Electron-microprobe monazite dating of ca. 1.71–1.63 Ga and ca. 1.45–1.38 Ga deformation in the Homestake shear zone, Colorado: Origin and early evolution of a persistent intracontinental tectonic zone

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ABSTRACT
The Homestake shear zone, one of the principal Precambrian structures within the Colorado mineral belt, has a history of tectonism that extends from the Proterozoic to the Tertiary. New field mapping, microstructural analysis, and electron-microprobe U-Th-Pb monazite dating of ca. 1.71–1.63 Ga and ca. 1.45–1.38 Ga deformation in the Homestake shear zone. To establish the absolute timing of individual tectonic episodes, we used the electron microprobe, U-Th-Pb, monazite dating to investigate the genesis and early evolution of the Homestake shear zone and elucidate the tectonic processes that established the trend of the Colorado mineral belt.

INTRODUCTION
Recurrent tectonism in continental interiors may be localized along zones of weakness embedded in the continental lithosphere. Modern examples include plate-boundary fault zones within orogenic systems (e.g., San Andreas, Anatolian system, Indus suture zone) as well as fault systems deep in continental interiors that respond to far-field stresses (e.g., Altn Tagh fault, Rocky Mountain faults, Colorado Plateau monoclines). Despite their significant role in continental tectonics, the genesis and evolution of such weak zones are poorly understood because their early history is commonly obscured by later deformation.

This study addresses the development of the Colorado mineral belt (Fig. 1A), a long-lived tectonic zone in the southern Rocky Mountains. In the mineral belt, northeast-trending, subvertical Proterozoic shear zones apparently localized Proterozoic magmatism (Sims and Stein, 1999), Paleozoic brittle faulting (Allen, 1994), Laramide-Tertiary fault reactivation, plutonism, and ore remobilization (Tweto and Sims, 1963), and present-day mantle velocity anomalies (Duerer, 1999).

We combine detailed field mapping, microstructural analysis, and the emerging technique of in situ, electron-microprobe, U-Th-Pb, monazite dating to investigate the genesis and early evolution of the Homestake shear zone and elucidate the tectonic processes that established the trend of the Colorado mineral belt.

GEOLOGIC BACKGROUND
The Homestake shear zone is a >10-km-wide, northeast-trending system of anastomosing, subvertical shear zones in the northern Sawatch Range. These shear zones comprise a wide variety of tectonites, including mylonite, ultramylonite, recrystallized mylonite, pseudotachylyte, cataclasite, breccia, and gouge that were mapped as cataclasite gneiss by Tweto (1974). Tweto and Sims (1963) postulated that the Homestake and other Precambrian shear zones had localized the band of Laramide-Tertiary ore deposits and plutons that defines the Colorado mineral belt (Fig. 1A).

The Proterozoic crust of the southwestern United States is a mosaic of juvenile arc terranes assembled to the southern margin of the Archean Wyoming craton between 1.8 and 1.6 Ga (e.g., Karlstrom and Bowring, 1988). The Homestake cuts a package of complexly folded and partially melted metasedimentary rocks, including biotite schist and gneiss, amphibolite, calc-silicate gneiss, marble, metachert, and metaturbidite. These rocks may represent part of a highly deformed forearc or backarc basin. The rocks were migmatized and deformed during intrusion of the monzogranite-diorite Cross Creek batholith and related intrusive rocks (ca. 1675 Ma [Rb-Sr]; Tweto and Lovering, 1977). A regional episode of A-type granitic plutonism (e.g., Anderson and Cullers, 1999) and tectonism (Nyman et al., 1994) is represented in the study area by the peraluminous St. Kevin batholith (1396 ± 40 Ma [U-Pb]; Doe and Pearson, 1969), which shows evidence for magmatic and solid-state deformation during one of the phases of displacement on the Homestake (Fig. 1A). One of the aims of this study is to determine how Paleoproterozoic plate-margin processes and Mesoproterozoic intracontinental tectonism contributed to the development of the shear zone.

METHODS
The kinematics and relative timing of deformation in the Homestake were ascertained through detailed field mapping and microstructural analysis of the diverse suite of tectonites in the shear zone. To establish the absolute timing of individual tectonic episodes, we used the electron microprobe at the University of Massachusetts, Amherst, to obtain in situ U-Th-Pb dates for monazite crystals that exhibit clear micro-
structural relationships with fabric elements (Williams et al., 1999). Because the microstructural context of the dated grains is preserved, radiometric dates can be linked with tectonic fabrics and events. A critical step in this technique is collecting U, Th, Pb, and Y compositional maps to identify chemical zoning within single monazite grains. Some compositional zones correspond to resolvable age domains that are interpreted to record multiple pulses of monazite growth. The <5 μm spatial resolution of the electron microprobe allows multiple domains to be differentiated where conventional isotopic techniques would yield mixed ages.

Monazite dates and errors reported in this study are based on the mean age and standard error of the mean (95% confidence level) for a population of spot analyses within a single age domain or grain. Spot ages were calculated from elemental analyses of U, Th, and Pb by assuming that all Pb in the crystal was derived from the decay of U and Th (i.e., assuming negligible common Pb; Parrish, 1990) and solving the decay equation (Montel et al., 1996).

TECTONIC FABRICS AND KINEMATICS

Our mapping and microstructural analysis reveal that different shear strands within the Homestake are characterized by distinct kinematics and deformation mechanisms. Thus, the shear zone appears to be a composite product of several deformation episodes at different crustal levels and with different kinematics.

D1: High-Temperature Subhorizontal Flow
The earliest recognizable deformation produced a composite tectonic fabric (S1; Fig. 1C). The main gneissic foliation, involving migmatitic leucosomes and aligned micas (S1a), was isoclinally folded (F1b) and then warped by small-scale asymmetric folds (F1c). Numerous centimeter- to meter-scale granite dikes parallel the F1c axial planes (S1c). We interpret the low-angle, nappe-style S1 folds as products of a high-temperature (T) progressive deformation (D1) involving subhorizontal flow of partially molten rocks. S1 is preserved as a distinct foliation in low-strain lenses within the shear zone as well as outside of the shear zone.

D2: High-Temperature Crustal Shortening
Much of the central Homestake consists of anastomosing S2 foliation domains where S1 has been completely transposed into a north-east-trending, subvertical orientation (Fig. 1B). These high-strain zones are characterized by shortened and/or sheared varieties of the migmatitic gneiss distinguished by straighter
foliation, finer grain size, and locally, by a steeply plunging stretching lineation defined by quartz ribbons and 1–10-cm-long flattened sillimanite prisms and needles. The quartz textures, sillimanite lineation, and lack of mylonitic textures are consistent with high-$T$ deformation. These S2 domains probably represent zones of concentrated general shear dominated by northwest-southeast contraction and vertical extension. Outside of the high-strain S2 domains, D2 shortening produced complex interference patterns formed by refolding of the initially subhorizontal F1 nappe folds.

D3: Mylonite Zones

A very different type of tectonite occurs in 1- to >30-m-wide mylonite zones that overprint older fabrics within S2 foliation domains (Fig. 1B). In the main 30-m-wide mylonite zone, foliation dips steeply southeast and lineation plunges steeply southwest. Highly asymmetric fabrics, including sigma porphyroclasts, S-C fabrics, and extensional shear bands (C’ fabrics), indicate southeast-side-down displacement with a minor dextral strike-slip component. Microstructures in quartz and feldspar are consistent with deformation at ~350–450 °C (Hirth and Tullis, 1994). Extensive development of subgrains within older high-$T$ quartz ribbons, chlorite- and oxide-filled cracks in brittlely boudined sillimanite, and extensional shear bands with chlorite alteration provide evidence for a low-$T$ southeast-side-down overprint within the D2 domains. The kinematics and deformation mechanisms suggest that this overprint may correlate with D3 mylonitization.

D4: Ultramylnite Zone

A >30-m-wide zone of intensely grain-size-reduced rock, including abundant ultramylonite and pseudotachylyte, overprints part of the main mylonite zone and can be traced at least 10 km to the southwest. A strong stretching lineation plunges steeply to the northeast, and microstructures record southeast-side-up shear with a minor dextral component. The ultramylonite zone is heterogeneous at all scales, encompassing both high-strain domains as well as lower strain lenses. Some of these preserve textures and shear sense consistent with the dismembered mylonite, suggesting that the ultramylonite overprints part of the mylonite zone. Undulose extinction and brittle fractures in both quartz and feldspar indicate low-$T$ deformation (~250–350 °C, Hirth and Tullis, 1994). Pseudotachylyte veins both parallel and crosscut the ultramylonitic foliation, and some are offset across ductile microshears; these relationships suggest coeval seismogenic brittle faulting and ductile shear in the ultramylonite zone.

AGE OF TECTONIC FABRICS

D1-D2: High-Temperature Fabrics

A series of zoned monazite crystals from one of the anastomosing S2 foliation domains (monazites 1–3 [designated m1–m4] of C97HS-1) lie within a composite S1–S2 foliation. Dates from these grains bracket the timing of S1 foliation development and its transposition into the steep S2 orientation. Monazite m1 contains a low-Y band where the grain apparently overgrew a matrix biotite flake aligned in the S1 foliation (Fig. 2A). Thus, the 1708 ± 6 Ma date recorded by m1 implies that S1 must have already existed at this time. The transition from D1 to D2 is recorded by monazite grains m2 and m3 from the same thin section. The ages and elongate morphology of cores in m2 (1711 ± 14 Ma) and m3 (1699 ± 4 Ma) are consistent with growth during S1 fabric development or reactivation. The younger asymmetric rim of m2 (1668 ± 8 Ma) may indicate shear on the S1 foliation as it was folded and rotated into a subvertical orientation. D2 fabrics appear to represent a protracted, multistage 1680–1630 Ma deformation episode with pulses of monazite growth recorded by distinct populations of dates at 1658 ± 5 Ma and 1637 ± 13 Ma (Fig. 3). The fractures in m2 and m3 are consistent with a low-$T$ overprint, possibly related to D3 displacement on the mylonite zone.

D3-D4: Mylonite and Ultramylnite

In contrast to the wide range of Paleoproterozoic ages observed in S1 and S2 domains, monazite grains from the mylonite and ultramylonite zones only yield dates younger than 1450 Ma (Fig. 3), indicating that monazite in the protoliths must have completely recrystallized during mylonitization. Thus, dates from these zones probably reflect the timing of mylonite deformation. Five small, euhedral-subhedral monazite crystals from the mylonite (K99HS-19, Fig. 2C) yield dates ranging from 1359 to 1381 Ma with a weighted average of 1372 ± 19 Ma. We interpret this date as the age of the main episode of southeast-side-down deformation in the mylonite zone (D3).

Samples from the S2 foliation domains record monazite growth coeval with mylonite deformation (Fig. 3). Small unzoned grains and overgrowths in sample K99HS-12 (Fig. 2B, m3, cap 2) and thin asymmetric rims in sample C00HS-8 (Fig. 3, C00HS-8, m1) yield dates between 1450 and 1380 Ma. These dates record monazite growth in the S2 domains, reflecting a thermal or fluid-flow event that may correlate with the low-$T$, southeast-side-down overprint in these rocks (see preceding). This suggests that this deformation was synchronous with D3 mylonitization. A muscovite $^{40}$Ar/$^{39}$Ar plateau age from a pegmatite located ~7.5 km south of the mylonite zone records cooling through ~350–300 °C at 1380 ± 1 Ma (Fig. 3), providing additional support for a thermal disturbance associated with D3 tectonism.

Monazite dates from the ultramylonite (K99HS-18a) are indistinguishable from the ca. 1390–1360 Ma dates obtained from the mylonite, but the morphology and microstructural setting of many of the grains suggest that...
that the ultramylonite may represent significant tectonic contraction and gravitational effects caused by oscillations in the balance between top-to-the-south and southeast-side-up ultramylonite could record a component of dextral displacement after 1375 Ma.

**DISCUSSION AND CONCLUSIONS**

Electron-microprobe U-Th-Pb geochronology enabled us to estimate the absolute timing of deformation in the Homestake by using the microstructural context of dated grains to link the inferred kinematics to in situ radiometric ages. A particularly useful result of this study is the finding that mylonitization can effectively reset monazite systematics (Fig. 3); hence, monazite geochronology can provide a reliable method for directly dating mylonitic deformation.

Our results show that the Proterozoic history of the Homestake shear zone was dominated by two protracted (50–100 m.y.) tectonic episodes, each consisting of resolvable pulses of deformation and monazite growth. During the first episode (1710–1630 Ma), mid-crustal deformation progressed from sub-horizontal flow (D1) to heterogeneous crustal shortening (D2). Monazite dates associated with D1 and D2 fabrics overlap in time (Fig. 3), suggesting that D1 fabrics may have been reactivated as they were folded and steepened during D2. This progression appears to be regional (Ilg et al., 1996) and may represent the evolution of subduction-related thrusting and nappe folding (D1) to collision-related contraction (D2) as juvenile arcs were assembled to form the lithosphere of southwestern Laurentia.

The second major tectonic episode (ca. 1450–1370 Ma) records a significant change in the tectonic setting, conditions, and kinematics of deformation. By the Mesoproterozoic, Colorado was well within the continental interior, perhaps 1000 km from the Laurentian margin. If D3 and D4 both occurred ca. 1380 Ma, as suggested by the monazite data (Fig. 3), the minor dextral component of both D3 and D4 could record a component of dextral strike slip associated with ca. 1.4 Ga transpression. The reversal in the dip-slip component recorded by the southeast-side-down mylonite and southeast-side-up ultramylonite could record local fluctuations in the strain field, perhaps caused by oscillations in the balance between tectonic contraction and gravitational extension within the deforming continental lithosphere. An alternative interpretation is that the ultramylonite may represent significantly later movement that did not entirely re-set the U-Th-Pb systematics of monazite—especially in low-strain lenses within the shear zone. This raises the intriguing possibility of Grenville-age (ca. 1.3–1.0 Ga) deformation in Colorado, consistent with a reported 1150 ± 150 Ma deformed pegmatite from the Homestake (Allen, 1994). However, the current data are insufficient to confirm or refute this interpretation (Fig. 3).

The Homestake shear zone provides a classic example of the evolution of initially low angle gneissic fabrics into a steep, mylonitic shear zone, followed by repeated reactivation of this zone during progressive exhumation of the mid-crust. We speculate that the tectonic trend may have been established during D1 as contractional strain was localized by crustal-scale ramps in thrust and nappe systems accommodating arc convergence and assembly. Alternatively, lithologic contrasts between relatively strong crustal blocks (e.g., Cross Creek batholith) and relatively weak forearc or backarc assemblages could have localized strain in the weaker rocks. In either case, once established, the zone of high-strain rocks seems to have localized D2 shortening (ca. 1680–1630 Ma) and enhanced the evolving structural lineament. Mylonitic deformation at 1450–1370 Ma exploited this preexisting weakness and initiated a transformation of the shear zone from a belt of enhanced general shear to a ductile fault zone dominated by simple-shear displacement.

Additional mapping and monazite dating suggest that the multistage tectonic evolution of the Homestake shear zone is representative of other Proterozoic shear zones in the Colorado mineral belt (McCoy et al., 2000). Thus, this persistent tectonic zone appears to have developed first as a system of diffuse high-strain zones related to continental assembly, Strain localization ca. 1.4 Ga reinforced the initial weakness, setting the stage for the later brittle faulting, plutonism, mineralization, and anomalous mantle that characterize the Colorado mineral belt.

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