Basement complexes in the Wasatch fault, Utah, provide new limits on crustal accretion

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ABSTRACT

New and reinterpreted isotopic data for crystalline rocks exposed in the Wasatch Range require a reevaluation of Precambrian crustal boundaries in Utah. Crystalline rocks of the Santaquin Complex underwent metamorphism prior to ca. 1670 Ma, consistent with Sr and Nd isotope data. Mafic to intermediate rocks have major element, trace element, and isotope ratios indicative of derivation in an arc accreted to the Archean craton in Proterozoic time, requiring the crustal suture to be north of the Santaquin Complex. Farther north, the Farmington Canyon Complex has been considered Archean based on published Nd model ages and discordant U/Pb zircon ages. However, Nd model ages and zircons could be inherited from sedimentary protoliths. U/Pb and electron microprobe ages of monazite have a mode at 1650 to 1700 Ma, concordant with the Santaquin Complex, and lack inheritance. We propose that the Farmington Canyon Complex was first cratonized from Archean-derived sediments in the Proterozoic, requiring a crustal suture to be north of it as well. Accretion ages of arc terranes in southeastern Wyoming are ~60–100 m.y. older than in Utah. Thus, a serious reevaluation of basement architecture in Utah is needed and a previously unrecognized temporal complexity of accretion is indicated.

Keywords: geochronology, igneous rocks, crustal origin, isotope geochemistry.

INTRODUCTION

The few Precambrian crystalline rock exposures in the Basin and Range and Colorado Plateau provide rare opportunities to document crust formation, tectonic setting, and deformational histories of the region. Two basement exposures are found just east of Santaquin, Utah, and north of Salt Lake City, Utah, in the footwall of the Wasatch fault (Fig. 1). The geological, geochemical, and isotopic characteristics of the Santaquin Complex and Farmington Canyon Complex reveal the time and mode of crust formation, and help locate a concealed crustal boundary between Archean and Proterozoic crust. This study illustrates the complexity of crustal accretion in North America and the advantages of basing crustal boundary models upon the direct examination of basement blocks rather than relying solely on isotopic studies of young plutons.

Geologic Setting

The Santaquin Complex exposes ~3 km^2 of igneous and metamorphic rocks (Fig. 2A). Bounded westward by the Wasatch fault, clastic sediments of the Neoproterozoic Big Cottonwood Formation unconformably overlie the Santaquin Complex to the east (Fig. 2B). Of the mappable subunits (Fig. 2B), pegmatitic granites, mafic syenite, and fine-grained leucogranite are largely unstrained, whereas other rocks are foliated. Hintze (1993) and Witkind and Weiss (1991) inferred the Santaquin Complex to be Archean by correlation to the Farmington Canyon Complex. Unlike the Santaquin Complex, the Farmington Canyon Complex has received considerable attention (e.g., Hedge et al., 1983; Bryant, 1988; Barnett et al., 1993).

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RESULTS

With the exception of electron microprobe monazite ages for the Farmington Canyon Complex, analytical results are reported only for the Santaquin Complex[1]. Data from previous studies of the Farmington Canyon Complex support the synthesis (Barnett et al., 1993; Bryant, 1988; Hedge et al., 1983).

Isotopic Data

A U/Pb age, ^{40}Ar/^{39}Ar ages, and microprobe ages of monazite determine the age of the Santaquin Complex. Zircons (method of Gehrels, 2000) from mafic syenite define a chord with an upper intercept of 1673 ± 23 Ma, a good estimate for the age of emplacement. This unstrained rock is younger than deformed rocks of the Santaquin Com-

[1]GSA Data Repository item 2002097, Chemical, isotopic, electron microprobe, U-Pb isotopic, and hornblende isotopic data, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.

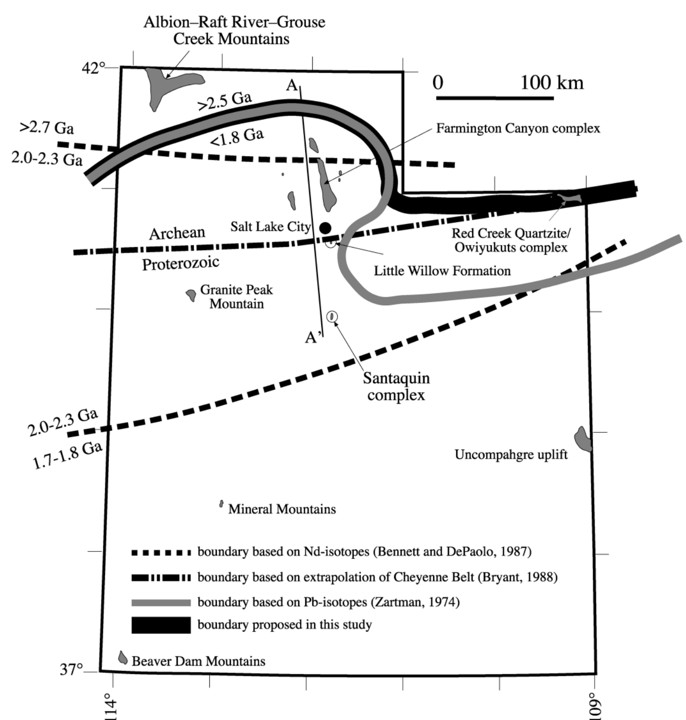

Figure 1. Distribution of exposed Precambrian crystalline rock as well as proposed crustal boundaries. Line A-A′ correlates to model of crust formation presented in Figure 5.

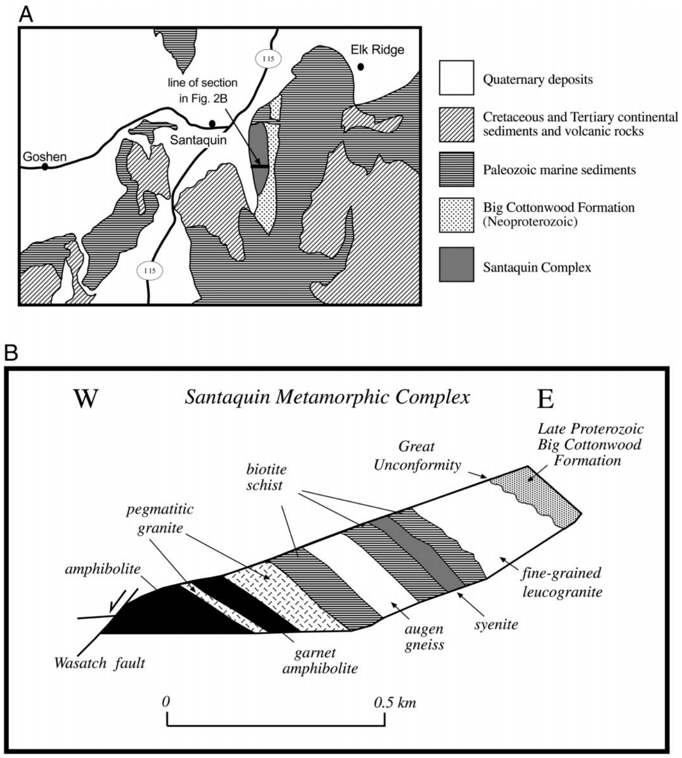

Figure 2. A: Geologic map of Santaquin, Utah, area (adapted from Hintze et al., 2000). B: Generalized cross section through Santaquin Complex.

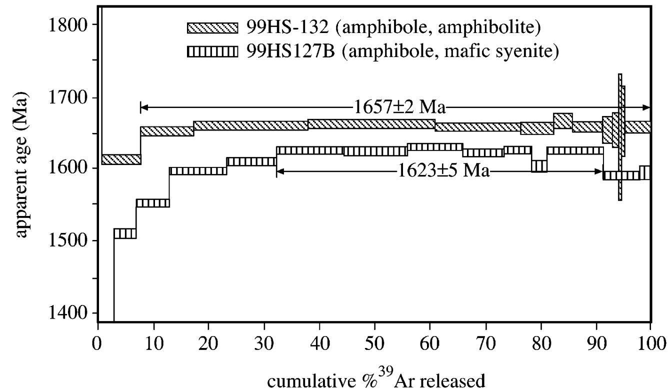

Figure 3. $^{40}Ar/^{39}Ar$ age spectra for amphiboles from Santaquin Complex.

plex. A $^{40}Ar/^{39}Ar$ plateau age was determined for hornblende from mafic syenite (1623 $\pm$ 5 Ma); the age represents the release of ~60% of the gas. For hornblende from amphibolite, the 1657 $\pm$ 2 Ma age represents >90% of the gas (Fig. 3). The $^{40}Ar/^{39}Ar$ ages represent the time that samples cooled below their closure temperature of ~550 °C.

Microprobe ages of monazite were determined for garnet-biotite schist collected near FCC111 of Barnett et al. (1993) and a garnet-biotite schist of the Santaquin Complex. A distinct mode exists between 1650 and 1700 Ma for both the Farmington Canyon Complex and Santaquin Complex (Fig. 4). The scatter is due to analytical artifacts (new analytical procedures will eliminate these; Michael Williams, 2002, personal commun.).

Four of six initial Sr isotope ratios ($^{87}Sr/^{86}Sr_i$) range from 0.701780 to 0.702701 and are similar to bulk earth values (~0.702) at 1700 Ma. Augen gneiss is more radiogenic (0.707742), whereas pegmatitic granite has an unreasonably low $^{87}Sr/^{86}Sr_i$ of 0.699872. $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ are positively correlated, and produce error chrons of 1919 $\pm$ 300 Ma, or 1776 $\pm$ 81 Ma if data are forced through bulk earth (Cameron et al., 1981). εNd_t values (at 1700 Ma) for 5 of 6 samples vary between 2.9 and 7.5 except for the extremely rare earth element enriched (Sm/Nd = 0.0594) mafic syenite (εNd_t = 14.7). Depleted Nd model ages (T_{dm}s) vary from 1460 to 1810 Ma (recalculated following Michard et al., 1985), except for syenite.

DISCUSSION

Crust Formation Processes

Although few samples are reported for the Santaquin Complex, chemical data are consistent with derivation in an arc. Low $^{87}Sr/^{86}Sr_i$ and high εNd_t at 1700 Ma suggest the formation of juvenile crust. Although pegmatitic granite (difficult to representatively sample) has an impossibly low $^{87}Sr/^{86}Sr_i$ ratio at 1700 Ma, the $^{87}Sr/^{86}Sr_i$ at 1400 Ma is ~0.7034. Although anorogenic granites were emplaced in the southwestern United States at this time (e.g., Anderson and Bender, 1989), low Nb and moderate Y contents suggest that this rock, as well as leucogranite and augen gneiss, is more akin to a volcanic arc granite rather than within plate or anorogenic granite (Pearce et al., 1984; Eby, 1992).

Mafic to intermediate rocks have high large ion lithophile to high field strength element ratios. Ba/Nb varies from 46 to 90 (this study; Vogel et al., 2002). Amphibolite and garnet amphibolite have major element compositions consistent with arc-volcanic protoliths (hawaiite and latite). Mafic syenite may represent an intrusive remnant of shoshonite, common in many arcs. Abundant accessory phases (titanite, apatite, and zircon) account for its unusually elevated incompatible trace elements and suggest that this rock represents a cumulate facies of alkaline magmatism. The geochemical data are consistent with derivation in an arc. It is improbable that nearly all geochemical characteristics would point to an arc origin by chance.

Age of Accretion

Mineral ages and isotopic indicators of the Santaquin Complex are consistent with accretion, metamorphism, and plutonism during the interval 1670–1700 Ma. Evidence for Archean inheritance is lacking. The 1673 Ma U/Pb age for mafic syenite, a minimum age for crust formation, has a relatively large uncertainty of $\pm$23 m.y. due to Pb loss. Thus, this sample is essentially concordant with the $^{40}Ar/^{39}Ar$ age of 1657 $\pm$ 2 Ma in amphibolite. This age is an excellent constraint on

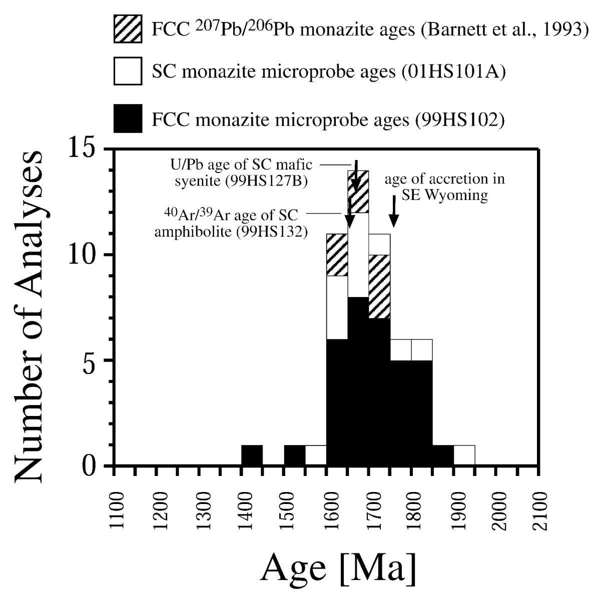

Figure 4. Histogram of monazite ages for schists of Farmington Canyon Complex (FCC; sampled near FCC-111 of Barnett et al., 1993), and Santaquin Complex (SC). Also shown are $^{207}Pb/^{206}Pb$ ages for monazite from FCC (Barnett et al., 1993).

the time of accretion unless cooling from peak metamorphic temperatures was very slow. This is unlikely for a contractional orogenic event, because rock uplift and denudation should drive rapid cooling. Monazite ages for the Santaquin Complex, although exhibiting scatter, are consistent with this interpretation (Fig. 4).

The Farmington Canyon Complex north of Salt Lake City (Fig. 1) has been considered Archean based on inheritance in U/Pb isotopes in zircon, old Nd T_{dm}s, and elevated $^{87}Sr/^{86}Sr_i$ of quartz monzonite orthogneiss, with a strong metamorphic overprint ca. 1800 Ma (e.g., Hedge et al., 1983). The Proterozoic overprint is based on quartz monzonite gneiss data that include a well-correlated whole-rock Rb-Sr isochron of 1808 $\pm$ 34 Ma, and discordant zircons with an upper intercept of 1780 $\pm$ 20 on a concordia plot. The Rb-Sr isochron has an $^{87}Sr/^{86}Sr_i = 0.7692$, indicative of a source with a lengthy residence time in the crust; however, it is based on samples physically separated by the Ogden thrust, complicating its interpretation.

Nd T_{dm}s (n = 3), recalculated from Hedge et al. (1983), yield model ages of 2790 and 3270 Ma for quartz-monzonite gneiss, whereas one amphibolite has an age of 2820 Ma. An Rb-Sr isochron for metasedimentary rocks of the Farmington Canyon Complex cannot be constructed, although bounding envelopes may be drawn with slopes of ca. 3600 to 2600 Ma (Hedge et al, 1983). Discordant zircon separates from metasedimentary rocks yield $^{207}Pb/^{206}Pb$ ages of 1770–2271 Ma (Hedge et al., 1983), indicative of some inheritance. Hedge et al. (1983) also reported unusual U/Pb ages of 1993 $\pm$ 22 and 2023 $\pm$ 4 Ma for granite gneiss in the Farmington Canyon Complex, although the ages represent the upper intercepts of two-point chords. We are reluctant to attach much significance to these ages. Nonetheless, the U/Pb, Sr, and Nd isotope systematics suggest that the Farmington Canyon Complex may have had an additional ~1000 m.y. crustal residence time relative to a ca. 1800 Ma metamorphic event. Yet the isotope systematics could also be the product of Proterozoic metamorphism of sediments with an Archean provenance (Barnett et al., 1993). Nd T_{dm}s and elevated $^{87}Sr/^{86}Sr_i$ only imply the approximate age of separation of source material from the mantle. Similarly, zircons could represent detrital grains residing in sedimentary rock until they underwent a major Proterozoic Pb-loss event.

Hornblende $^{40}Ar/^{39}Ar$ ages in the Farmington Canyon Complex range from 1586 to 1656 Ma. The $^{207}Pb/^{206}Pb$ ages of metasedimentary monazite vary from 1644 to 1711 Ma (Fig. 4), ~100 m.y. younger than the Rb-Sr age described here. Although this discordance is difficult to explain, microprobe ages of monazite are consistent with U/Pb results (Fig. 4). Although less precise, they allow testing for large age gradients within and between grains. Microprobe data for the Farmington Canyon Complex lack evidence for Archean metamorphism.

Early estimates for the closure temperature of monazite to Pb loss ranged from 530 (Wagner et al., 1977) to $\geq$700 °C (Copeland et al., 1988). Recent estimates range from 700 to $>$900 °C (e.g., Murphy, 2001; Braun et al., 1998; Dahl, 1997; van der Pluijm et al., 1994; Kingsbury et al., 1993). Monazite in metasedimentary rocks is thought to crystallize from sedimentary phosphate during prograde metamorphism ($>$500 °C; Kingsbury et al., 1993). The high closure temperature of monazite suggests that Archean metamorphism should be recorded. The lack of Archean inheritance strongly indicates that the Farmington Canyon Complex was first cratonized between 1650 and 1710 Ma, whereas an Archean provenance for Farmington Canyon Complex protoliths is consistent with Sr and Nd isotope characteristics, combined with radiogenic Pb inheritance in zircon.

Crustal Boundaries

Sr, Nd, and Pb isotopes have been used to map basement age provinces, although such maps differ in detail (Fig. 1). In the western United States, such maps are often based on isotopic measurements of Mesozoic and younger plutons, perhaps owing to the paucity of Precambrian outcrop.

In this context, a review of three selected models (e.g., Zartman, 1974; Bennett and DePaolo, 1987; Bryant, 1988; Fig. 1) illustrates the value of direct observation of basement rocks where possible. The model of Bennett and DePaolo (1987) suggests that the Santaquin Complex should be 2000–2300 Ma, which is clearly not the case.

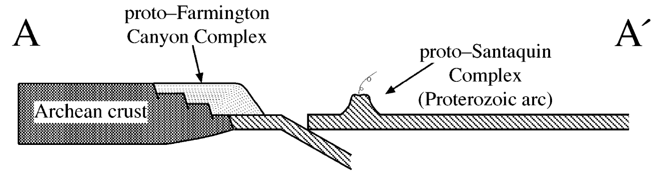

Figure 5. Hypothetical model for accretion of arcs to Archean Wyoming province. See Figure 1 for line of section.

Another model is based in part on large-scale surface features. Bryant (1988) proposed that the suture separating Archean rocks of the Wyoming province from Proterozoic basement (e.g., Cheyenne belt, Karlstrom and Houston, 1984), which can be traced in surface exposures as far west as the eastern Uinta Mountains (Owiyukuts Complex; Sears et al., 1982), underlies the Uinta axis (Karlstrom and Houston, 1984; Fig. 1). Farther west, a series of Tertiary intrusions and volcanic rocks were emplaced in an east-west belt at the same latitude, perhaps exploiting the crustal suture west of the Uinta Mountains (Vogel et al., 1997, 2002). Wright and Snoke (1993) argued that the boundary is exposed at ~40.5°N latitude in the Ruby Mountains of northeastern Nevada. Although the boundary may be well defined in northeastern Nevada and northeastern Utah, our reinterpretation requires the boundary to be placed to the north and east of the Farmington Canyon Complex, at variance with the model of Bryant (1988).

Although the Archean-Proterozoic crustal boundary we propose (Fig. 1) is partly coincident with Zartman's (1974), it is defined by geologic structure and mineral ages. We diverge with Zartman where his boundary fails to pass through the Red Creek Quartzite–Owiyukuts Complex, although Zartman published his synthesis before Sears et al. (1982) identified the suture in Utah. In addition to separating Archean rocks (Armstrong and Hills, 1967; Egger et al., 2000) of the Albion–Raft River–Grouse Creek Range from the Farmington Canyon Complex, our boundary passes to the east of the complex and northeast of the Little Willow Formation (Fig. 1), another small outcrop of basement rocks in the footwall of the Wasatch fault. We place the boundary to the north of the Little Willow Formation. The only constraints on its age are Nd T_{dm}s of 1600–1800 Ma for the nearby Little Cottonwood stock and silicic rocks of the Bingham igneous complex (Maughan, 2001; Farmer and DePaolo, 1983). The boundary is drawn parallel to the axis of the Uinta Mountains through the Owiyukuts–Red Creek Quartzite Complex in extreme northeastern Utah, conforming to the structural grain of the Uinta Mountains.

We propose that the Farmington Canyon Complex was a sequence of sediments shed from the Archean Wyoming province (Fig. 5), providing the isotopic antiquity seen in zircon, Sr, and Nd isotope data. The sediments could have been deposited at any time after crust formation and prior to metamorphism ca. 1700 Ma. The only real constraint on depositional age is from the Nd T_{dm} determined on an amphibolite with a basaltic composition (including high Ni and Cr). If this rock was originally emplaced as a mantle-derived flow or sill, its model age may approximate its emplacement age, suggesting that the stratigraphic age of the sedimentary package onto (or into) which it was emplaced was older. However, we are reluctant to attribute too much significance to a single analysis.

As a passive margin prior to accretion, we envisage that older, colder, and denser oceanic lithosphere was subducted to produce an arc or sequence of arcs (represented by the Santaquin Complex) accreted to the Wyoming Province beginning ca. 1700 Ma in northern Utah (Fig. 5). This is distinctly younger than accretion in the Cheyenne belt of southern Wyoming, ca. 1760 Ma (e.g., Duebendorfer and Houston, 1987; Resor et al., 1996; Scoates and Chamberlain, 1997; Frost et al., 2000). Differences in the age of accretion of ~60 m.y. along the strike of the crustal boundary are reasonable, because Phanerozoic orogenies often span time scales to 100 m.y. (Duebendorfer and Houston, 1987; Van Schmus, 1980). Due to extensive Phanerozoic cover, it may be difficult to determine whether the Santaquin Complex represents accretion of a distinct terrane, or an obliquely accreted arc. Nonetheless, the temporal disparity of accretion in Utah and Wyoming appears real based on mineral ages reported here.

South of the Santaquin Complex, basement rocks in the Mineral Mountains have ages of ca. 1720 Ma (Aleinikoff et al., 1986), distinctly older than the Farmington Canyon Complex and Santaquin Complex. Such older ages may simply reflect a prior geologic history in the blocks accreted to North America. By analogy, rocks with long and complex geological histories (e.g., Jurassic ophiolites in Indonesia) are currently being accreted to Australia as that continent merges in a complex way with Southeast Asia (e.g., Hall and Blundell, 1986).

CONCLUSIONS

The relationship of the Santaquin Complex and Farmington Canyon Complex to adjacent rock bodies and geologic structures provides a rare glimpse into the geologic history of Utah over the past 1700 m.y. The results obtained for the Santaquin Complex and reinterpretation of the Farmington Canyon Complex emphasize the value of directly investigating basement rocks, where possible, to delineate crustal boundaries. Most Santaquin Complex rocks have chemical characteristics consistent with juvenile crust formed in an arc. By contrast, the Farmington Canyon Complex is interpreted to represent the Proterozoic cratonization of passive margin sediments with an Archean provenance.

Isotopic constraints place the age of crust formation and accompanying amphibolite facies metamorphism between 1650 and 1700 Ma for the Santaquin Complex. Overall, the age of initial metamorphism of the Farmington Canyon Complex is indistinguishable from the Santaquin Complex (Fig. 4). We suggest that the docking of the arc terrane represented by the Santaquin Complex was a driving force for metamorphism of the sedimentary sequence represented by the Farmington Canyon Complex, thereby explaining the concordance in age between the two bodies. This reinterpretation of the Farmington Canyon Complex requires a major reconsideration of the boundary geometry between Archean and Proterozoic basement in Utah (Fig. 1).

We suggest that accretion in Utah occurred ~60–100 m.y. later than in southeastern Wyoming, emphasizing the temporal complexity of accretion along strike in suture zones. However, extensive cover of basement rocks may preclude determining whether the difference in age between northern Utah and southeastern Wyoming is due to the arrival of different terranes, oblique convergence, or some other factor.

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