Introduction: EarthScope IDOR project (deformation and magmatic modification of a steep continental margin, western Idaho–eastern Oregon) themed issue

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ABSTRACT

The EarthScope IDOR (Idaho-Oregon) project was designed to investigate the formation of the steep accretionary boundary associated with the American continental margin. Following Giorgis et al. (2007), we refer to the Salmon River suture zone as the zone of western Idaho that records the collision of the accreted terranes of the Blue Mountains with North America. The western Idaho shear zone (WISZ), in contrast, is a younger shear zone within the overall Salmon River suture zone. Although accretion occurred by the Late Jurassic–Early Cretaceous (Walker, 1986; Selverstone et al., 1992; Snee et al., 1995; LaMaskin and Dorsey, 2016), the accretionary boundary was significantly modified by the mid-Cretaceous subvertical WISZ (e.g., McClelland et al., 2000; Giorgis et al., 2005). Unusually sharp isotopic gradients (Sr, Nd, O) representing the edge of continental lithosphere correspond to the surface location of the WISZ (Tikoff et al., 2001). Structural studies in the WISZ suggested dextral transpression with strong east-west shortening (Giorgis and Tikoff, 2004; Giorgis et al., 2005).

The EarthScope IDOR (Idaho-Oregon) project was designed to unravel the tectonic history along this boundary. This project was submitted to the EarthScope program of the National Science Foundation (primary investigators: Tikoff, Hole, Russo, and Vervoort). Specifically, the IDOR project investigated the tectonic history of western Idaho and eastern Oregon, including collision (e.g., Salmon River suture zone), syn-collisional to postcollisional transpressional deformation (e.g., WISZ), voluminous...
Figure 1. (A) Location of the study area in the western United States. WISZ—Western Idaho shear zone; BM—Blue Mountain terranes (diagram originally from Wyld et al., 2006). (B) Regional geological map of eastern Oregon and western Idaho (sed—sedimentary). The boxes indicate the areas of study for the publications within this themed issue.
Cretaceous and Miocene magmatism (e.g., Idaho batholith, Columbia River basalt flows), and active extensional deformation. In particular, work concentrated on the role of the steep accreted terrane-craton boundary in Idaho and Oregon as a major controlling feature for both subsequent deformation (e.g., Tikoff et al., 2001; Giorgis et al., 2006, 2008; Lund et al., 2008) and magmatism (e.g., Carlson and Hart, 1987; Leeman et al., 1992).

The following are the three overarching questions driving the EarthScope IDOR project.

1. How do fundamental lithospheric boundaries, such as the juxtaposition of continental and oceanic lithosphere at the WISZ, guide subsequent deformation and magmatism?
2. How do magmatism and extensional deformation cause modification (destabilization) of the continental lithosphere, and at what lithospheric levels?
3. What are the implications of this destabilization for magmatism, deformation, and evolving lithospheric strength?

**THREE REJECTED MODELS**

The study area was chosen because prior work had suggested that it contained an attribute that is unique in the North American Cordillera, i.e., an offset vertical, lithospheric-scale boundary (Fig. 2). This vertical geometry would allow investigation of the effect of different lithospheric layers on deformation and magmatism. Cretaceous intrusive rocks record a whole-lithospheric vertical boundary beneath western Idaho (e.g., the exposed WISZ; Manduca et al., 1992); however, the mantle isotopic signature of Miocene basaltic rocks (Hart, 1985; Carlson and Hart, 1987; Hart and Carlson, 1987; Leeman et al., 1992) indicates that the edge of continental mantle is ~120 km to the east of the exposed WISZ in eastern Oregon (Fig. 2). This observation led Leeman et al. (1992) to hypothesize that the subvertical WISZ, i.e., the boundary between oceanic arc and continental lithosphere, is cut and offset along a Sevier orogeny detachment (Fig. 2). This interpretation was supported by geophysical work (Evans et al., 2002). Miocene magmatism, including the extrusion of the voluminous Columbia River basalt flows, appears to be localized on a sharp boundary in the mantle beneath eastern Oregon (Carlson and Hart, 1987), while extensional deformation is localized on the steep crustal boundary in western Idaho (Fig. 2). Confirmation and elaboration of this model required geophysical imaging to determine whether the offset exists, at what lithospheric level it occurs, and how later geological events modify the regional lithospheric structure. Therefore, our three proposed models addressed different aspects of an offset (Fig. 2): (1) the crustal detachment model of Leeman et al. (1992) (Fig. 2B); (2) a possible detachment within the lithospheric mantle (Fig. 2C); or (3) a curved WISZ (Fig. 2D). In the last model, contractional deformation in the Sevier fold and thrust belt is driven by emplacement of the voluminous granites of the Idaho batholith (e.g., Smith, 1981).

We did not know what to expect for a crustal geometry along the accreted terrane-craton boundary in western Idaho–eastern Oregon. As a result of the data presented in this volume and published elsewhere (e.g., Stanciu et al., 2016), none of the three models originally proposed is viable. The primary reason to reject these models is that the geophysical
evidence clearly shows that the accreted terrane-craton boundary, currently defined by WISZ, continues vertically through the crust and offsets the Moho by ~7 km. This result is clearly demonstrated by both the active source seismic data (Davenport et al., 2017) and the IDOR Project broadband seismic results (Stanciu et al., 2016). This interpretation is also corroborated by the study of Kurz et al. (2016), who maintain that the isotopic break, recorded by the Miocene basaltic rocks (e.g., Hart, 1985; Carlson and Hart, 1987), indicates the limit of the Olds Ferry magmatic arc relative to the other terranes of the Blue Mountains. The Olds Ferry terrane shows more enriched compositions in relation to the isotopic data (e.g., Sr, Nd, and Pb), and thus reflects interaction with continental material. The extent of the Olds Ferry terrane also appears to demarcate the region of mafic underplating, as observed in the IDOR geophysical data (e.g., Stanciu et al., 2016; Davenport et al., 2017).

The proposed model, based on the IDOR work, is shown in Figure 2E. We first summarize the contributions in this volume that resulted in this new view.

CONTRIBUTIONS IN THIS VOLUME

There are ten papers on various aspects of the Salmon River suture zone and surrounding areas included in this volume. Although many papers are from researchers funded through the EarthScope IDOR projects, there are also independent researchers with important contributions from this region. The first four papers concentrate on the WISZ, including its along-strike extension to the north. The following two papers concentrate on the tectonic history of the accreted terranes. The next three papers document deformation, exhumation, and emplacement rates in the Idaho batholith. The final paper describes the results from the active source seismic study that spans the entire region. The locations of all of the study areas presented in this volume are shown in Figure 1.

Braudy et al. (2016) concentrate on the WISZ in the location where the shear zone is transected by the active seismic line (West Mountain, Idaho; Davenport et al., 2017). Braudy et al. (2016) document a primary bend in the shear zone, from a north-south-oriented foliation observed in the north to a 020-oriented fabric observed to the south. The latter orientation is consistent with that observed in the WISZ south of the western Snake River Plain in the Owyhee Mountains (Benford et al., 2010). The mapping in Braudy et al. (2016) also determined the presence of a metasedimentary screen within the WISZ. These metasedimentary exposures provide the first estimates of pressure and temperature conditions within the WISZ of ~4.4 kbar and ~730 °C. New U-Pb zircon geochronology data constrain the initiation deformation in the WISZ to ca. 103 Ma, and Lu-Hf garnet geochronology indicates that peak metamorphism during WISZ deformation occurred ca. 98 Ma. Geochemistry and zircon xenocrysts also suggest deeper crustal imbrication that formed during terrane accretion prior to WISZ deformation.

Montz and Kruckenberg (2017) report on the Potters Pond migmatite domain, which occurs near the change in orientation of the WISZ on West Mountain, Idaho. Their structural mapping indicates two distinct periods of protracted migmatite formation that are constrained by U-Pb zircon analysis. The first episode, in the Early Cretaceous, occurred during known deformation in the Salmon River suture zone. The second episode, in the mid-Cretaceous, occurred during dextral transpressional deformation on the WISZ. The data of Montz and Kruckenberg (2017) are the first direct confirmation of a two-stage model for deformation in western Idaho, with an earlier Salmon River suture zone overprinted by a later WISZ (e.g., McClelland et al., 2000). Furthermore, their study documents symmetamorphic fabric development east of the initial S' isotope ($^{187}_{\text{Os}}$/Sr = 0.706 isopleth), thus providing the first direct evidence for Salmon River suture zone deformation on the cratonic side of the arc-continent boundary.

The deformation in the Syringa embayment, along the 90° bend of the Sr 0.706 isopleth in central Idaho, is the topic of a paper by Schmidt et al. (2016). Field-based and microstructural analyses indicate reverse (northeast side up) shear along the Ahsahka shear zone, which is present in this region. This result is corroborated using the crystallographic vorticity axis method of Michel et al. (2015) on quartzites that indicates horizontal vorticity vectors. Schmidt et al. (2016) also present U-Pb zircon data that suggest that similar age deformation occurs in the Ahsahka shear zone and the WISZ located to the south. Finally, Schmidt et al. (2016) document the presence of two right-lateral, transpressional, northeast-trending fault and/or shear zones in the Syringa embayment, the Limekiln and Mount Idaho deformation zones. These features modify and offset the original orientation of Ahsahka shear zone and the WISZ, and were active until ca. 54 Ma. The Limekiln and Mount Idaho deformation zones were also reactivated after eruption of the Miocene Columbia River Basalt.

The transpressional nature of the WISZ is the subject of the paper by Giorgis et al. (2016). The fabrics of the WISZ contain a steeply dipping foliation and a downdip lineation, and it was previously suggested that this pattern reflects transpressional deformation (e.g., Giorgis et al., 2005). Giorgis et al. (2016) first use a series of well-exposed outcrops with late-stage dikes to document boudinage and folding consistent with dextral transpressional kinematics. An estimate of kinematic vorticity, using tails on porphyroclasts within the shear zone, suggests a convergence vector oriented 60° or slightly higher. These methods are supplemented by microstructural analyses of deformed quartzites on West Mountain, including the crystallographic vorticity axis method of Michel et al. (2015). These analyses indicate subvertical vorticity axes, when normal faulting is restored, and dominantly prism <2< slip. These data are compared to the data in Schmidt et al. (2016), who utilized the same methods. Together, these data are consistent with a ~60° orientation of convergence, which leads to dextral transpressional deformation in West Mountain and convergent deformation in the Ahsahka shear zone.

Kurz et al. (2016) use exposures in Hells Canyon and elsewhere in the Blue Mountains terrain to compare the Wallowa and Olds Ferry magmatic arcs; their isotopic (Sr, Nd, and Pb) evidence indicates that the Olds Ferry arc is isotopically enriched, consistent with its formation as a fringing continental arc. In contrast, the Wallowa terrane is isotopically depleted and likely reflects a more outboard oceanic position. New U-Pb zircon data provide the geochronological context for the isotopic data. Based on new results, Kurz et al. (2016) argue that the three different crustal columns (from northwest to east-west, Wallowa, Olds Ferry, and North America) have been connected to distinct mantle reservoirs since the early Mesozoic; in their model, the west to east spatial variability in the isotopic compositions sampled by Neogene mantle rocks results from this lithospheric structure. This model contrasts sharply with the interpretation of Leeman et al. (1992), who suggested that the edge of continental mantle is ~120 km to the west of the exposed WISZ. The Kurz et al. (2016) interpretation resolves the issue of the isotopic compositions of the Neogene volcanic rocks in a manner consistent with the seismic results of Davenport et al. (2017).

Gaschnig et al. (2017) examine Cretaceous igneous rocks and sediments on the southernmost part of the exposed Blue Mountain terranes in easternmost Oregon. A series of four plutons intrude the Blue Mountain terranes on or near the Conner Creek fault, which separates the Izie and Baker terranes. These plutons are dated from 129.4 to 123.8 Ma and crosscut the fault and constrain the timing of motion. The (U-Th)/He zircon studies on these plutons indicate a middle Cretaceous cooling age through ~200 °C. Gaschnig et al. (2017) also present a detrital zircon
These results indicate Paleozoic–Mesozoic ages with subtle, but important, differences from the ages of magmatism in the Blue Mountains and WISZ region. Furthermore, radiogenic Hf isotopic compositions of these zircons indicate that they were derived from juvenile accreted terrane lithosphere. Together these data suggest that the source of the detrital zircons is the Insular terrane, which is inferred to have been located immediately west of the field area during deposition (ca. 95 Ma).

Byerly et al. (2016) investigate the internal fabrics of the Idaho batholith using a combination of microstructures, shape-preferred orientation of minerals, and the anisotropy of magnetic susceptibility technique. This study utilizes the same sampling locations of the U-Pb zircon age and geochemistry studies of Gaschnig et al. (2010, 2013) and Braudy et al. (2016). Gaschnig et al. (2010) showed that the Atlanta lobe, which constitutes most of the central parts of the Idaho batholith, is distinctly younger than the Bitterroot lobe found only in the northern part of the Idaho batholith. Because the microstructures are mostly magmatic, Byerly et al. (2016) utilize the existing geochronologic framework to interpret spatial and temporal patterns of fabric development within the batholith. They conclude that the oldest igneous rocks on the western edge of the batholith contain a consistent north-south–oriented fabric, the Atlanta lobe contains weak and nonconsistently fabric, and the young Bitterroot lobe exhibits a consistent north-west–striking foliation. Byerly et al. (2016) suggest that the Atlanta lobe may have been intruded during a time of crustal plateau formation, and the lack of consistently oriented fabric resulted from emplacement in a neutral tectonic stress environment (due to topographic effects), in an overall contractional setting, and/or sill-like emplacement.

Fayon et al. (2017) use (U-Th)/He zircon thermochronometry to constrain the exhumation of the southern part of the Idaho batholith. Samples were taken throughout the border zone, early metaluminous, Atlanta lobe, and Challis magmatic suites. These samples were collocated with, or used the zircon separates from, the samples reported in Gaschnig et al. (2010, 2011, 2013) and Braudy et al. (2016). Three distinct spatial domains are evident in their data. First, rocks affected by the WISZ exhibit a west to east younging in (U-Th)/He zircon ages, reflecting the spatial migration in magmatism and/or deformation. These rocks cooled earlier than any rocks in the adjacent Atlanta lobe. Second, rocks from the Atlanta lobe exhibit a pattern of cooling ages as a function of elevation, which are interpreted to indicate isobaric cooling in the absence of tectonic activity. Fayon et al. (2017) indicate that the cooling age pattern is consistent with the Atlanta lobe forming in a crustal plateau. Third, younger (U-Th)/He zircon ages in the Sawtooth Range indicate recent exhumation associated with extensional deformation. Gaschnig et al. (2016) examine the nearly continuous record of Cretaceous–Paleogene magmatism in Idaho and interpret the relationship of core and rim ages in zircons to suggest that much of the magmatic record in Idaho has been obscured. These underrepresented episodes of magmatism include the presence of (1) a middle Cretaceous magmatic arc that was significantly shorted in an east-west direction by the WISZ; (2) a ca. 100–85 Ma Sierran-style arc that was disrupted, obscured, and cannibalized by the latest Cretaceous Atlanta peraluminous suite; and (3) a northward extension of the Atlanta peraluminous suite that was in turn disrupted, obscured, and assimilated by the younger Bitterroot metaluminous and peraluminous suites. Based on this interpretation, Gaschnig et al. (2016) make estimates of the magmatic flux rates for the Idaho segment of the northern Cordillera.

Davenport et al. (2017) report on the active source seismic data from the EarthScope IDOR project. The east-west–oriented seismic line is centered on the current boundary between the oceanic accreted terranes of the Blue Mountains Province and the Precambrian craton and Idaho batholith. The accreted terrane crust at the western end of this transect is ~27 km thick, with seismic velocities that indicate intermediate to mafic composition. The Precambrian crust at the transect’s western end exhibits slower seismic velocities, consistent with more felsic lithologies. Below or slightly eastward of the exposed portions of the WISZ, the Moho is offset by ~7 km. This offset is interpreted to result from strike-slip motion. Davenport et al. (2017) interpret the mid-crustal reflector at ~20 km depth to indicate a melt source zone for the Atlanta lobe of the Idaho batholith. On the accreted terrane side, there is a large, high-amplitude reflected phase ~8 km above the Moho. This reflector is interpreted as the top of a mafic underplating layer, which is spatially coincident with the feeder dikes of the Columbia River Basalt Group.

**PROPOSED MODEL**

Figure 2E shows a schematic model that has emerged from both the EarthScope IDOR group and other researchers working in this area. This model has several distinctive aspects relative to the earlier proposed models (Figs. 2B–2D). First, the WISZ continues throughout the crust and offsets the Moho; the crust is ~7 km thicker on the cratonic (east) side (Davenport et al., 2017; Stanciu et al., 2016). The presence of a crustal-scale WISZ was invoked to explain why Miocene–recent extensional deformation appears to be localized along this boundary (Tikoff et al., 2001). Second, the vertical nature of the boundary suggests a strong component of strike-slip deformation, as inferred from kinematic studies of the WISZ (Giorgis and Tikoff, 2004; Giorgis et al., 2016). It is also consistent with the overprinting concept of McClelland et al. (2000), in which the accretionary boundary (Salmon River suture zone) is distinctly older than the late-stage transpressional zone (WISZ). The contribution by Montz and Kruckenberg (2017) provides compelling evidence for a discrete two-step development, in addition to addressing the formation of migmatites in the region. Third, as discussed here, the Kurz et al. (2016) study makes sense of the isotopic data recorded by the Miocene basaltic rocks (e.g., Hart, 1985; Carlson and Hart, 1987). The Miocene Columbia River basalts flows apparently underplated the Olds Ferry terrane.

The other aspect illuminated by IDOR research is the nature of the Idaho batholith, based on the geochronological and geochemical data (Gaschnig et al., 2010, 2011, 2013, 2016). Byerly et al. (2016) and Fayon et al. (2017) both indicate that the Idaho batholith likely intruded into a crustal plateau, continuous with the proposed crustal plateau in central Nevada (Nevadaplano; e.g., Wolfe et al., 1997; DeCelles, 2004). Notably, the WISZ is not intruded by younger (ca. 80–67 Ma; Atlanta lobe) magmatism associated with the Idaho batholith, nor are the (U-Th)/He zircon ages in the WISZ reset by the Idaho batholith (Fayon et al., 2017).

Together, these studies have illuminated the formation of a subvertical boundary, one of many such boundaries that occur within the North American Cordillera. We hope that these studies also provide a solid foundation for future work into both the tectonic evolution and geodynamic processes exemplified in the region.

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