstruct the paleoelevation of the basin catchments. Here we reconstruct paleoelevations using two approaches (Fig. 6). The first approach constrains paleorelief based on a thermodynamic model of Rayleigh condensation as air masses experienced adiabatic cooling and rain is extracted from the clouds (Rowley et al., 2007). Abundant geologic evidence suggests a high standing Cordilleran hinterland of >2 km existed during the Late Cretaceous–Paleogene (DeCelles, 2004; Fuentes et al., 2011, 2012; Snell et al., 2014). In the northern Cordillera, a region of ~4 km high with unknown relief and extent most likely existed to the west of the study area during the early middle Eocene (Wolfe et al., 1998; Mulch et al., 2007; Mix et al., 2011; Chamberlain et al., 2012). It has been proposed that the broad high Cordilleran hinterland blocked atmospheric moisture transported by westerly flow from the Pacific Ocean, and promoted the flow of moisture from the southeast that was transported from the

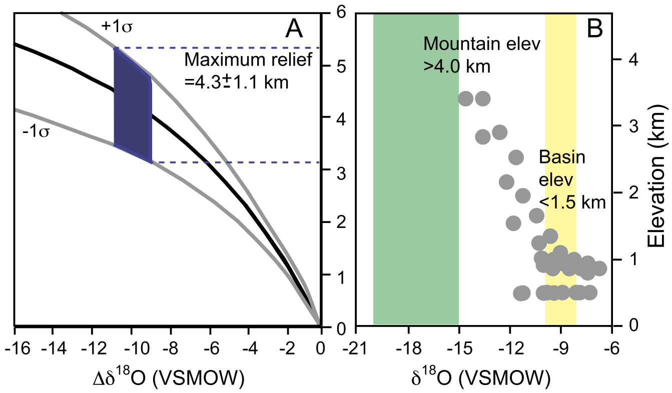

Fig. 6. A. Paleorelief estimate based on a thermodynamic air-mass lifting Rayleigh condensation model (Rowley, 2007). B. Paleoelevation estimates of mountains and basin floor based on the predicted Eocene precipitation $\delta^{18}O$ values at different elevations in the eastern flank of the Cordillera using isotope-enabled global climate model (Feng et al., 2013). See the text in section 6.3 for details.

Gulf of Mexico as summer monsoons (Chamberlain et al., 2012; Feng et al., 2013). Therefore, this approach assumes that moisture from the Gulf of Mexico reached the northern Cordillera during the middle and late Eocene and underwent orographic lift leading to rain-out and a lowering of the $\delta^{18}O$ values. The difference in isotopic composition of precipitation ($\Delta\delta^{18}O$) between high-elevation sites and contemporaneous basin floor was calculated as the difference between the most negative river and lake water $\delta^{18}O$ values and basinal precipitation $\delta^{18}O$ values. Based on the modeled isotopic lapse rate, and considering variations of relative humidity and sea surface temperature in the vapor origin area (Rowley, 2007), the $\Delta\delta^{18}O$ values of -10.8 to -8.6‰ yield a maximum relief between the basin and the surrounding mountains of 4.3 ± 1.1 km (1σ) (Fig. 6A). Although the warm Eocene sea surface temperature tends to increase the estimate to the upper limit (Rowley, 2007), this effect may be canceled by the fact that the model does not consider vapor mixing, which tends to increase precipitation $\delta^{18}O$ values in continental interior (e.g., Poulsen and Jeffery, 2011; Feng et al., 2013). This estimate of high relief remained nearly stable during the middle and late Eocene based on our nearly constant $\Delta\delta^{18}O$ values. This high Eocene topography was possibly inherited from the latest Cretaceous high elevation of the Canadian Cordilleran front (Fan and Dettman, 2009).

The second approach considers vapor mixing caused by vertical and horizontal advection of air masses and recycling. By using a predicted change of precipitation $\delta^{18}O$ values derived using isotope-enabled global climate model (GCM), which considers vapor mixing in the eastern flank of the Cordillera and the warm climate during the Paleogene (Feng et al., 2013), we constrain the paleoelevations of the mountains and basin floor based on the absolute $\delta^{18}O$ values of the alpine snowmelt and basin precipitation. The ancestral mountain ranges of the Lewis thrust front that provided alpine snowmelt to the basin, rose more than 3.5 km above the basin floor based on the low water $\delta^{18}O$ values (<-15‰) of high elevation runoff sources (Fig. 6B). The elevation of the basin floor, based on the reconstructed basinal precipitation $\delta^{18}O$ values (-10.1 to -9.0‰), was lower than 1.5 km (Fig. 6B). This high topography and high relief paleogeography was maintained during the middle and late Eocene (Fig. 5).

6.4. Significance for Cordillera tectonics

The middle–late Eocene paleotopography of the Cordilleran orogenic front based on the analysis of the sympatric groups of mollusks and their isotopic signatures suggest that the ancestral mountain ranges surrounding the Kishenehn basin possessed significant relief and attained elevations potentially up to 4–5 km (Fig. 7). Basins similar to the Kishenehn basin form a network of middle Eocene–early Miocene half grabens and grabens superposed on the Cordilleran fold-and-thrust belt that extends from southern British Columbia to southern Utah (Constenius, 1996). They are a manifestation of the overall collapse of the Cordilleran orogen and contemporaneous with the development of metamorphic core complexes in the hinterland of the orogen.

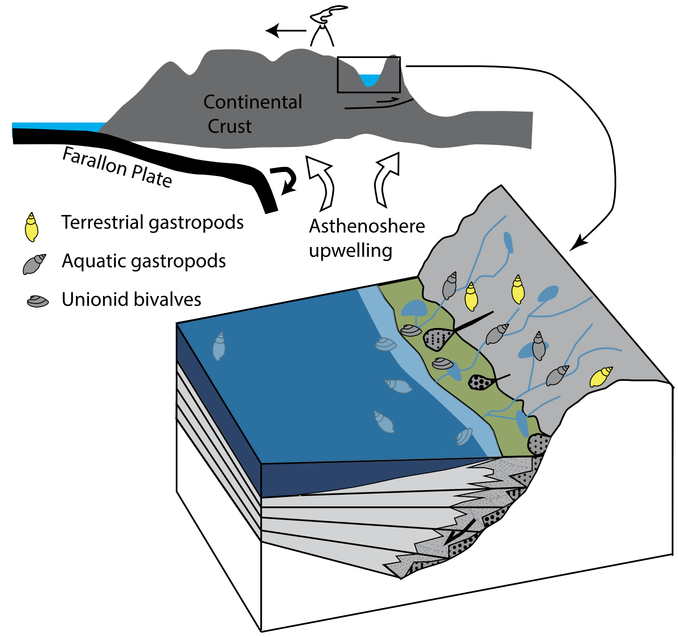

Fig. 7. Inferred tectonic setting and estimated paleogeography of the Kishenehn Basin and its drainage in northwestern Montana during the Eocene. Westward migration of arc magmatism and slab rollback are based on Coney and Reynolds (1977) and Constenius (1996). Note that mantle upwelling and isostatic uplift induced by Farallon slab removal or lower lithosphere delamination can equally support the high Eocene elevation in our study area.

The initiation of tectonic subsidence of the Kishenehen basin was concurrent with the formation of metamorphic core complexes (e.g., Kettle, Shuswap, Priest River) and associated extensional structures (e.g., Republic, Chu Chua, and Falkland grabens) in orogenic hinterland of southern British Columbian, northeast Washington and northern Idaho (Mulch et al., 2004, 2007; Foster et al., 2007), mafic magmatism in the northwestern North America (Haeussler et al., 2003), and the magmatism in the Challis volcanic field during the middle Eocene (Schmandt and Humphreys, 2011). These overlapping geologic events have been variously explained as resulting from gravitational collapse of previously overthickened crust following crustal shortening (Wernicke et al., 1987), associated with the rapid drop in North America–Pacific plate convergence rate (Engebretson et al., 1985), rollback of the Farallon plate (Coney and Reynolds, 1977; Humphreys, 1995; Constenius, 1996; Chamberlain et al., 2012), lower lithosphere removal (Sonder and Jones, 1999), development of slab window (e.g., Breitsprecher et al., 2003; Haeussler et al., 2003), or a combination of these plate tectonic elements. Our results suggest that the elevation of the Cordilleran orogenic front was at least 4 km high before middle Eocene extension, and the extension only created low half-graben basins (<1.5 km) and dissected the orogen front into rugged topography during the middle Eocene. This high topography and high relief topography in the northern Cordilleran orogenic front persisted for a period of at least 12 Myr during the middle and late Eocene.

Our paleoelevation reconstruction in northeastern Montana, when integrated with the existing paleoelevation datasets, improves our understanding of paleotopography of the northern Cordilleran orogen during the early and late Eocene. Based on the δ^{18}O value difference between unaltered unionid fossils and paleosol carbonates, Fan and Dettman (2009) suggested that the front of the Cordilleran orogenic belt in southern Canada was ~4.3 km high during the latest Cretaceous, and in northern Montana was ~4.3 km high during the earliest Paleogene. Even though high elevation of Cordilleran hinterland and associated maximum crustal thickness were likely to be attained at the end of the crustal shortening during the earliest Eocene (Fuentes et al., 2011, 2012), no available data directly constrain the paleotopography of the Cordilleran orogen during the early Eocene. Published stable isotope paleoelevation data in British Columbia and Washington (Mulch et al., 2007) and in the Cordilleran hinterland in Nevada (Cassel et al., 2014) suggest that the Cordilleran hinterland was at least 3 km during the middle and late Eocene. Paleoflora evidence from the extensional basins (Republic, Chu Chua, Falkland) in British Columbia suggested paleoelevations of 2.5–2.9 km during the early middle Eocene (Wolfe et al., 1998). The existing paleoaltimetry data seem to show a high plateau with less rugged topography extended from British Columbia to Nevada in the Cordilleran hinterland, but a more rugged and dissected orogenic front during the middle Eocene.

The synchronous collapse of the orogenic front and the maintenance of a high and broad hinterland plateau during the middle and late Eocene have geodynamic significance for Eocene extension. The direct implication of our results is that the Cordilleran hinterland reached at least 4 km before gravitational collapse, and the crust thickness reached >55 km by assuming Airy isostatic compensation. The maintenance of high topography during the Eocene suggests that either the crust was overthickened during the preceding contractile tectonics, and high topography was continuously supported by an extended, yet thick crust, or lithosphere scale extension was associated with thermal uplift caused by mantle upwelling related to the removal of the Farallon plate slab (Mix et al., 2011; Chamberlain et al., 2012), lower lithosphere delamination (Sonder and Jones, 1999), or a slab window (e.g., Breitsprecher et al., 2003; Haeussler et al., 2003). Given that there is no geologic evidence for an overthickened crust and >5 km of topography in the Cordilleran orogen, we speculate that the presence of high surface elevations at the beginning and at least 12 Myr after the onset of the extension reflects an inherited thick crust supported by hot asthenosphere, and the persistence of high elevation must be sustained by thermal uplift and possibly isostatic uplift associated with lower lithosphere delamination or slab removal. Additionally, Neogene Basin and Range extensional tectonics, which was of higher magnitude than the late Paleogene extension in the Great Basin area (Wernicke et al., 1987), had very limited influence on the region north of southern Montana (Wernicke et al., 1987), suggesting that the present moderate crust thickness (~40 km, Perry et al., 2002) of the surroundings of the Kishenehen basin must have been achieved during the Eocene and Oligocene. The gradual cooling of lithosphere during the late Paleogene and Neogene may have eventually decreased the mean elevation of the study area. It is worth noting that although our study suggests that mantle upwelling was critical to the persistent existence of high elevation in the Cordilleran orogenic front during the middle Eocene, the data can not directly assess whether this mantle upwelling was caused by lower crust delamination, removal of Farallon slab, or a slab window in northwestern North America. Future study may address this issue by examining the spatial and temporal patterns of surface uplift in the area.

7. Conclusions

We constrain the paleorelief of the Kishenehn basin in the northern Cordilleran orogenic front during Eocene extensional tectonics by studying the δ^{18}O values of molluscan fossils and paleosol carbonates. These molluscan fossils include three sympatric groups living in tropical wet, semi-arid subtropical, and temperature environments. Careful examinations to the mollusk fossils and paleosol carbonates suggest that they did not experience diagenesis. Our results show that the δ^{18}O values of the mollusks vary between −18.8‰ and −7.0‰, and this highly variable isotope record lasted from the early middle Eocene to the late Eocene. The δ^{18}O values of the paleosol carbonates vary between −13.5‰ and −10.9‰ in the early middle Eocene. By assuming carbonate formation temperatures based on the living habits of the modern analogs of these mollusk fossils, the calculated river and lake water δ^{18}O values were in the range of −19.8‰ to −6.3‰ (VSMOW), and the basinal precipitation δ^{18}O values were in the range of −10.1 to −7.6‰ (VSMOW). The large differences in ancient climatic habitats associated with the mollusks and in surface water δ^{18}O values suggest that the catchments feeding surface waters in the Kishenehn basin were at variable elevations and received different amounts of precipitation during the Eocene. By using a previously developed thermodynamic Rayleigh condensation model, and comparing reconstructed surface water δ^{18}O values to predicted precipitation δ^{18}O values for the east flank of the Eocene Cordillera based on a previous isotope-enabled global climate model, the paleorelief of the Kishenehn basin was ~4 km. This high topography and high relief paleogeography existed soon after the initiation of the extension, and continued for 12 Myr. The high topography during the initial collapse suggests that the elevation of the Cordilleran orogenic front was at least 4 km high, and the crust thickness may have reached >55 km before extension. The maintenance of high topography during the Eocene extension most likely resulted from the combination of an inherited thick crust from the preceding contractional tectonics, isostatic rebound of the crust following steepening and removal of the subducted Farallon plate, and thermal uplift caused by mantle upwelling in northwestern North America.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2016.10.038.

References

Balakrishnan, M., Yapp, C.J., 2004. Flux balance model for the oxygen and carbon isotope compositions of land snail shells. Geochim. Cosmochim. Acta 68, 2007–2024.

Breecker, D.O., Sharp, Z.D., McFadden, L.D., 2009. Seasonal bias in the formation and stable isotopic composition of pedogenic carbonate in modern soils from central New Mexico, USA. Geol. Soc. Am. Bull. 121, 630–640.

Breitsprecher, K., Thorkelson, D.J., Groome, W.G., Dostal, J., 2003. Geochemical confirmation of the Kula–Farallon slab window beneath the Pacific Northwest in Eocene time. Geology 31, 351–354.

Cassel, E.J., Breecker, D.O., Henry, C.D., Larson, T.E., Stockli, D.F., 2014. Profile of a paleo-orogen: high topography across the present-day Basin and Range from 40 to 23 Ma. Geology 42, 1007–1010.

Chamberlain, C.P., Mix, H.T., Mulch, A., Hren, M.T., Kent-Corson, M.L., Davis, S.J., Horton, T.W., Graham, S.A., 2012. The Cenozoic climatic and topographic evolution of the western North American Cordillera. Am. J. Sci. 312, 213–262.

Coney, P.J., Reynolds, S.J., 1977. Cordilleran Benioff zones. Nature 270, 403–406.

Constenius, K.N., 1982. Relationship between the Kishenehn Basin and the Flathead listric normal fault system and Lewis thrust salient. In: Powers, R.B. (Ed.), Geologic Studies of the Cordilleran Thrust Belt. Rocky Mountain Association of Geologists, pp. 817–830.

Constenius, K.N., 1988. Structural configuration of the Kishenehn Basin delineated by geophysical methods, northwestern Montana and southeastern British Columbia. Mt. Geol. 25, 13–28.

Constenius, K.N., 1996. Late Paleogene extensional collapse of the Cordilleran foreland fold and thrust belt. Geol. Soc. Am. Bull. 108, 20–39.

DeCelles, P.G., 2004. Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western U.S. Am. J. Sci. 304, 105–168.

Dettman, D.L., Lohmann, K.C., 2000. Oxygen isotope evidence for high altitude snow in the Laramide Rocky Mountains of North America during the late Cretaceous and Paleogene. Geology 28, 243–246.

Dettman, D.L., Reische, A.K., Lohmann, K.C., 1999. Controls on the stable isotope composition of seasonal growth bands in aragonitic fresh-water bivalves (unionidae). Geochim. Cosmochim. Acta 63, 1049–1057.

Dewey, J.F., 1988. Extensional collapse of orogens. Tectonics 7, 1123–1139.

Engebretson, D.C., Cox, A., Gordon, R.G., 1985. Relative motions between oceanic and continental plates in the Pacific basin. In: Geological Society of America Special Paper, vol. 206. 59 pp.

Fan, M., Dettman, D.L., 2009. Late Paleocene high Laramide ranges in northeast Wyoming: oxygen isotope study of ancient river water. Earth Planet. Sci. Lett. 286, 110–121.

Feinstein, S., Kohn, B., Osadetz, K., Price, R.A., 2007. Thermochronometric reconstruction of the prethrust paleogeothermal gradient and initial thickness of the Lewis thrust sheet, southeastern Canadian Cordillera foreland belt. In: Sears, J.W., Harms, T.A., Evenchick, C.A. (Eds.), Whence the Mountains? Inquiries into the Evolution of Orogenic Systems: A Volume in Honor of Raymond A. Price. In: Geological Society of America Special Paper, vol. 433, pp. 167–182.

Feng, R., Poulsen, C.J., Werner, M., Chamberlain, P.C., Mix, H.T., Mulch, A., 2013. Early Cenozoic evolution of topography, climate, and stable isotopes in precipitation in the North American Cordillera. Am. J. Sci. 313, 613–648.

Foster, D.A., Doughty, P.T., Kalakay, T.J., Fanning, C.M., Coyner, S., Grice, W.C., Vogl, J., 2007. Kinematics and timing of exhumation of metamorphic core complexes along the Lewis and Clark fault zone, northern Rocky Mountains, USA. In: Till, A.B., Roeske, S.M., Sample, J.C., Foster, D.A. (Eds.), Exhumation Associated with Continental Strike-Slip Fault Systems. In: Geological Society of America Special Paper, vol. 434, pp. 207–232.

Fuentes, F., DeCelles, P.G., Constenius, K.N., Gehrels, G.E., 2011. Evolution of the Cordilleran foreland basin system in northwestern Montana. Geol. Soc. Am. Bull. 123, 507–533.

Fuentes, F., DeCelles, P.G., Constenius, K.N., 2012. Regional structure and kinematic history of the Cordilleran fold-thrust belt in northwestern Montana, USA. Geosphere 8, 1104–1128.

Haeussler, P.J., Bradley, D.W., Wells, R.E., Miller, M.L., 2003. Life and death of the Resurrection plate; evidence for its existence and subduction in the northeastern Pacific in Paleocene–Eocene time. Geol. Soc. Am. Bull. 115, 867–880.

Hough, B., Fan, M., Passey, B.H., 2014. Clumped and oxygen isotope evidence for summer formation of soil carbonate in Wyoming and western Nebraska. Earth Planet. Sci. Lett. 391, 110–120.

Humphreys, E.D., 1995. Post-Laramide removal of the Farallon slab, western United States. Geology 23, 987–990.

Kim, S., O'Neil, J.R., 1997. Equilibrium and nonequilibrium oxygen isotope effects in synthetic carbonates. Geochim. Cosmochim. Acta 61, 3461–3475.

Kim, S., O'Neil, J.R., Hillaire-Marcel, C., Mucci, A., 2007. Oxygen isotope fractionation between synthetic aragonite and water: influence of temperature and Mg^{2+} concentration. Geochim. Cosmochim. Acta 71, 4704–4715.

Kohn, M.J., Dettman, D.L., 2007. Paleoaltimetry from stable isotope compositions of fossils. In: Kohn, M.J. (Ed.), Paleoaltimetry: Geochemical and Thermodynamic Approaches. In: Reviews in Mineralogy & Geochemistry, vol. 66, pp. 119–148.

Lachenbruch, A.H., Morgan, P., 1990. Continental extension, magmatism and elevation; formal relations and rules of thumb. Tectonophysics 174, 39–62.

Lechler, A.R., Niemi, N.A., Hren, M.T., Lohmann, K.C., 2013. Paleoelevation estimates for the northern and central proto-Basin and Range from carbonate clumped isotope thermometry. Tectonics 32, 295–316.

Liu, M., 2001. Cenozoic extension and magmatism in the North American Cordillera: the role of gravitational collapse. Tectonophysics 342, 407–433.

Machel, H.G., Burton, E.A., 1992. Factors governing cathodoluminescence in calcite and dolomite, and their implications for studies of carbonate diagenesis. SEPM Short Course Notes 25, 37–57.

McFadden, R.R., Mulch, A., Teyssier, C., Heizler, M., 2015. Eocene extension and meteoric fluid flow in the Wildhorse detachment, Pioneer metamorphic core complex, Idaho. Lithosphere, 37–57. http://dx.doi.org/10.1130/L429.1.

McMechan, R.D., 1981. Stratigraphy, Sedimentology, Structure and Tectonic Implications of the Oligocene Kishenehn Formation, Flathead Valley Graben, Southeastern British Columbia. Ph.D. thesis. Queen's University, Kingston, Ontario. 327 pp.

McMechan, R.D., Price, R.A., 1980. Reappraisal of a reported unconformity in the Paleogene (Oligocene) Kishenehn Formation: implications for Cenozoic tectonics in the Flathead Valley graben, southeastern British Columbia. Bull. Can. Pet. Geol. 28, 37–45.

Mix, H., Mulch, A., Kent-Corson, M.L., Chamberlain, C.P., 2011. Cenozoic topography of the western North American Cordillera. Geology 39, 87–90.

Mulch, A., Teyssier, C., Cosca, M.A., Vanderhaeghe, O., Vennemann, T., 2004. Reconstructing paleoelevation in eroded orogens. Geology 32, 525–528.

Mulch, A., Teyssier, C., Cosca, M.A., Chamberlain, C.P., 2007. Stable isotope paleoaltimetry of Eocene core complexes in the North American Cordillera. Tectonics 26, TC4001. http://dx.doi.org/10.1029/2006TC001995.

Osadetz, K.G., Kohn, B.P., Feinstein, S., Price, R.A., 2004. Foreland belt thermal history using apatite fission-track thermochronology: implications for Lewis thrust and Flathead fault in the southern Canadian Cordilleran petroleum province. In: Swennen, R., Roure, F., Granath, J.W. (Eds.), Deformation, Fluid Flow, and Reservoir Appraisal in Foreland Fold and Thrust Belts. In: American Association of Petroleum Geologists Hedberg Series, vol. 1, pp. 21–48.

Perry, H.K.C., Eaton, D.W.S., Forte, A.M., 2002. LITH5.0: a revised crustal model for Canada based on Lithoprobe results. Geophys. J. Int. 150, 285–294.

Pierce, H.G., Constenius, K.N., 2001. Late Eocene–Oligocene nonmarine mollusks of the northern Kishenehn basin, Montana and British Columbia. Ann. Carnegie Mus. 70, 1–112.

Pierce, H.G., Constenius, K.N., 2014. Terrestrial and aquatic mollusks of the Eocene Kishenehn Formation, Middle Fork Flathead River, Montana. Ann. Carnegie Mus. 82, 305–329.

Poulsen, C.J., Jeffery, M.L., 2011. Climate change imprinting on stable isotopic compositions of high-elevation meteoric water cloaks past surface elevations of major orogens. Geology 39, 595–598.

Rowley, D., 2007. Stable isotope-based paleoaltimetry: theory and validation. Rev. Mineral. Geochem. 66, 2352.

Russell, L.S., 1964. Kishenehn Formation. Bull. Can. Pet. Geol. 12, 536–543.

Schmandt, B., Humphreys, E., 2011. Seismically imaged relict slab from the 55 Ma Siletzia accretion to the northwest United States. Geology 39, 175–178.

Shanahan, T.M., Pigati, J.S., Dettman, D.L., Quade, J., 2005. Isotopic variability in the aragonite shells of freshwater gastropods living in springs with nearly constant temperature and isotopic composition. Geochim. Cosmochim. Acta 69, 3949–3966.

Smith, M.E., Singer, B., Carroll, A.R., 2003. $^{40}Ar/^{39}Ar$ geochronology of the Eocene Green River Formation, Wyoming. Geol. Soc. Am. Bull. 115, 545–565.

Snell, K.E., Koch, P.L., Druschke, P., Foreman, B.Z., Eiler, J.M., 2014. High elevation of the "Nevadaplano" during the Late Cretaceous. Earth Planet. Sci. Lett. 386, 52–63.

Snell, K.E., Thrasher, B.L., Eiler, J.M., Koch, P.L., Sloan, L.C., Tabor, N.J., 2012. Hot summers in the Bighorn Basin during the early Paleogene. Geology 41, 55–58.

Sonder, L.J., Jones, C.H., 1999. Western United States extension: how the west was widened. Annu. Rev. Earth Planet. Sci. 27, 417–462.

Wernicke, B.P., Christiansen, R.L., England, P.C., Souder, L.J., 1987. Tectonomagmatic evolution of Cenozoic extension in the North American Cordillera. In: Coward, M.P., Dewey, J.F., Hancock, P.L. (Eds.), Continental Extensional Tectonics. In: Geological Society Special Publication, vol. 28. Geological Society, Oxford, ISBN 9780632016051, pp. 203–221.

Wolfe, J.A., Forest, C.E., Molnar, P., 1998. Paleobotanical evidence of Eocene and Oligocene paleoaltitudes in midlatitude western North America. Geol. Soc. Am. Bull. 110, 664–678.