1996

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Recommended Citation

Phillip G. Resor, Kevin R. Chamberlain, Carol D. Frost, B Ronald Frost, and Arthur W. Snoke. "Direct dating of deformation; U-Pb age of syndeformational sphene growth in the Proterozoic Laramie Peak shear zone" Geology 24.7 (1996): 623-626.

Direct dating of deformation: U-Pb age of syndeformational sphene growth in the Proterozoic Laramie Peak shear zone

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ABSTRACT

In this paper, we show that deformation can be dated by combining mesoscopic and microscopic structural observations with an understanding of metamorphic mineral reactions and U-Pb ages of newly grown sphene (titanite). This approach can be used on a variety of rock types that have been deformed at a wide range of metamorphic conditions. In an example from the Proterozoic Laramie Peak shear zone of southeastern Wyoming, a single period of syntectonic sphene growth in sheared mafic dikes is documented both by a strong spatial relationship between deformation and metamorphism and by sphene microtextures. U-Pb analyses of sphene separates give overlapping concordant or nearly concordant ages with a weighted mean of the $^{207}Pb/^{206}Pb$ ages of 1763 ± 7 Ma. We interpret this direct age of deformation as evidence that the Laramie Peak shear zone records the cratonic response to the 1.78–1.74 Ga Cheyenne belt collisional event.

INTRODUCTION

The ability to date deformation directly by radiometric techniques is a powerful tool for improving our understanding of the temporal evolution of orogenic belts. Previous efforts at directly dating deformation have involved many of the major isotopic systems, including Rb-Sr, $^{40}Ar/^{39}Ar$, and U-Pb (e.g., Page and Bell, 1986; Dunlap et al., 1991; Getty and Gromet, 1992). Of these, the U-Pb system offers many advantages because the multiple decay chains in the U-Pb system, plotted on a concordia diagram, provide a means for determining whether a chronometric mineral had a simple history, or whether it has undergone multiple growths or later disturbance. Getty and Gromet (1992) used the U-Pb system to date dynamically recrystallized sphene and monazite. However, their approach requires identification and isolation of grains that have been *completely* recrystallized and therefore have been completely reset isotopically.

In this paper we take a different approach. We selected a rock with no preexisting sphene and, using textures and metamorphic reactions, established that mineral growth accompanied deformation. It is important to note that this technique does not involve cooling ages, isotopic resetting, or recrystallization of preexisting minerals, but instead relies simply on the identification of syndeformational growth of sphene and its U-Pb age of crystallization. As such, this technique avoids many of the ambiguities that have complicated previous attempts to date deformation and metamorphism. The study area selected to demonstrate this technique is the Proterozoic Laramie Peak shear zone of southeastern Wyoming, where mafic dikes with no igneous sphene are sheared and metamorphosed in a mid-crustal amphibolite-grade mylonite zone.

GEOLOGIC SETTING

The Laramie Peak shear zone (Chamberlain et al., 1993) is located in the north-central Laramie Mountains of southeastern Wyoming (Fig. 1). The shear zone is a steeply dipping, northeast-striking, 300–500-m-wide zone of high shear strain that over a short distance grades northward into weakly deformed granitic rocks of the Archean Laramie batholith (Condie, 1969). Deformation in the Laramie Peak shear zone occurred in the amphibolite facies, as evidenced by the stability of hornblende + plagioclase (An_{57}) in mafic rocks and the crystal-plastic deformation of feldspar in granitic rocks. South of the shear zone occur Archean granitic rocks, migmatitic layered gneisses, and enclaves of supracrustal rocks that are intruded by a widespread suite of ca. 2.0 Ga mafic dikes (Cox et al., 1995). These rocks are variably deformed and typically contain fabrics similar in style and orientation to the shear zone, although considerably less intense.

Kinematic indicators, including composite foliations (S-C and C–C′), asymmetric sigmoidal porphyroclasts, and asymmetric folds, indicate south-side-up sense of shear. Rocks south of the shear zone have been metamorphosed at upper amphibolite facies conditions, with peak metamorphic pressure estimated at >6–7 kbar and temperatures in excess of 600 °C (Patel, 1992). North of the shear zone, rocks were metamorphosed at lower pressure conditions, estimated not to exceed 4 kbar on the basis of the presence of andalusite in metapelitic rocks (Snyder, 1992; Chamberlain et al., 1993). The Laramie Peak shear zone is an important discontinuity in U-Pb apatite ages; there are older ages (>2.0 Ga) to the north and younger ages (<1.8 Ga) to the south (Chamberlain et al., 1993). On the basis of these data, Chamberlain et al. (1993) suggested at least 10 km of south-side-up, differential vertical uplift across the shear zone.

The Laramie Peak shear zone is near two major Early Proterozoic collisional zones (Fig. 1): the Cheyenne belt 60 km to the south

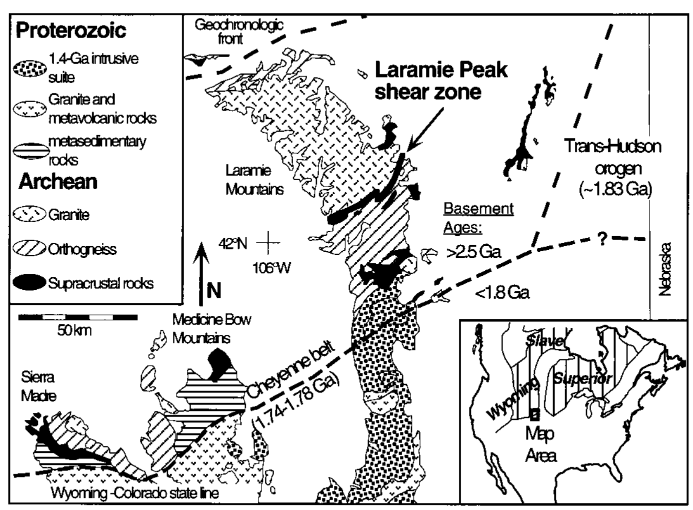

Figure 1. Sketch map of Precambrian geology of southeastern Wyoming. Geochronologic front in northern Laramie Mountains (Peterman and Hildreth, 1978) has been cited as evidence for northern extent of tectonic burial due to thrusting during Cheyenne belt collision (Karlstrom and Houston, 1984). Laramie Peak shear zone located in central Laramie Mountains records intracratonic response to this collision.

and the Dakota segment of the Trans-Hudson orogen >70 km to the east. The Cheyenne belt lies along the southern margin of the Wyoming province and is the suture between the Archean Wyoming province to the north and the Proterozoic Colorado province to the south. The current model for the belt involves a collision between island-arc terranes and the Archean craton between 1.78 and 1.74 Ga with a fold and thrust belt extending ~120 km to the north, burying the craton beyond the location of the Laramie Peak shear zone (Karlstrom and Houston, 1984; Houston et al., 1989). The eastern boundary of the Wyoming province is not exposed, but has been inferred from geophysical anomalies (e.g., Thomas et al., 1987) to be the extension of the ca. 1.83 Ga (Bickford et al., 1990) Trans-Hudson orogen. The Laramie Peak shear zone may record the cratonic response at mid-crustal levels to one or perhaps both of these orogens, and a precise age of deformation is necessary to understand fully the tectonic significance of the shear zone.

SAMPLING STRATEGY

To determine the timing of deformation within the Laramie Peak shear zone we chose to analyze sphene from a strongly deformed portion of an amphibolitized diabase dike. There are several advantages to selecting the mafic dikes as dating targets over other rock types involved in the shear zone: (1) there is no sphene in the original igneous assemblage; (2) the dikes have relatively simple metamorphic and deformational histories; and (3) individual dikes can be traced from the country rocks into the shear zone. Strain partitioning in the mafic dikes has led to the local preservation of weakly to undeformed parts of the dikes that contain the mineral assemblage orthopyroxene + clinopyroxene ± olivine + calcic plagioclase (An_{64}) + titanomagnetite, interpreted to be the primary igneous assemblage. No sphene has been observed in this assemblage, but the deformed, metamorphosed assemblage hornblende + plagioclase (An_{57}) + sphene + magnetite + quartz ± ilmenite contains abundant sphene (up to 2% modal). The mafic dikes crosscut earlier fabrics in surrounding migmatitic gneisses but contain only one fabric system that parallels the foliation and lineation within the Laramie Peak shear zone. In addition, individual dikes can be traced from the country rocks into the shear zone, and one can study both undeformed and deformed portions of a single dike. Taken together, these characteristics indicate that there has been only one period of sphene growth within the mafic dikes and that this growth is associated with the Laramie Peak shear zone. The geochronology sample (PRW 211) comes from a strongly deformed portion of a ~30-m-wide dike that intersects the main mylonitic shear zone at a high angle, where it is attenuated and sheared into parallelism with the mylonitic fabric (Fig. 2).

METAMORPHIC AND MICROSTRUCTURAL EVIDENCE FOR SYNDEFORMATIONAL GROWTH OF SPHENE

Sphene growth during amphibolite facies metamorphism of the diabase dikes can be modeled by an end-member reaction such as anorthite + ilmenite + clinopyroxene + orthopyroxene + H_2O = sphene + hornblende. The validity of this model reaction is supported by the presence of overgrowths of sphene on ilmenite and the lower average anorthite content (An_{57} vs. An_{64}) of the metamorphic plagioclase in the amphibolitized mafic dikes. Metamorphic effects are localized around deformation zones that appear to have acted as syntectonic conduits for fluids (e.g., Knipe and McCaig, 1994), whereas the undeformed parts of the dikes have remained relatively dry and unmetamorphosed. Similar relationships between deformation and metamorphism in mafic rocks have been observed in other studies (e.g., Beach, 1973; Brodie and Rutter, 1985; Nyman and Tracy, 1993).

Microstructures also indicate that sphene growth was synchronous with deformation. Sphene generally occurs as elongate clusters of lenticular grains in discrete layers parallel to the foliation. This parallelism with the foliation suggests growth or recrystallization during deformation. In addition, sphene overgrowths on ilmenite have a preferential distribution. Elongate aggregates of sphene extend parallel to foliation from central ilmenite grains; there is little to no sphene overgrowth on surfaces of ilmenite grains parallel to the foliation (Fig. 3). These sphene overgrowths, oriented with respect to deformational fabrics, suggest that sphene was replacing ilmenite during deformation, possibly by the reaction mentioned above.

U-Pb GEOCHRONOLOGY

We separated sphene from the sheared amphibolitized dike (PRW 211) and analyzed for U and Pb isotopic compositions (see note in Table 1 for details). Optical and isotopic analyses of sphene from the mafic dike are all consistent with a single population of sphene. Sphene grains have uniform color, morphology, size, and U and Pb concentrations. The grains are colorless to pale yellow, lenticular fragments, 0.1 mm in diameter. There is no visible evidence of overgrowth textures such as core-rim relationships that would indicate multiple periods of sphene growth. U and Pb concentrations are consistently low, ranging between 1 and 2 ppm (Table 1).

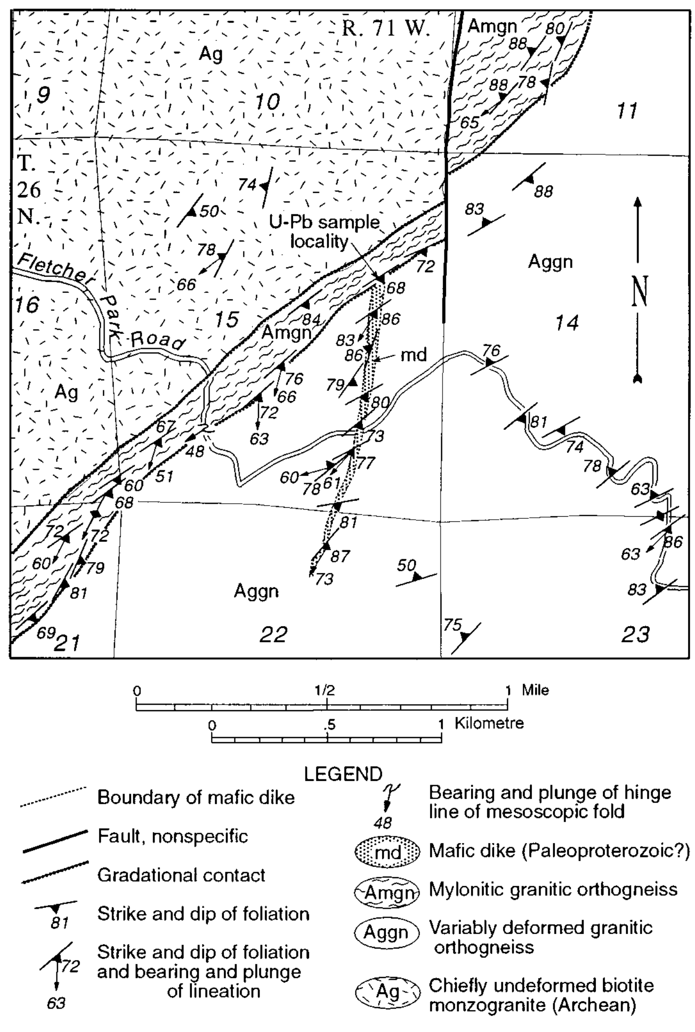

Figure 2. Geologic map of Fletcher Park area and mafic dike sample locality. Geology by A. W. Snoke (1993 and 1994). Only mafic dike that was dated with U-Pb techniques is shown. Area is widely intruded by mafic dikes of Paleoproterozoic age; distribution of these dikes is shown in Snyder et al. (1995).

Blank-corrected $^{206}Pb/^{204}Pb$ ratios of sphene ranged between 77 and 100 for this sample. At these values it is important to correct the U-Pb data with appropriate initial Pb isotopic compositions. We used the Pb isotopic composition in coexisting plagioclase feldspar that was dissolved in steps (modified after Ludwig and Silver, 1977). We believe that this composition of Pb is an appropriate initial composition because feldspar was involved in the sphene-forming reaction, and the Pb isotopic compositions of both minerals should have equilibrated at that time.

Five sphene fractions were selected from three different magnetic splits of the original sample of the amphibolitized mafic dike. A fairly large number of grains (~550) were required for each fraction due to the low concentrations of Pb and U. For two of the magnetic splits, both an air-abraded (after Krogh, 1982) and an unabraded fraction were analyzed to test for any age variations within crystals. The resulting points from the five analyzed fractions are all concordant or nearly concordant with overlapping $^{207}Pb/^{206}Pb$ ages (Table 1, Fig. 4). The weighted mean of the $^{207}Pb/^{206}Pb$ ages is 1763 ± 7 Ma (mean square of weighted deviates [MSWD] = 0.758). We interpret the concordant ages as evidence that the U-Pb system in these sphene grains has remained isotopically closed since 1.76 Ga. We interpret this age as a crystallization age rather than a cooling age, because the crystallization of sphene in the mylonite is interpreted to have occurred during shearing and rapid uplift of the southern block. Temperature estimates of decompression, based on garnet rim–biotite thermometry (Patel, 1992; Chamberlain et al., 1993), are 500–550 °C, lower than closure temperature estimates for sphene of this size (~580 °C; Cherniak, 1993; Heaman and Parrish, 1991; Mezger et al., 1991; Scott and St. Onge, 1995).

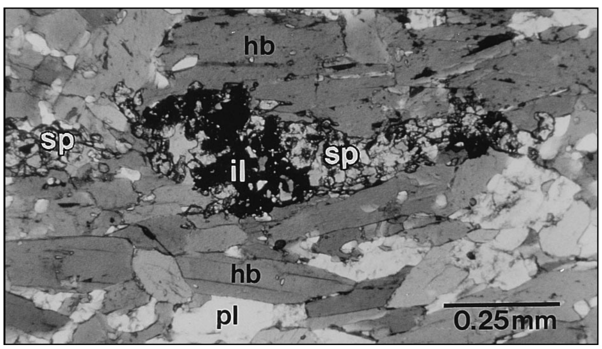

Figure 3. Photomicrograph showing textural relationships of syntectonic sphene with other coexisting phases in sheared and recrystallized mafic dike. Sphene (sp—light color, high relief) has partially replaced ilmenite (il—opaque) and preferentially grown parallel to foliation. Lower relief, dark gray, and white are hornblende (hb) and plagioclase (pl), respectively. Field of view is 1.25 mm.

DISCUSSION

By combining structural and microstructural observations with U-Pb sphene ages we have obtained a direct age of deformation associated with the Laramie Peak shear zone. This age of 1.76 Ga overlaps the best constraints on the timing of the Cheyenne belt collision (the 1.76–1.74 Ga late synkinematic Sierra Madre granite; Premo and Van Schmus, 1989; Houston et al., 1989) and is signif-

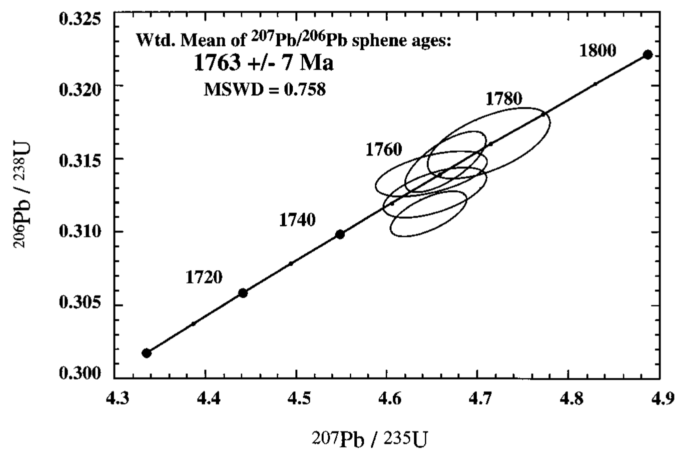

Figure 4. Concordia plot of U-Pb data from syntectonic sphene from sheared, amphibolitized mafic dike (PRW 211). Individual points are air-abraded and unabraded fractions from different magnetic splits. All points overlap and are interpreted as multiple analyses of single age. MSWD is mean square of weighted deviate.

TABLE 1. SPHENE U-Pb ISOTOPIC DATA FROM SHEARED AND AMPHIBOLITIZED MAFIC DIKE SAMPLE PRW211

Fractions*	Weight	Concentrations			Corrected values†							Age (Ma)			Rho‡
	(mg)	U (ppm)	Tot Pb (ppm)	com Pb (ppm)	$^{206}Pb/^{204}Pb$	$^{206}Pb§/^{238}U$	%err	$^{207}Pb§/^{235}U$	%err	$^{207}Pb§/^{206}Pb§$	%err	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	
m8nm10	1.46	1.13	0.82	0.31	83.17	0.3139	0.51	4.6481	1.31	0.1074	1.11	1760	1758	1756±20	0.56
m10nm12	0.91	1.07	0.82	0.33	77.02	0.3162	0.73	4.7143	1.41	0.1081	1.15	1771	1770	1768±21	0.58
m10nm12aa	0.79	1.52	1.09	0.41	84.06	0.3148	0.65	4.6650	0.93	0.1075	0.68	1764	1761	1757±12	0.69
m12nm14	1.39	1.14	0.85	0.33	79.43	0.3127	0.54	4.6529	1.18	0.1079	0.97	1754	1759	1765±18	0.58
m12nm14aa	1.37	1.53	1.00	0.33	100.00	0.3112	0.46	4.6457	0.94	0.1083	0.75	1747	1758	1770±14	0.61

* m, nm refer to magnetic susceptibility in degrees of dip on Franz Barrier style magnetic-separator. aa indicates air abraded.

† Corrected for mass discrimination and blank, % errors are 2σ.

§ Radiogenic.

‡ Error correlation

Note: Sphene was dissolved in 100 μl concentrated HF and 500 μl 6*N* HCl. Aliquots were spiked with a mixed $^{235}U/^{208}Pb$ spike. Pb and U were purified using HCl-HBr chemistry after Tilton (1973), and HCl chemistry after Krogh (1973), respectively. Pb and U samples were loaded onto single rhenium filaments with silica gel and graphite, respectively, for isotopic analysis on a multiple collector VG Sector mass spectrometer. Mass discrimination factors of 0.094% ± 0.06% for Pb and 0% ± 0.06% for U were determined by multiple analyses of NBS SRM 981 and U-500, respectively. PBDAT (Ludwig, 1988) and ISOPLOT (Ludwig, 1991) were used to reduce raw mass spectrometer data; correct for blanks (measured as 10–50 pg for Pb); and calculate uncertainties, concordia intercepts, and weighted averages. Isotopic compositions for initial Pb came from analyses of the least radiogenic dissolution step of coexisting feldspars ($^{206}Pb/^{204}Pb$, 15.43 ± 0.015; $^{207}Pb/^{204}Pb$, 15.50 ± 0.023; $^{208}Pb/^{204}Pb$, 36.56 ± 0.073), dissolved in 5% HF after Ludwig and Silver (1977). The weighted average of the $^{207}Pb/^{206}Pb$ ages (MSWD = 0.758) is used as a final age because the analyses overlap concordia, and variation appears to represent random error around a single age.

icantly younger than the Trans-Hudson orogen (ca. 1.83 Ga; Bickford et al., 1990). We therefore interpret the age of deformation as further evidence that the Laramie Peak shear zone is an intracratonic response to the Cheyenne belt island arc–continent collision. The duration of movement along the Laramie Peak shear zone cannot be determined from this single age; however, some constraints can be determined from additional data. Initial motion along the shear zone could have occurred no earlier than 1.79 Ga, the age of the island-arc terranes involved in the Cheyenne belt collision (Premo and Van Schmus, 1989). In addition, U-Pb apatite ages south of the shear zone indicate that uplift related to the zone was rapid, with associated cooling to below 450 °C by 1736 ± 20 Ma (Chamberlain et al., 1993).

CONCLUSION

Sphene dating is well established, and U-Pb ages of sphene have been interpreted previously to reflect timing of metamorphism (e.g., Mezger et al., 1991; Hanson et al., 1971; Tucker et al., 1986). However, the aspect of this study that sets it apart from earlier ones is the establishment of syndeformational growth of sphene in a rock that did not contain sphene prior to deformation. The establishment that there was only one period of sphene growth that occurred during deformation removes many potential problems. In this study, there was no risk that the sphene data would reflect mixtures of grains or domains with different ages, as is a possibility in studies of granitic rocks (e.g., Hanson et al., 1971; Tucker et al., 1986) and rocks with preexisting sphene that underwent dynamic recrystallization (e.g., Getty and Gromet, 1992). Furthermore, in cases such as this one, where the inferred metamorphic temperatures (500–550 °C) are below the closure temperature for sphene, U-Pb data reflect a direct date on crystallization and deformation, rather than simply a cooling age that represents a younger limit on the time of deformation. The structural and microstructural U-Pb sphene dating method presented here can be used to date deformation directly with precisions better than ±1% over a wide range of temperatures, from the low-temperature stability limit of sphene (<300 °C), to the closure temperature of sphene for U-Pb (~550–700 °C, depending on effective diffusion radius and cooling rate).

ACKNOWLEDGMENTS

Funding for this project was supplied in part by National Science Foundation grants EAR-9205825 and EAR-9218458 and the University of Wyoming College of Arts and Sciences. We thank Peter Gromet and Mike Williams for helpful reviews of the manuscript, and Pat Bickford for a constructive review of an earlier version.

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Manuscript received November 29, 1995
Revised manuscript received March 25, 1996
Manuscript accepted April 5, 1996