Continental-scale detrital zircon provenance signatures in Lower Cretaceous strata, western North America

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ABSTRACT

Lower Cretaceous strata and the underlying sub-Cretaceous unconformity in western North America record a profound, but poorly understood change in sedimentation patterns and basin dynamics in the Cordilleran foreland basin. To better understand the regional sedimentary systems and provenance during Early Cretaceous time, we sampled 10 Lower Cretaceous sandstone and conglomerate units that overlie the sub-Cretaceous unconformity in Canada and the United States for detrital zircon uranium-lead (U-Pb) geochronology. These Lower Cretaceous strata contain two distinct detrital zircon U-Pb age signatures. A "northern" signature, present in strata in Alberta and British Columbia, contains zircons with ages of ca. 120 Ma and 1850 Ma, and is composed of zircons from the Cordilleran arc and grains recycled from strata of the Canadian miogeocline. A "southern" signature, present in strata from southwestern United States to central Montana, contains zircons with ages of ca. 160 Ma, ca. 250–650 Ma, and ca. 1040 Ma, and consists of zircons from the Cordilleran arc and grains recycled from late Paleozoic strata and Mesozoic eolianite units in the western United States. We propose that the differences in detrital zircon U-Pb age populations between northern and southern areas of western North America are due to differences in zircon populations in the sediment source strata exposed in the contemporaneous thrust belt, and possibly a subtle paleohydraulic divide in Montana. These distinct provenance signatures along the Cordillera suggest that the mechanisms responsible for Early Cretaceous changes in foreland basin dynamics occurred along the length of the Cordillera in both the U.S. and Canada.

INTRODUCTION

The Early Cretaceous Epoch was an important time in the evolution of western North America and the Cordilleran foreland basin. Stratigraphically, it is marked by a major unconformity, commonly called the sub-Cretaceous unconformity, which is present from the southwestern United States to the Yukon Territory in Canada (Heller and Paola, 1989; Hayes et al., 1994). The cause of this unconformity is still debated, but is often attributed to regional isostatic uplift or the passage of a flexural forebulge (cf. Heller et al., 1988; Currie, 1998). Overlying this unconformity is a series of Lower Cretaceous sandstone and conglomerate units that record an unprecedented progradation of coarse-grained material into, and possibly even beyond, the Cordilleran foreland basin (Heller and Paola, 1989). To explain such a profound change in basin dynamics and sediment progradation, most hypotheses argue for regional (hundreds of kilometers in wavelength) surface uplift in the Cordilleran fold-thrust belt and proximal portions of the foreland basin during Early Cretaceous time (Heller and Paola, 1989). Proposed mechanisms for this uplift include the cessation of thrusting and isostatic rebound (Heller et al., 1988), lithospheric delamination, or decreased dynamic subsidence (e.g., Heller et al., 2003; DeCelles, 2004). It is unclear if these hypothesized tectonic events occurred along the entire western margin of North America or if they occurred in specific locations, and synorogenic sediments were then transported longitudinally along the axis of the Cordilleran foreland basin.

A better understanding of the Early Cretaceous tectonic processes and large-scale sedimentation patterns in western North America has been hampered by the fact that the tectonic and sedimentary records from this time period are difficult to decipher (e.g., Martin et al., 2010). However, by delineating sediment source areas and pathways, the application of recently developed provenance techniques to Lower Cretaceous strata may provide new insight into the tectonic and sedimentary dynamics of western North America during Early Cretaceous time.

We sampled Lower Cretaceous conglomerate and sandstone units directly above the sub-Cretaceous unconformity in Canada and the northern United States for uranium-lead (U-Pb) detrital zircon geochronology (Fig. 1). These data are combined with recent studies of Lower Cretaceous strata in the southwestern United States (Dickinson and Gehrels, 2008; Lawton et al., 2010) to provide a >2000 km north-south span of detrital zircon U-Pb ages from Lower Cretaceous strata. Two distinct U-Pb detrital zircon age signatures are present in Lower Cretaceous conglomerate and sandstone units overlying the sub-Cretaceous unconformity in western North America. The "northern" signature is present primarily in Alberta and British Columbia and is composed of zircons from the Cordilleran arc and zircons recycled from Canadian miogeoclinal strata exposed in the fold-thrust belt. The "southern" signature is present from the southwestern United States to central Montana, and is composed of zircons from the Cordilleran arc and

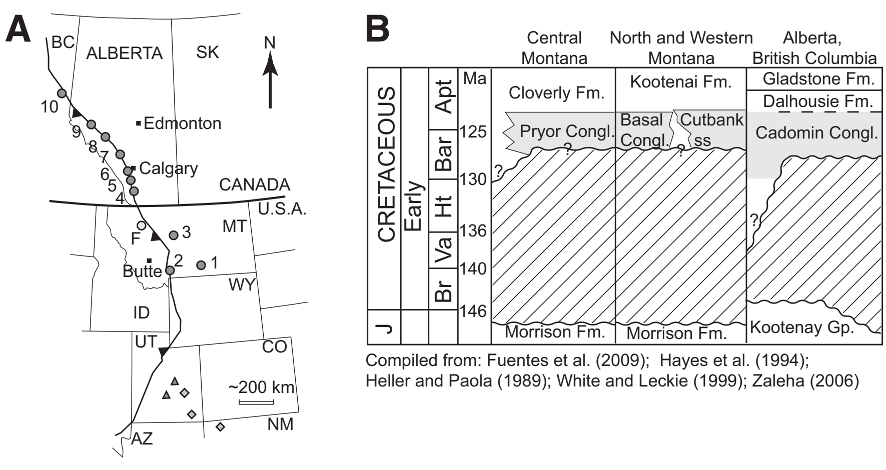

Figure 1. Location of samples and Lower Cretaceous stratigraphy, western North America. A: Circles denote location of samples collected in western North America. Numbers correspond to data presented in Figure 2; sample labeled F is from Fuentes et al. (2009); triangles are from Lawton et al. (2010); diamonds are from Dickinson and Gehrels (2008). BC—British Columbia, SK—Saskatchewan, ID—Idaho, MT—Montana, WY— Wyoming, AZ—Arizona, NM—New Mexico, CO—Colorado, UT—Utah. B: Stratigraphy in study area, with sampled units highlighted. Hachured area represents an unconformity. J—Jurassic, Br—Berriasian, Va—Valanginian, Ht—Hauterivian, Bar—Barremian, Apt—Aptian, Congl.—conglomerate, ss—sandstone, Fm.—formation, Gp.—group. Geologic time scale is from Walker and Geissman (2009).

zircons recycled from Mesozoic eolianites and late Paleozoic strata exposed in thrust sheets in the western and southwestern United States. These data allow Lower Cretaceous strata to be divided into distinct assemblages based on detrital zircon U-Pb ages and provide new constraints for tectonic and sedimentary reconstructions of the Early Cretaceous Cordilleran foreland basin in western North America.

LOWER CRETACEOUS STRATA

Lower Cretaceous strata in western North America overlie the sub-Cretaceous unconformity (Fig. 1) in most of the foreland basin and are composed of chert and quartzite pebble to cobble conglomerate deposited in fluvial environments (Heller and Paola, 1989). These units have multiple names, including the Buckhorn Conglomerate of the Cedar Mountain Formation, the Pryor Conglomerate of the Cloverly Formation, the (informal) basal conglomerate of the Kootenai Formation, and the Cadomin Conglomerate (Fig. 1). In several locations, the lithologic units overlying the sub-Cretaceous unconformity are composed of sandstone, such as the Cutbank Sandstone of the Kootenai Formation in Montana (Fig. 1). The lithological character and absence of fossils in these units make them difficult to date accurately. In most studies a Barremian age is typically assigned for the base of the strata (Fig. 1; Heller and Paola, 1989; Hayes et al., 1994; Zaleha, 2006; Fuentes et al., 2009); however, in some locations, particularly in westernmost regions, the base of the deposits may be older (White and Leckie, 1999; Zaleha, 2006). An early Aptian age is commonly assigned to the upper boundary of these units (Heller and Paola, 1989; Hayes et al., 1994; Zaleha, 2006; Fuentes et al., 2009).

METHODOLOGY

We collected 10 samples from stratigraphic units overlying the sub-Cretaceous unconformity for detrital zircon U-Pb age analysis (Fig. 1). Individual samples were processed with standard crushing and pulverizing procedures followed by density and magnetic separation. The U-Pb geochronology of detrital zircons from the samples was conducted by laser ablation–multicollector–inductively coupled plasma mass spectrometry (LA-MC-ICPMS) at the University of Arizona LaserChron Center. The analyses involve ablation of zircon with a laser using a spot diameter of 10–50 µm. Information on sample lithology and detailed descriptions of the processing and analytical methods are presented in the GSA Data Repository.[1]

RESULTS

Detrital zircon analysis yielded 939 U-Pb ages with acceptable concordance (see the Data Repository). The three samples from Montana contain detrital zircons with two primary U-Pb age populations (Fig. 2). The youngest age population is ca. 160 Ma and the older age population is ca. 1040 Ma. In addition, these samples have multiple grains with ages between ca. 250 and 650 Ma.

The seven samples from the Cadomin Conglomerate in Alberta and British Columbia contain two principal U-Pb age populations (Fig. 2). The youngest population has ages of ca. 120 Ma and displays a relatively narrow age distribution. The other significant population has ages of ca. 1850 Ma.

INTERPRETATION

Northern Signature

Samples from the Cadomin Conglomerate contain two primary populations, ca. 120 Ma and ca. 1850 Ma (Fig. 3). We interpret the younger of these populations to be derived from Cordilleran arc-related sources in western North America. Numerous volcanic and igneous rocks with similar U-Pb zircon ages are present in the Cordilleran magmatic arc (e.g., Armstrong and Ward, 1993) and paleocurrent data demonstrate that Lower Cretaceous sediments were, at least in part, derived from the west (McLean, 1977). We interpret the ca. 1850 Ma detrital zircons to be recycled grains derived from Canadian miogeocline strata exposed in the Cordilleran fold-thrust belt to the west (Fig. 3). In particular, lower Paleozoic strata (e.g., the Cambrian Gog and Hamill Groups) and Neoproterozoic strata (e.g., Horsethief Creek Group) are dominated by zircon grains with ca. 1850 Ma ages (Fig. 3; Gehrels and Ross, 1998). A derivation of sediments from lower Paleozoic and Neoproterozic rocks during Early Cretaceous time is further supported by the work of Schultheis and Mountjoy (1978), who used petrographic analyses to determine that quartzite clasts in the Cadomin Conglomerate were shed from Cambrian strata exposed in the Canadian Cordillera.

Southern Signature

Samples from Lower Cretaceous strata in Montana contain two principal populations, ca. 160 Ma and ca. 1040 Ma, with ages scattered between ca. 250 and 650 Ma (Figs. 2 and

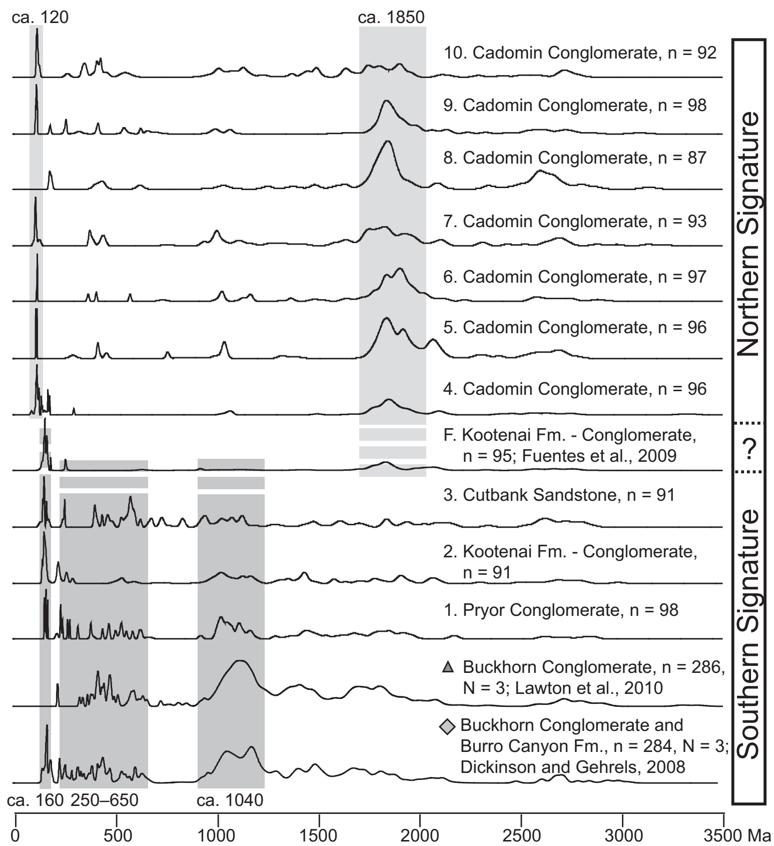

Figure 2. Detrital zircon normalized probability plots for Lower Cretaceous samples. Samples 1–3 are from Montana; n is number of analyses, N is number of samples (one, unless otherwise noted). Samples 4–10 are from Cadomin Conglomerate in western Alberta and northeastern British Columbia. Highlighted areas show common trends and numbers refer to age values of particular population. See text for discussion; for complete results, see the Data Repository (see footnote 1).

[1]GSA Data Repository item 2011127, western North America detrital zircon data, ages, and methods, is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

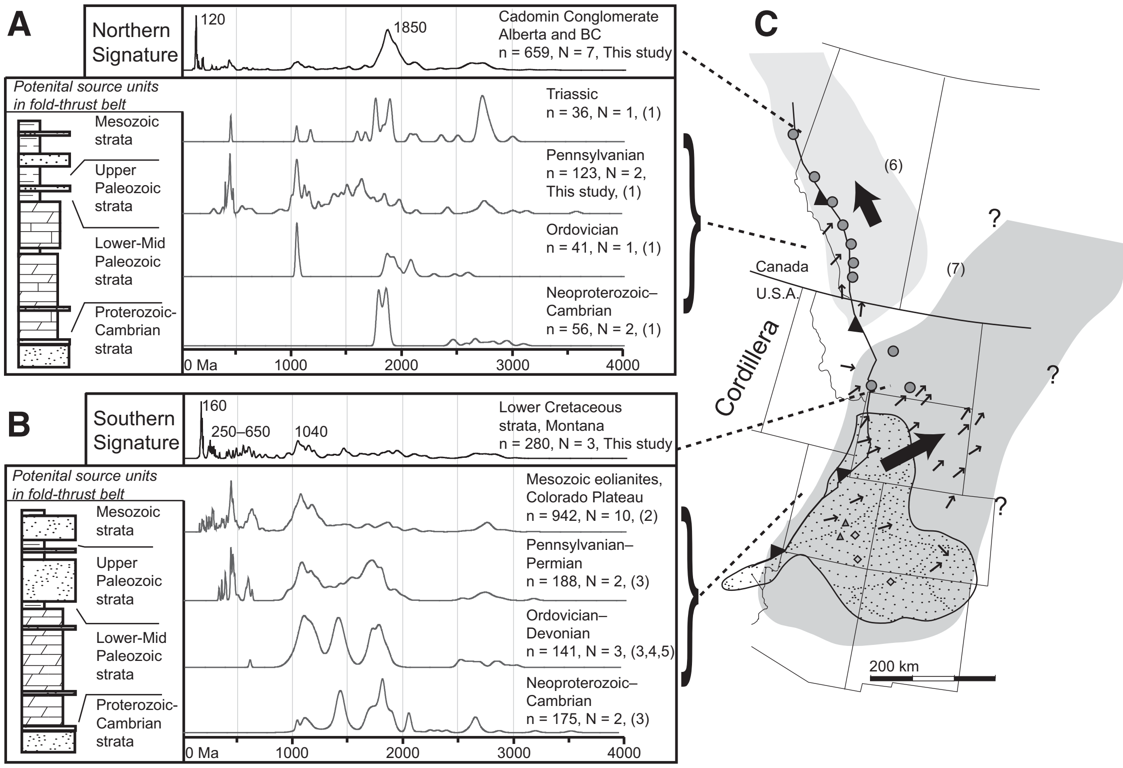

Figure 3. Detrital zircon data from Lower Cretaceous strata, likely sediment source areas in western North America, and locations of detrital zircon provenance signatures. A: Detrital zircon ages of Lower Cretaceous strata in western Alberta and British Columbia (BC) are dominated by ca. 120 Ma and ca. 1850 Ma populations. Detrital zircons were derived from Cordilleran arc sources and miogeoclinal strata in Canadian Cordillera, particularly Neoproterozoic–Cambrian units. See text for details. B: Detrital zircon ages of Lower Cretaceous strata in Montana represent southern signature and consist of populations of ca. 160, 250–650, and 1040 Ma grains. These distributions are consistent with those from strata in southwestern United States (see Fig. 2). Detrital zircons in these units were derived from Cordilleran arc sources and Mesozoic eolianite strata and late Paleozoic units in Cordilleran fold-thrust belt. C: Representation of detrital zircon U-Pb age signatures in western North America (shaded zones). Large arrows highlight our interpretations of general sediment transport direction during Early Cretaceous time; smaller arrows are abridged paleocurrent data originally compiled by Heller and Paola (1989). Distribution of Mesozoic eolianite strata is shown by stippled region and is included to display general correspondence between these units and Lower Cretaceous strata with similar detrital zircon ages. 1—Gehrels and Ross (1998) and Ross et al. (1997); 2—Dickinson and Gehrels (2009); 3—Lawton et al. (2010); 4—Gehrels and Dickinson (1995); 5—Smith and Gehrels (1994). Sources for locations of paleodrainage divides: 6—Leckie and Smith (1992) and Hayes et al. (1994); 7—D. Leckie (2010, personal commun.).

3). Given the paleocurrent data (Heller and Paola, 1989) and Cordilleran arc-related rocks of similar age located in the inferred source area (Armstrong and Ward, 1993), we interpret the population of ca. 160 Ma detrital zircons in strata in Montana to have been derived from the Cordilleran magmatic arc. We interpret the remaining zircon populations (ca. 250–650, and ca. 1040 Ma) to have been derived largely from late Paleozoic and Mesozoic strata, specifically Triassic–Jurassic eolian sedimentary units that were exposed in the contemporaneous fold-thrust belt (Fig. 3; Lawton et al., 2010). This interpretation is based on the following: (1) the Mesozoic eolianite units have detrital zircon grains with age populations similar to those in the Lower Cretaceous strata in Montana, including large populations of ca. 1040 Ma grains (Fig. 3); (2) detrital zircon age populations in Lower Cretaceous strata in the southwestern United States that are demonstrably recycled from Mesozoic eolianite units (Dickinson and Gehrels, 2008; Lawton et al., 2010) are similar to the detrital zircon age populations of Lower Cretaceous strata in Montana (Fig. 2); (3) the eolianite strata are widespread and voluminous units, and thus capable of being a significant source of detrital zircons (Fig. 3); and (4) regional paleocurrent data suggest a southwestern provenance (Fig. 3).

DISCUSSION AND CONCLUSION

Detrital zircon U-Pb ages from Lower Cretaceous strata overlying the sub-Cretaceous unconformity in western North America contain at least two distinct signatures. The northern signature is exemplified by the Cadomin Conglomerate in western Canada, which contains detrital zircons with U-Pb age populations of ca. 120 and 1850 Ma. These zircons are interpreted to have been derived from the Cordilleran magmatic arc and recycled from Canadian miogeocline strata exposed in the contemporaneous fold-thrust belt (e.g., Schultheis and Mountjoy, 1978). The southern signature is present in sedimentary units from the southwestern United States to Montana, and contains U-Pb age populations of ca. 160 and 1040 Ma, with multiple grains with ages between 250 and 650 Ma. Zircons associated with the southern signature are interpreted to have been derived from the Cordilleran magmatic arc and recycled from Mesozoic eolianite strata and late Paleozoic rocks that were exposed in the contemporaneous fold-thrust belt in the western United States (e.g., Lawton et al., 2010).

Two hypotheses, which are not mutually exclusive, provide plausible explanations for the spatial distribution of detrital zircon U-Pb age signatures in Lower Cretaceous strata in western North America. The first hypothesis relates the distribution of U-Pb ages to the presence, and absence, of particular stratigraphic units that would have been exposed in the Lower Cretaceous fold-thrust belt. Early Cretaceous strata in western North America with detrital zircons with ages between 250 and 650 Ma and a population of ca. 1040 Ma (southern signature) correspond to the spatial distribution of Mesozoic eolianite units with similar zircon age populations (Fig. 3); the three samples from Montana are included in this set because paleocurrent data suggest a similar provenance. The eolian deposits do not extend into Canada; therefore, these units would not have been a source of sediment in the Canadian portion of the fold-thrust belt. Similarly, Lower Cretaceous strata with detrital zircon U-Pb ages of ca. 1850 Ma (northern signature) correspond to exposures of Canadian miogeocline strata. The southern termination of the Canadian miogeocline strata occurs in approximately northern Idaho at the trans-Idaho discontinuity (Price and Sears, 2000; Dickinson, 2004), at a latitude corresponding to the break in the detrital zircon age signatures. Although similar strata are present in the southwestern United States, it is likely that their zircon contribution to Lower Cretaceous synorogenic strata was diluted by zircons from late Paleozoic and Mesozoic units in the region (Fig. 3).

Alternatively, it is possible a region in present-day Montana may have served as a paleohydraulic divide, effectively separating detrital material derived from the U.S. Cordillera from the foreland basin in Canada. Paleocurrent data and paleogeographic reconstructions suggest that two regional paleofluvial systems existed in western North America during Early Cretaceous time. One fluvial system emanated from the U.S. Cordillera with paleoflow directed to the east-northeast, while the other system was derived from the Cordillera in northern Montana and southern Canada and flowed axially along the foreland basin to the north-northwest (McGookey, 1972; McLean, 1977; Hayes et al., 1994; Miall et al., 2008). The hypothesized divide corresponds to the change in detrital zircon age signatures and is located near the Great Falls Tectonic Zone (GFTZ), a northeast-trending region that has been periodically active from Proterozoic to Holocene time (O'Neill and Lopez, 1985). The correspondence between the location of the GFTZ and the hypothesized paleodivide suggests, but does not necessitate, a causal relationship. We propose that the ultimate control on the distribution of detrital zircon U-Pb ages is likely a combination of the spatial distribution of particular sediment source rocks and possibly a subtle paleohydraulic divide in present-day Montana.

The results of this study also help constrain the spatial distribution of the geodynamic changes that influenced foreland basin sedimentation during Early Cretaceous time in western North America (e.g., isostatic rebound, decreased dynamic subsidence; Heller and Paola, 1989; DeCelles, 2004). If the proposed tectonic events occurred only in one specific region of the Cordilleran fold-thrust belt, with sediments transported axially along the foreland basin, the detrital zircon provenance of Lower Cretaceous strata throughout western North America should be uniform. Our data demonstrate that this is not the case. The evidence of an efflux of sediment shed from both the United States and Canadian Cordillera suggests that uplift of thrust belt sources took place along the length of the Cordilleran orogen, indicating that a particular tectonic process controlling uplift (e.g., isostatic rebound) also occurred roughly simultaneously along the length of the Cordillera.

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