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Geologic Mapping and Geochronology of the Heavens gate 7.5-Minute Quadrangle: How Long Does it Take to Accrete an Island Arc to a Continent?

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GEOLOGIC MAPPING AND GEOCHRONOLOGY OF THE HEAVENS GATE 7.5-MINUTE QUADRANGLE: HOW LONG DOES IT TAKE TO ACCRETE AN ISLAND ARC TO A CONTINENT?

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Master of Science, Geospatial Sciences in Geography, Geology, and Planning

By

Samuel Gordon DeYoung

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ABSTRACT

The Blue Mountain province of western Idaho and eastern Oregon is composed of a mélange of geologic terranes that represent Permian and Triassic island arcs that collided with North America in the Mesozoic, resulting in westward growth of the continent. Separating these accreted rocks from North America are the mid- crustal metamorphic rocks of the Salmon River suture zone. Containing units and features associated with the accreted island arc terranes and suture zone is the Heavens Gate 7.5-minute quadrangle, located in Idaho county, Idaho. Within the quadrangle the Salmon River suture zone is divided into structural blocks by a series of N-S trending, east dipping thrust faults, the Morrison Ridge, Rapid River, and Pollock Mountain thrust faults (west to east). Formal units mapped within the quadrangle include the Hunsaker Creek and Wild Sheep Creek Formations (Seven Devils Group), the Morrison Ridge Formation, Lucille Slate, the Lightning Creek, Fiddle Creek, and Squaw Creek Schists (Riggins Group), and the Imnaha Basalt. Informal units mapped include tonalitic and quartz diorite plutons, quaternary deposits, and the Pollock Mountain Amphibolite and Cold Springs Orthogneiss and migmatite. Rocks of the Seven Devils Group, part of the Wallowa oceanic island arc, are folded into a north plunging anticline within the central portion of the map, with folding bracketed by zircon geochronology at 140-130 Ma. The anticline is cut by the Morrison Ridge thrust fault, emplacing the Martin Bridge Formation and Lucille Slate above the Seven Devils Group. Structurally above these units lies the Riggins Group, exposed east of the Rapid River and above the Rapid River thrust fault. The highest structural sheet contains the Pollock Mountain Amphibolite and Cold Springs orthogneiss. Zircon geochronology of volcanic, deformed and undeformed plutonic, and metamorphic rocks were used to determine that thrust fault development in the Salmon River suture zone occurred out of sequence with nearly synchronous activation along the Morrison Ridge thrust to the west (pre-123 Ma) and the Pollock Mountain thrust to the east (117 Ma). The approximately 109 Ma. Rapid River thrust was the final thrust fault to develop in the region.

KEYWORDS: Blue Mountains province, Salmon River suture zone, Heavens Gate quadrangle, zircon geochronology, western Idaho shear zone, arc-continent collision

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I dedicate this thesis to Katy, Sol, and Ryan.

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OVERVIEW

Continents are assembled over geologic time through the collision of crustal blocks with larger continents. The Blue Mountain province of Oregon, Idaho, and Washington contains portions of two Permian-Triassic island arc systems, the Olds Ferry and Wallowa island arcs (Vallier, 1977; Brooks and Vallier, 1978; Silberling et al., 1992). The island arcs were accreted to North America between Triassic and Late Cretaceous time; however, the exact timing and sequence of these collisional events is uncertain. The pre-collisional Laurentian margin between arc-affinity rocks and the Precambrian North America are separated by a zone of mid-crustal metamorphic rocks within the Salmon River suture zone (Hamilton, 1963; Lund and Snee, 1988; Manduca et al., 1993; Giorgis et al, 2005; Gray and Oldow, 2005). Recorded in the Salmon River suture zone metamorphic rocks and structures is the progressive deformation coeval with collision and accretion (Silberling et al., 1984; Lund and Snee, 1988; Avé Lallemant, 1995; Wyld and Wright, 2001; Blake et al., 2009; Gray et al., 2012). This study explores the timing of collision and deformation through a combination of geologic mapping and U-Pb zircon geochronology.

This study includes (1) descriptions of lithologies across the arc-continent boundary, (2) high resolution 1:24,000 scale geologic mapping, (3) structural relationships of the lithotectonic assemblages, (4) U-Pb zircon geochronology of volcanic, deformed and undeformed plutonic, and metamorphic rocks to bracket mountain building deformation, and, using these data, (5) estimates for shortening across the Salmon River suture zone.

The order and timing of three west dipping thrust faults is explored, from west to east, the Morrison Ridge, Rapid River, and Pollock Mountain thrusts. A model for non-sequential thrusting is proposed, and exhumation rates for movement along the thrust faults in the Pollock Mountain and Rapid River plates are calculated to compare with loading rates for the Rapid River plate.

INTRODUCTION

Continental assembly occurs through the collision and accretion of geologic terranes along active plate margins (Coney et al., 1980; Scholl et al., 1986). These subduction related accretionary complexes are important lithotectonic units in orogenic belts and are an indication of Phanerozoic-type, plate-tectonic processes (Hamilton, 1963; McCall, 2003; Shervais,well 2006). Accretionary complexes can reflect a long history spanning large periods of geologic time that may involve collisional deformation events as well as subduction-accretion processes (Byrne, 1984; Scholl and von Huene, 2007). Therefore, these complexes can include a wide variety of rock types that may not have formed in a specific tectonic setting (Shervais, 2006). Beyond having potentially multiple geologic settings as an origin, the collision of displaced terranes along continental margins is frequently accompanied by contractional deformation and crustal thickening, leading to regional metamorphism (Chamberlain and Karabinos, 1987). The variety of formational environments and presence of multiple deformational events have resulted in a poor understanding of many aspects of the history of long-lived accretionary complexes (Schwartz et al., 2010) and the rate at which continents are "grown" by these collisions is unknown.

As much as 70 percent of the North American Cordillera is made up of terranes (Coney et al., 1980) which have been accreted to the Laurentian margin since Early Mesozoic time (Grow and Atwater, 1970; Engebretson et al., 1985). As an active Andean style margin (Coney et al., 1980; Jordan, 1981; Shervais 2006) thousands of kilometers of oceanic lithosphere have been subducted by the Pacific Ocean's northern rim (Grow and Atwater, 1970; Engebretson et al., 1985) during this time, the Mesozoic arc assemblages and associated fore- and back arc basins have been sutured to the continental margin leaving little to no evidence of the vast Proterozoic Pacific Ocean in our current Pacific Ocean (Coney et al., 1980). Rather, all indication of the existence of Mesozoic Andean style arc complexes must be found on the margins of the North American continent.

This study focuses on the timing of deformation and metamorphism in one specific region along the active margin of North America, the Blue Mountain province of Washington, Oregon, and Western Idaho, as well as two zones of mid-crustal deformation: the Salmon River suture zone and the western Idaho shear zone, which separate the island-arc affinity rocks from the Laurentian craton (Lund and Snee, 1988; Gray and Oldow, 2005). Four accretionary complexes comprise the Blue Mountain geologic province, the Wallowa, Baker, Olds Ferry, and Izee terranes (Brooks and Vallier, 1978; Silberling et al., 1992) (Fig. 1). The Wallowa and Olds Ferry represent island arcs, while the Baker terrane is a structurally complex oceanic mélange, and the Izee is a basin terrane (Schwartz et al., 2010).

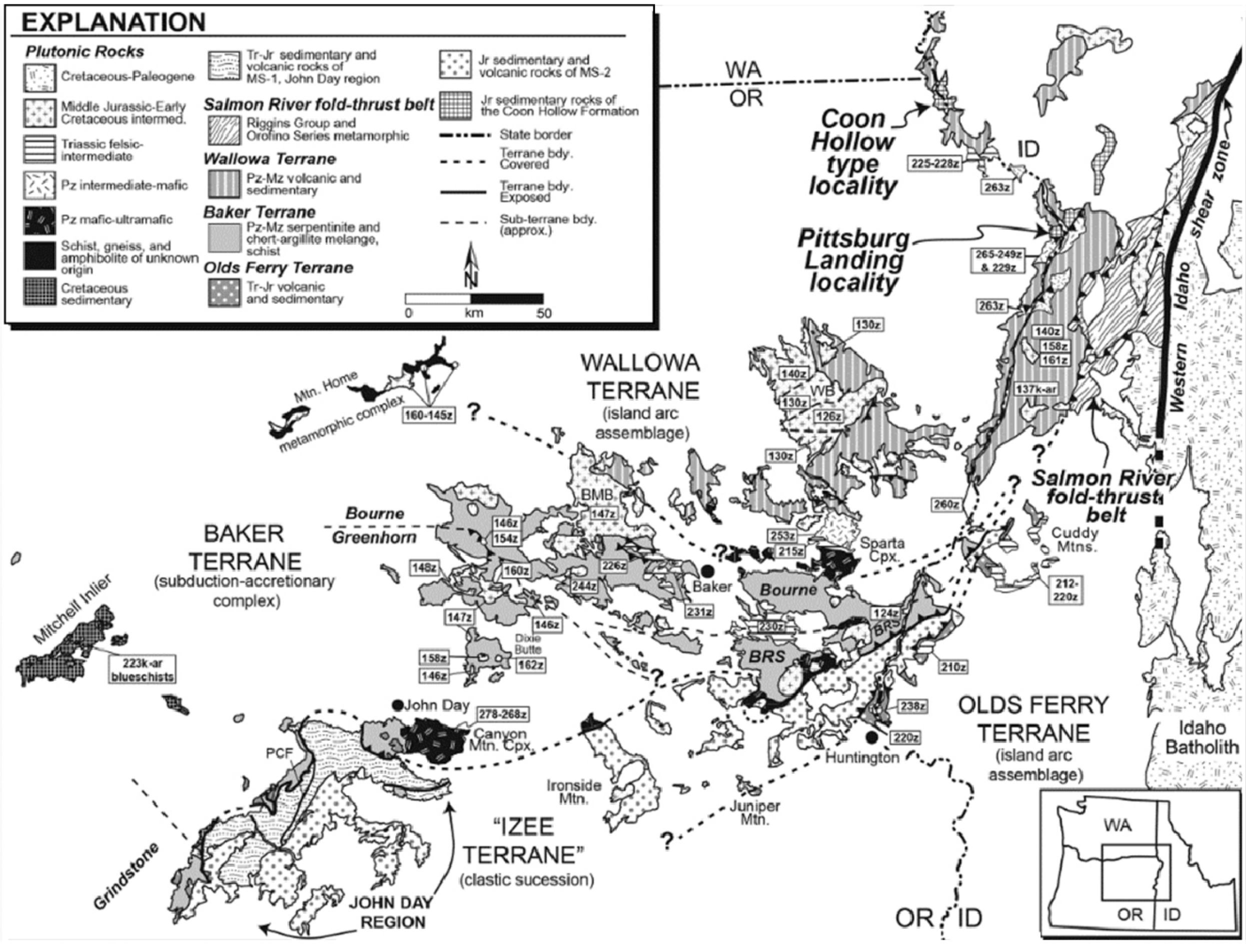


Figure 1. Simplified geologic map of the Blue Mountain province (from LaMaskin et al., 2015). Salmon River Belt is used interchangeably with Salmon River suture zone.

LOCATION

The Heavens Gate 7.5-minute quadrangle (latitudes 45°22 ′30″ to 45°15′00″; longitudes 116°30′00″ to 116°22’30″) is within Idaho County, Idaho (Fig. 2). Land use within the quadrangle is a mixture of national forest and privately-owned land. Two national forests extend into the quadrangle with Nez Perce National Forest in the northern portion of the quadrangle and the Payette National Forest to the south. The Hells Canyon Wilderness lies just west of the quadrangle. The northeastern portion of the quadrangle can be accessed by Rapid River Road that terminates just west of the Rapid River Fish Hatchery at the trailhead for West Fork Rapid River trail (no.113) which follows the Rapid River, providing access to the central portion of the quadrangle. Eastern areas along White Bird Ridge are accessed by Forest Road 624 that leads to multiple trails at Wildhorse Saddle. Northwestern areas of the quadrangle can be accessed by Forest Roads 2109 and 517 leading up to Heavens Gate. The highest point on the quadrangle is Vista Point lookout at 8,429 feet, and the lowest point on the quadrangle is 2120 feet near the Rapid River in the northeastern corner. Peaks in the quadrangle include Vista Point lookout (8429 feet), Mount Sampson (6462 feet), Cannon Ball Mountain (7178 feet), and Bryan Mountain (8358 feet). These peaks are recreationally frequented by the general public along trails maintained by the forest service. No lakes are present on the quadrangle, and drainage on the quadrangle is in the form of many small tributaries leading to the Rapid River which trends roughly north-south across the quadrangle. The West Fork of the Rapid River flows approximately west-east across the center of the quadrangle where it feeds into the main channel of the Rapid River. The flow direction is to the northeast for the main channel of the Rapid River, and to the east for the West Fork. The primary use of the area currently is cattle grazing

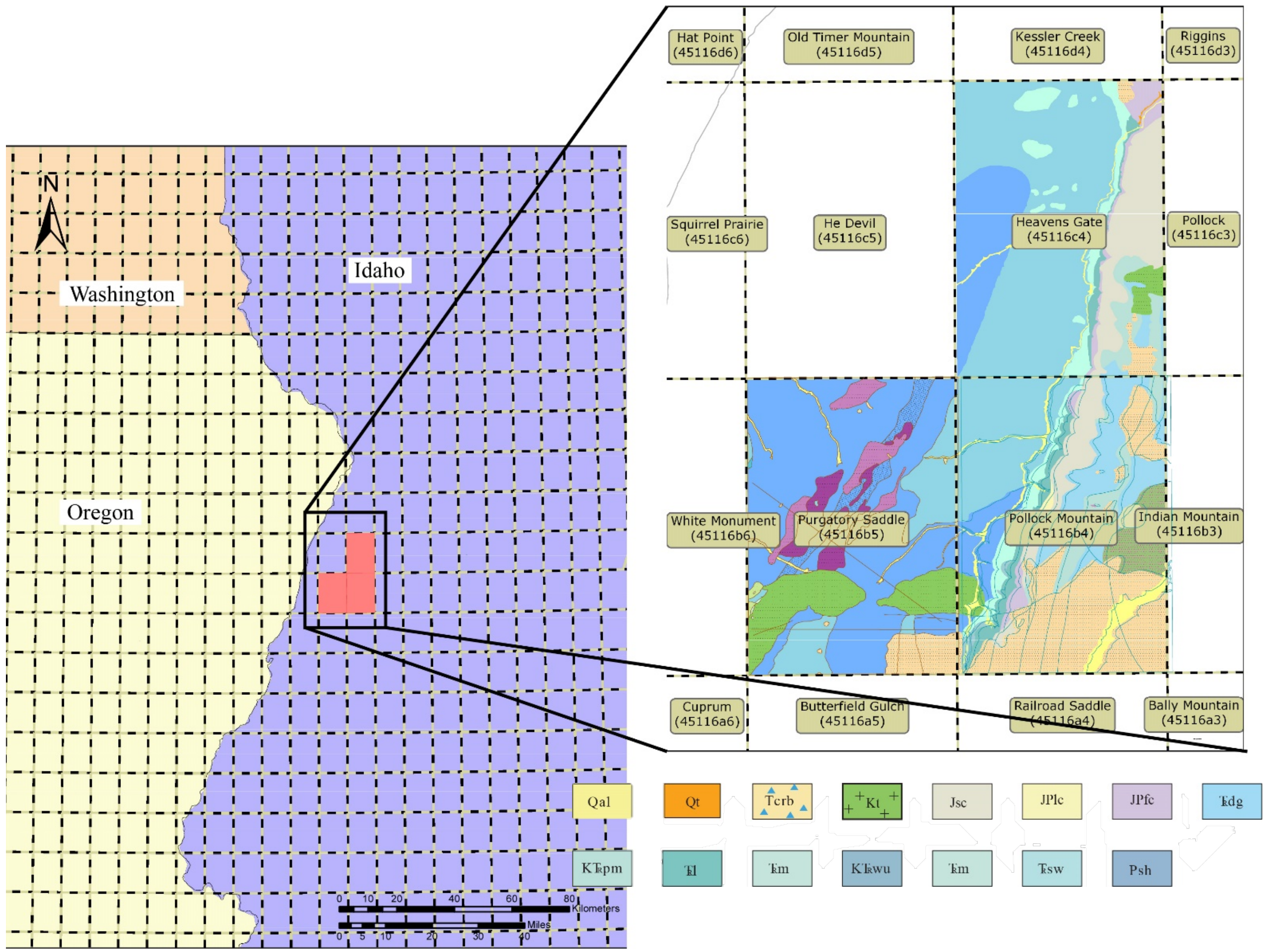


Figure 2. Location of Heavens Gate 7.5-minute quadrangle. Simplified geology of Heavens Gate, Pollock Mountain, and Purgatory Saddle 7.5-minute quadrangles. Inset shows basic geology of Heavens Gate, Pollock Mountain, and Purgatory Saddle 7.5" Quadrangles. Black dashed lines represent 7.5-minute quadrangles. Red shaded quadrangles are Heavens Gate (upper right), Purgatory Saddle (lower left), and Pollock Mountain (lower right). Legend in upper right for geologic maps of the three quadrangles. Full descriptions and names present on plate 1, 1:24,000 geologic map of Heavens Gate 7.5-minute quadrangle.

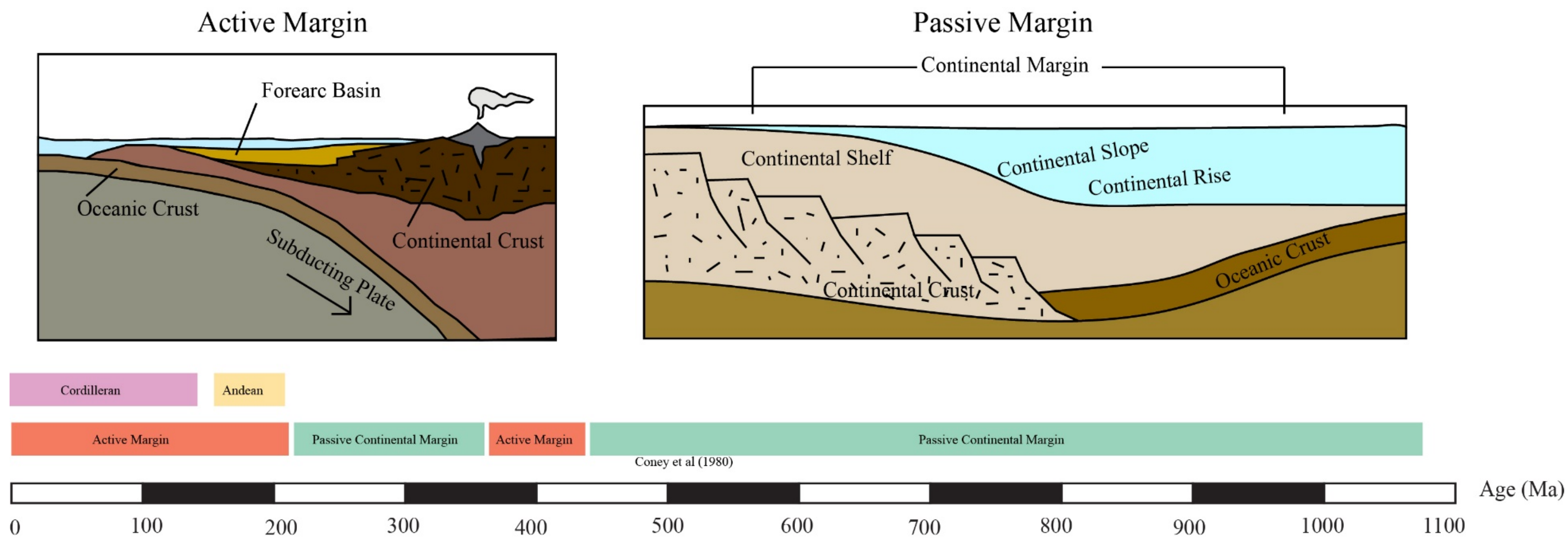
and backcountry hiking and backpacking. Historically there have been copper and gold mining operations in the region (White, 1968; Bookstorm et al., 1998; Simmons et al., 2007). Abandoned pits are present within the units of the Seven Devils group, primarily near limestone units which have been intruded by plutons. The closest cities to the quadrangle are Riggins (7.1 miles) to the northeast and New Meadows (33 miles) to the south. The locations of the Heavens Gate, Pollock Mountain, and Purgatory Saddle 7.5-minute quadrangles can be seen in Figure 2. showing the location and basic geology of these three quadrangles.

GEOLOGIC SETTING

The Heavens Gate 7.5-minute quadrangle is located to the east of the Blue Mountain province, and west of the North American craton. With a variety of tectonic regimes occurring throughout geologic time, the geology of the area is complicated by many sequences of collisional accretions to the craton. From west to east, the region has three primary geologic areas: (1) accreted terranes of the Blue Mountain province, (2) the mid-crustal, arc affinity rocks of the Salmon River suture zone, and (3) cratonic rocks of the North American continent.

Regional Tectonic History

Throughout much of the late Precambrian through the early Paleozoic the western margin of North America was a passive continental margin (Fig. 3) across which a sedimentary wedge was forming as the proto-Pacific Ocean opened (Dickinson 1976; Coney et al., 1980; Bond et al., 1984). Other than brief periods of convergence and subsequent collision in the Mid-Paleozoic (Antler Orogeny), the outbuilding of this wedge continued for nearly 700 million years without interruption (Coney et al., 1980). Eventually this regime ended in the late Triassic to middle Jurassic period, with the Pacific margin being convergent or transform ever since (Dickinson, 1976; Coney et al., 1980). Prior to collision in the Cretaceous to Eocene time, this region was an Andean style tectonic margin characterized by east-dipping subduction of oceanic crust, a magmatic arc and forearc basin, and an east verging thrust belt and foreland basin (Dickinson, 1976; Coney et al., 1980; Jordan, 1981). Following the transition to a convergence and subduction dominated margin, Paleozoic terranes along the edge of the original passive continental margin must then have been accreted to or subducted by that margin during



Tectonic History of Western North American Margin

Figure 3. Simplified Tectonic history of western North American margin. Figure shows a simplified representation of a passive and active margin, and tectonic history of the western margin of North America. Transition from passive to active continental margin. Scale is in millions of years. Andean style tectonic margins are characterized by east dipping subduction of oceanic crust, a magmatic arc and forearc basin, and foreland basin (modified after Dickinson, 1976; Coney et al., 1980; Jordan, 1981). Cordilleran style tectonic margins are characterized by accretion of island arcs to continental craton.

Mesozoic-Cenozoic time (Coney et al., 1980). Driving this accretion was the subduction of plates which were once present in the Proto-Pacific Ocean (Coney et al., 1980; Engebretson et al., 1985). Little to no evidence of the vast Proterozoic Pacific Ocean remains today in our current Pacific Ocean, rather all evidence of it now must be found on the margins of the North American continent (Coney et al., 1980). With initiation of island arc accretion to Laurentia, tectonism transitioned to a Cordilleran style convergent margin (Dewey and Bird, 1970); which persisted until the modern day, and ultimately led to the construction of the North American Pacific Northwest. A timeline of margin type for the Laurentian western margin is shown in Figure 3.

The major Cenozoic-Mesozoic deformation of the western Cordillera is thought to be related to the plate interactions that occurred along the North American margin (Atwater, 1970). The subduction of the Farallon plate (McKenzie and Morgan, 1969), occurring during most of the Mesozoic and Cenozoic (Schmid et al., 2002), was the result of this convergent boundary. Magnetic anomaly patterns in the Pacific Ocean (Atwater, 1970), combined with plate tectonic theory described by McKenzie and Morgan (1969), indicate that a trench must have existed in the Pacific Ocean in the Mesozoic and Cenozoic times (Atwater, 1970). Due to the symmetric geometry of spreading ridges, the half-ridge patterns provide evidence for the subduction occurring at this time (Atwater, 1970).

Blue Mountain Province

The Blue Mountains province, located in Oregon, Washington, and Idaho is composed of a series of rock assemblages that were accreted to the western margin of North America during subduction prior to uplift of the Rocky Mountains (Coney et al., 1980; Engebretson et al., 1985).

Terranes are geologic units at a regional scale which are characterized by a stratigraphic, igneous, or metamorphic sequence that is coherent and exhibits depositional continuity (Coney et al., 1980). These sequences must be different from adjacent terranes, or a nearby craton (Coney, 1989). The Blue Mountains province is composed of four terranes, the Olds Ferry, Baker, Izee, and Wallowa, as shown in Figure 1. The Wallowa and Olds Ferry are island arcs, formed by subduction driven magmatism (Hamilton, 1969; Vallier, 1977) in an Andean style margin (Dickinson, 1976; Jordan, 1981). The Izee terrane represents an oceanic basin (Schwartz et al., 2010), while the Baker terrane is an amalgamation of oceanic suite rocks (Schwartz et al., 2010). These terranes exhibit the magmatism, metamorphism, and sedimentation which was occurring here from the late Paleozoic to the Mesozoic (Dickinson, 1979; Walker, 1986; Schwartz et al., 2010). These terranes are intruded by late Jurassic-Early Cretaceous plutonic complexes which are exposed below the accreted (primarily) Cenozoic rocks (Schwartz et al., 2010).

The Wallowa terrane is an island-arc system composed of a Permian-Triassic island-arc sequence that has been overlain by extensive Permian- to Jurassic-aged volcanic and volcaniclastic rocks (Vallier, 1977; Gray and Oldow, 2005; Kays et al., 2006). Volcanic and sedimentary rocks of the Wallowa terrane are approximately eight kilometers thick (Gray and Oldow, 2005; Kays et al., 2006). These rocks have been metamorphosed at zeolite or lower greenschist conditions in the east (Gray and Oldow, 2005). Some have argued that the Wallowa and Olds Ferry arc terranes represent a single complex arc system (Vallier, 1995) while others classify the Wallowa-Olds Ferry superterrane as an exotic, intraoceanic arc (Ferns and Brooks, 1995; LaMaskin et al., 2008). The plutonic basement rocks here range in age from 264 to 225 Ma (Walker, 1986; 1995). The Permian to Triassic Seven Devils Group was from 264 to 225 Ma (Walker, 1986). The Permian to Triassic Seven Devils Group was deposited directly on crystalline basement and is composed of metavolcanic rocks (Gray and Oldow, 2005; Kays et al., 2006) including metavolcaniclastics greenstone facies, primarily basalt and andesite, with some metaconglomerate and brechiated greenstone (Vallier, 1977, 1995). The Seven Devils Group is unconformably overlain by the shallow-water carbonate platform and slope/basin rocks referred to as the Martin Bridge Formation, an Upper Triassic, massive and thin-bedded limestone (Brooks and Vallier, 1978; Gray and Oldow, 2005; LaMaskin and Dorsey, 2016). In turn the Martin Bridge Formation is overlain by siliciclastic and carbonate rocks of Upper Triassic to Lower Jurassic aged Hurwal Formation (Brooks and Vallier, 1978; Gray and Oldow, 2005; LaMaskin and Dorsey, 2016). In certain parts of the terrane, such as the Hells Canyon of the Snake River, the Coon Hollow Formation unconformably overlies units of the Seven Devils Group (Brooks and Vallier, 1978; Gray and Oldow, 2005; LaMaskin and Dorsey, 2016).

The Baker terrane is a long-lived accretionary complex, which has an associated forearc (Schwartz et al., 2010). This ancient terrane (late Paleozoic-Early Mesozoic) lies between the Wallowa arc to the north and the Olds Ferry island arc to the south east and is the oldest as well as the most complex arc structurally (Schwartz et al., 2010). This terrane contains fragments of ocean floor rock (minor component), island arc volcanic, plutonic, and sedimentary rocks all fragmental and extensively disrupted (Schwartz et al., 2010). Preserved within the terrane is evidence of deposition, magmatism, metamorphism, and structural processes related to the Wallowa and Olds Ferry arcs (Fern and Brooks, 1995).

The Olds Ferry terrane is an arc assemblage made up primarily of middle to late Triassic weakly metamorphosed volcanic and volcanoclastic rocks along with some isolated packages of sedimentary rocks (Schwartz et al., 2010). The volcanogenic rocks are primarily andesitic, with minor basalts and rhyolites as well (Schwartz et al., 2010). The underlying basement rocks are not exposed at the surface in this terrane. Volcanism in this arc possibly lasted into the Early Jurassic (Tumpane et al., 2010). Correlative Middle to Late Triassic volcanic rocks with the Quesnel terrane in British Columbia and the fringing arc system in Nevada and eastern California suggest that the Olds Ferry terrane rocks represent a fringing, continental margin island arc (Miller, 1987; Oldow et al., 1989; Wyld and Wright, 2001; Gray and Oldow, 2005; Dorsey and LaMaskin, 2007).

The Izee basin is primarily composed of a thick succession of marine sedimentary rocks that record deposition in a long lived forearc basin located between an east dipping subduction zone lying to the west and a magmatic arc in the east (Brooks and Vallier, 1978). Sedimentary rocks in the Izee basin have both volcaniclastic and chert constituents that may have been sourced from the Triassic Huntington Formation of the Olds Ferry terrane and the oceanic crust rocks from the Baker terrane (Lund, 2004; LaMaskin and Dorsey, 2016). Outcrops of andesite and rhyolite tuffs occur with Jurassic aged strata of the Weatherby Formation, which indicate that volcanism was occurring during the formation of the Izee terrane (Lund, 2004; LaMaskin and Dorsey, 2016). The Weatherby Formation is coeval with and potentially related to Middle Jurassic rocks at the top of the Wallowa terrane (White et al., 1992).

Salmon River Suture Zone

The collision between terranes of the Blue Mountain province and North America in the

Paleozoic resulted in deformation along the continental margin, driving tectonic burial and metamorphism (Walker, 1986; Vallier, 1995). The Salmon River suture zone is a north-south trending feature that marks the boundary between the volcanic rocks in the Blue Mountains province, and the rocks of North American affinity Precambrian in central Idaho (Lund and Snee, 1988; Gray and Oldow, 2005) (Fig. 4). The highest-grade metamorphism in the Blue Mountain province are exposed within the Salmon River suture zone, a roughly north-south trending metamorphic zone made up of metasedimentary and metavolcanic rocks of island arc affinity (Silberling et al., 1984; Lund and Snee, 1988; Avé Lallemant, 1995; Wyld and Wright, 2001; Blake et al., 2009; Gray et al., 2012) with inferred Mesozoic and Paleozoic protoliths that lie between the volcanic arc assemblages in the western margin of North America in Oregon and Idaho (Hamilton, 1963; Brooks and Vallier, 1978; Gray and Oldow, 2005). This metamorphism in the Salmon River suture zone is compatible with estimates for timing of collision between the Blue Mountain province island arc terranes, and the western North American Margin between 144-128 Ma (Selverstone et al., 1992; Getty et al., 1993; McKay, 2011; McKay et al., 2017) with estimates for collision beginning around 159 Ma (Schwartz et al., 2010; 2011).

Rocks of the Salmon River suture zone record progressive deformation that occurred during collisional accretion (Silberling et al., 1984; Lund and Snee, 1988; Avé Lallemant, 1995; Wyld and Wright, 2001; Blake et al., 2009; Gray et al., 2012), and the zone is characterized by east dipping, west directed thrust faults (Aliberti, 1988). These four thrust faults, active between 141 and 109 Ma (based on zircon geochronology), split the Salmon River suture zone into structural blocks. From west to east these are the Heavens Gate, Morrison Ridge, Rapid River, and Pollock Mountain thrusts (Plate 1; Fig. 4). The Heavens Gate thrust fault does not fall within the borders of the Heavens Gate 7.5-minute quadrangle; it is exposed near Windy Saddle, west of the Heavens Gate 7.5-minute quadrangle, and marks the limit of synmetamorphic deformation and volcanogenic rocks (Gray and Oldow, 2005; Gray et al., 2012). The western boundary of the Salmon River suture zone is generally defined by the shallowly east dipping Heavens Gate fault (Fig. 4), which carries upper greenschist to amphibolite grade rocks of the Salmon River suture zone over lower greenschist rocks of the Wallowa terrane (Gray and Oldow, 2005). The western Salmon River suture zone is made up of greenschist facies volcaniclastic and carbonate rocks which correspond to the Martin Bridge Formation, in the Morrison Ridge thrust (Vallier, 1977). The eastern Salmon River suture zone is composed of two east dipping, west directed thrust plates; the Rapid River plate and Pollock Mountain plate (Aliberti, 1988). Metamorphic grade ranges from gneissic amphibolite and orthogneiss (Aliberti, 1988; McKay et al., 2017) in the Pollock Mountain plate, to greenschist and upper amphibolite facies in the Rapid River plate (McKay et al., 2017).The Salmon River suture zone overlies late Paleozoic and Mesozoic volcanic arc rocks of the Wallowa terrane on a shallowly east dipping fault in the west, and to the east the North American rocks are separated from it by the western Idaho shear zone (Aliberti, 1988; Lund and Snee, 1988; Gray and Oldow, 2005). The eastern boundary of the Salmon River suture zone is contained within the western Idaho shear zone and corresponds to the $^{87}Sr/^{86}Sr = 0.706$ isopleth (Armstrong, 1975; Kistler and Peterman, 1973; Armstrong et al, 1977; Manduca et al., 1993), which represents the boundary between North American affinity rocks of the Proterozoic Laurentian craton to the east and accreted rocks to the west.

The western Idaho shear zone is a north-south striking shear zone directly east of, and partly contained within, the Salmon River suture zone (Giorgis et al., 2008). The western Idaho

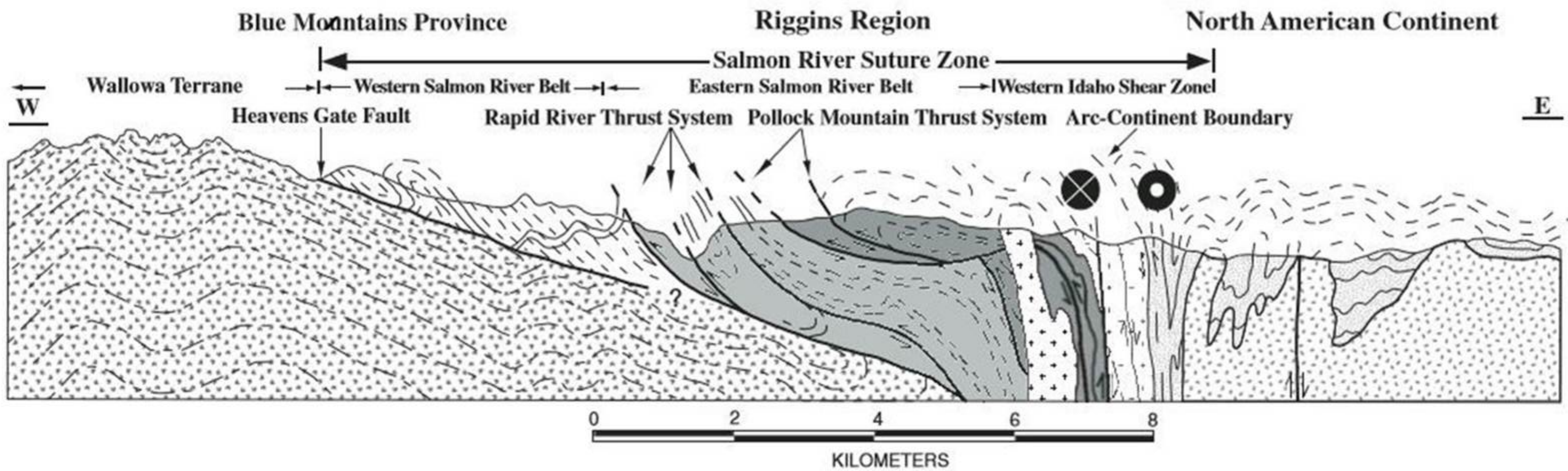


Figure 4. Regional cross section from the accreted terranes (west) to the North American craton (east). From Blake et al. (2009).

shear zone was active in the late Cretaceous (Giorgis et al., 2005). The western Idaho shear zone is a steeply dipping dextrally transpressive system which may have been responsible for much of the shortening which occurred within the Salmon River suture zone (McClelland et al., 2000; Tikoff et al., 2001; Giorgis et al., 2008). Gravity surveys suggest that the Salmon River suture zone is underlain by crust of similar density and thickness as the Izee and Baker terranes (Nandi, 2018).

North America

To the east of the Salmon River suture zone lies the Precambrian Laurentian Continent. The Mesozoic western Laurentian margin is represented by Precambrian age (Dickinson and Gehrels, 2009) crystalline basement rocks. This continental margin experienced orogenies occurring from the Proterozoic (Wopmay Orogen) through the Paleozoic (Dickenson and Gehrels, 2009). The continental margin was modified by the Idaho batholith which was emplaced between Late Cretaceous to Eocene times (Fig. 5) as tonalitic sheet-like plutons were emplaced adjacent to the suture zone (Manduca et al., 1993; Lee, 2004; McClelland and Oldow, 2007; Giorgis et al., 2008; Gaschnig et al., 2010). Magmatism began with emplacement of the Croesus stock in the southeastern Atlanta lobe of the Idaho Batholith at 98 Ma (Lund et al., 2008; Gaschnig et al., 2010) with the largest component of the Idaho Batholith forming between 83 and 67 Ma (Unruh et al., 2008; Gaschnig et al., 2010). Plutonism continued on the western Laurentian margin until as late as 53 Ma (Gaschnig et al., 2010) in the Bitterroot complex.

Accretion Models

The first model for the timing of accretion is that of an Early Cretaceous to Late Jurassic

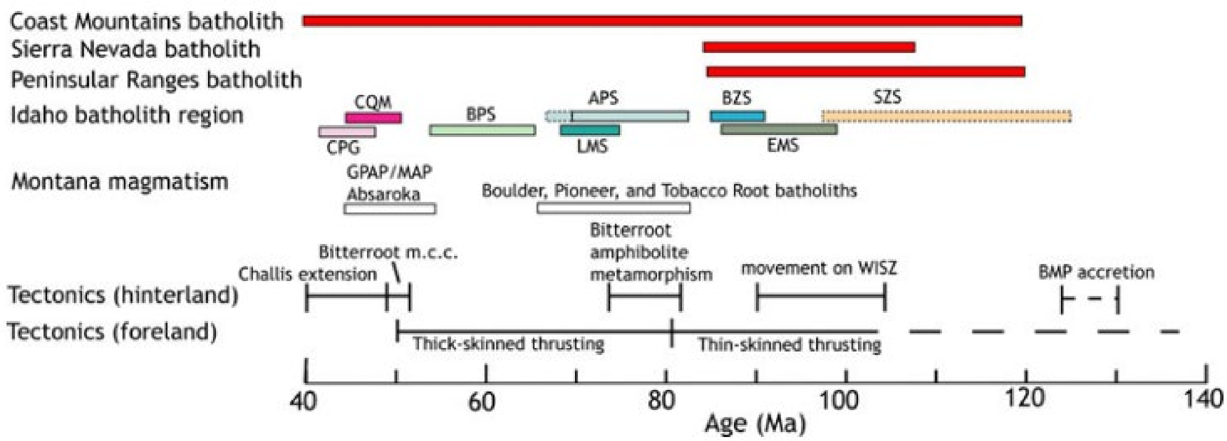


Figure 5. Schematic time line showing major episodes of magmatism in the greater Idaho batholith system from Gaschnig et al., 2010. *APS* Atlanta peraluminous suite, *BMP* Blue Mountains Province, *BPS* Bitterroot peraluminous suite, *BZS* border zone suite, *CPG* Challis pink granite suite, *CQM* Challis quartz monzodiorite suite, *EMS* early metaluminous suite, *GPAP/MAP* Great Plains alkalic province/Montana alkalic province, *LMS* late metaluminous suite, *MCC* metamorphic core complex, *SZS* suture zone suite.

docking with North America (Fig. 6) (Getty et al., 1993; Schwartz et al., 2010; 2011; Žák et al., 2015; McKay et al., 2017). Structural relationships within the Baker terrane and U-Pb zircon ages of post kinematic, fault stitching plutons bracket deformation at 159 to 157 Ma at the Baker-Wallowa boundary (Schwartz et al., 2010; 2011). The (now) N-S directed shortening features of the Baker terrane record a short-lived episode of deformation related to the collision of the Wallowa island arc with the continental margin Olds Ferry island arc at 159-154 Ma (Schwartz et al., 2011) following which, the brittle to semi brittle deformation zones record the Baker terrane being thrust over these collided arcs (154 Ma.) (Schwartz et al., 2011). Early NE-SW terrane oblique shortening is interpreted as recording an early stage of attachment of the welded Blue Mountain superterrane (Wallowa and Olds Ferry arcs) to the North American continental margin around 140 Ma (Žák et al., 2015). Deformation then switched to pure shear (NNE-SSW) shortening associated with crustal thickening and refolding of synclines into smaller scale folds, an event related to continued impingement of the terrane onto the North American continental margin around 135-128 Ma (Žák et al., 2015). Upon collision, the northern section of the superterrane became locked and difficult to further deform, leading to reorientation of the principle shortening to roughly NNW-SSE, and the deformable southern section rotated clockwise around 126 Ma (Žák et al., 2015). Metamorphism in the Salmon River suture zone is compatible in age with collision and attachment of the Blue Mountains province to North America between 144-128 Ma (Selverstone et al., 1992; Getty et al., 1993; McKay, 2011; McKay et al., 2017), which may correlate to similar accretionary orogenesis to the south associated with the coeval Nevadan orogeny (Graymer and Jones, 1994; LaMaskin et al., 2015).

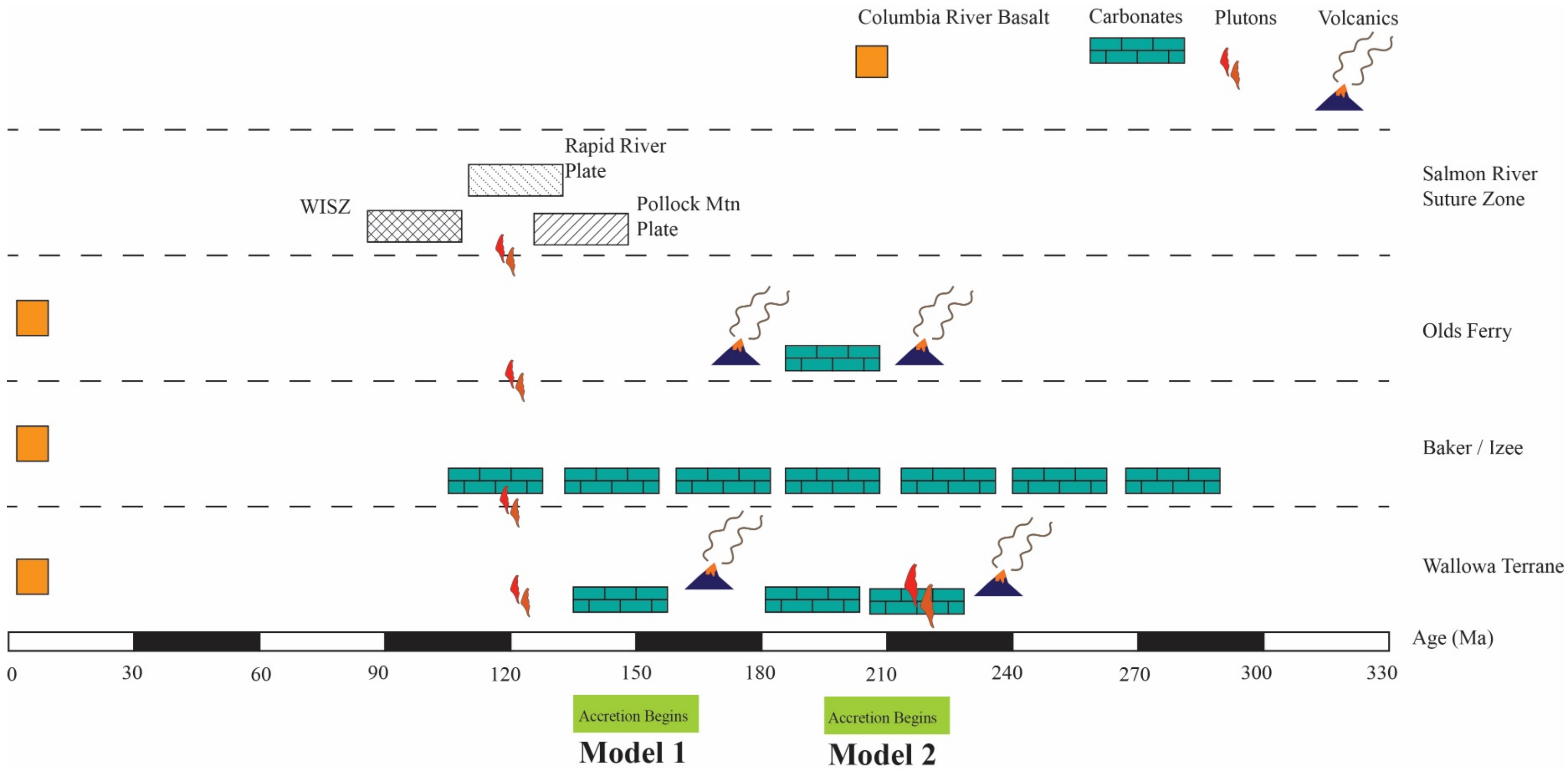


Figure 6. Timeline of tectonic models for accretion of Blue Mountain province terranes to North American. One model proposes a Late Jurassic to Early Cretaceous accretion of island arcs (Model 1), while the other proposes an Early Jurassic timing (Model 2) for docking with North America. The timing of formation for various units is estimated. Carbonates are represented by teal limestone symbols, volcanics are shown with volcanos, and plutons are represented by plumes of magma. The timing of burial and metamorphism for the Pollock Mountain plate, the Rapid River plate, and the western Idaho shear zone are (WISZ) displayed.

An alternative model for the age of accretion sites temporal and spatial variations in the geochemistry of Wallowa terrane mudrocks to indicate that during Late Triassic to Early Jurassic time (Fig. 6), the terrane was still an intra-oceanic island arc (LaMaskin et al., 2008). Evidence for this model also includes the existence of a regional angular unconformity below the Coon Hollow formation, which must have occurred between 197 and 160 Ma (LaMaskin et al., 2015).

PREVIOUS INVESTIGATIONS

Mining reports by multiple mine inspectors for the state of Idaho (White, 1968; Bookstorm et al., 1998; Simmons et al., 2007) provide the earliest documentation of the rocks in the area around the Heavens Gate 7.5-minute quadrangle. In the southern Seven Devils region Livingston and Laney (1920) documented some of the early mining activities.

The earliest geologic mapping and documentation of the rocks in the Heavens Gate quadrangle was produced by Hamilton (1963) at a 1:125,000 scale. Hamilton (1963) was the first to formulate any tectonic interpretations of the region and hypothesized that metamorphism was occurring related to an intrusion of the 100-54 Ma Idaho batholith (Gaschnig et al., 2010). The Seven Devils volcanics mapped by Hamilton (1963) were stratigraphically differentiated as the Seven Devils Group later by Vallier (1967, 1977). The Salmon River suture zone was mapped by Hamilton (1963), Aliberti (1988), Manduca (1988), and White (1968), then compiled by Lund (2004) at a 1:125,000 scale. The Lucille 7.5-minute quadrangle (Lewis et al., 2011) covers the distribution of metamorphic rocks of the Salmon River suture zone. Other 7.5-minute quadrangles mapped in the area include Riggins Hot Springs (Blake et al., 2016), Pollock Mountain (Nandi pers. comm., 2018), and Purgatory Saddle (Nandi pers. comm., 2018). A geologic transect map covers the arc-continent boundary (Gray, 2013), which extends across the northernmost portion of the Heavens Gate 7.5-minute quadrangle. U-Pb zircon ages for the units of fault stitching plutons (Schwartz et al., 2010; 2011), and garnet Sm-Nd ages of metamorphism (Getty et al., 1993; McKay et al., 2017), provide estimates for ages of island arc accretion.

GEOLOGIC UNITS

The formal stratigraphic units present in the Heavens Gate quadrangle include the Hunsaker Creek Formation and Wild Sheep Creek Formation of the Seven Devils Group (Fig. 7), named and described by Vallier (1977), the Morrison Ridge Formation and Lucille Slate, the Lightning Creek Schist, Fiddle Creek Schist, and Squaw Creek Schist of the Riggins Group. In addition, the Imnaha Basalt of the Columbia River Basalt Group is present. The Pollock Mountain Amphibolite and intercalated orthogneiss, and migmatite, as well as Cretaceous tonalite and quartz diorite plutons are mapped as informal units in the region. Morrison Ridge thrust sheet units include Triassic limestone and marble, as well as the Lucile Slate. All geologic units described are represented in Appendix B, geologic map of the Heavens Gate 7.5-minute quadrangle.

Seven Devils Group (Permian-Triassic)

Hunsaker Creek Formation (Permian). The Permian Hunsaker Creek Formation is the oldest stratigraphic unit exposed in the quadrangle. The Hunsaker Creek Formation was first named and described by Vallier (1977) for the thick sequence of metamorphosed strata exposed along the Snake River canyon and within the canyons of tributaries of the Snake River, particularly Hunsaker Creek (Vallier, 1977). This formation consists of siliceous greenstone facies (pyroclastic breccia and conglomerate) including both metavolcaniclastics with quartz clasts, and metabasalt flows with quartz porphyries. Clasts in the volcaniclastics are polymictic and include basalts, sedimentary rocks, and some plutonic rock. Brachiopod species in the Hunsaker Creek Formation are Early Permian faunal assemblages and constrain the unit's age

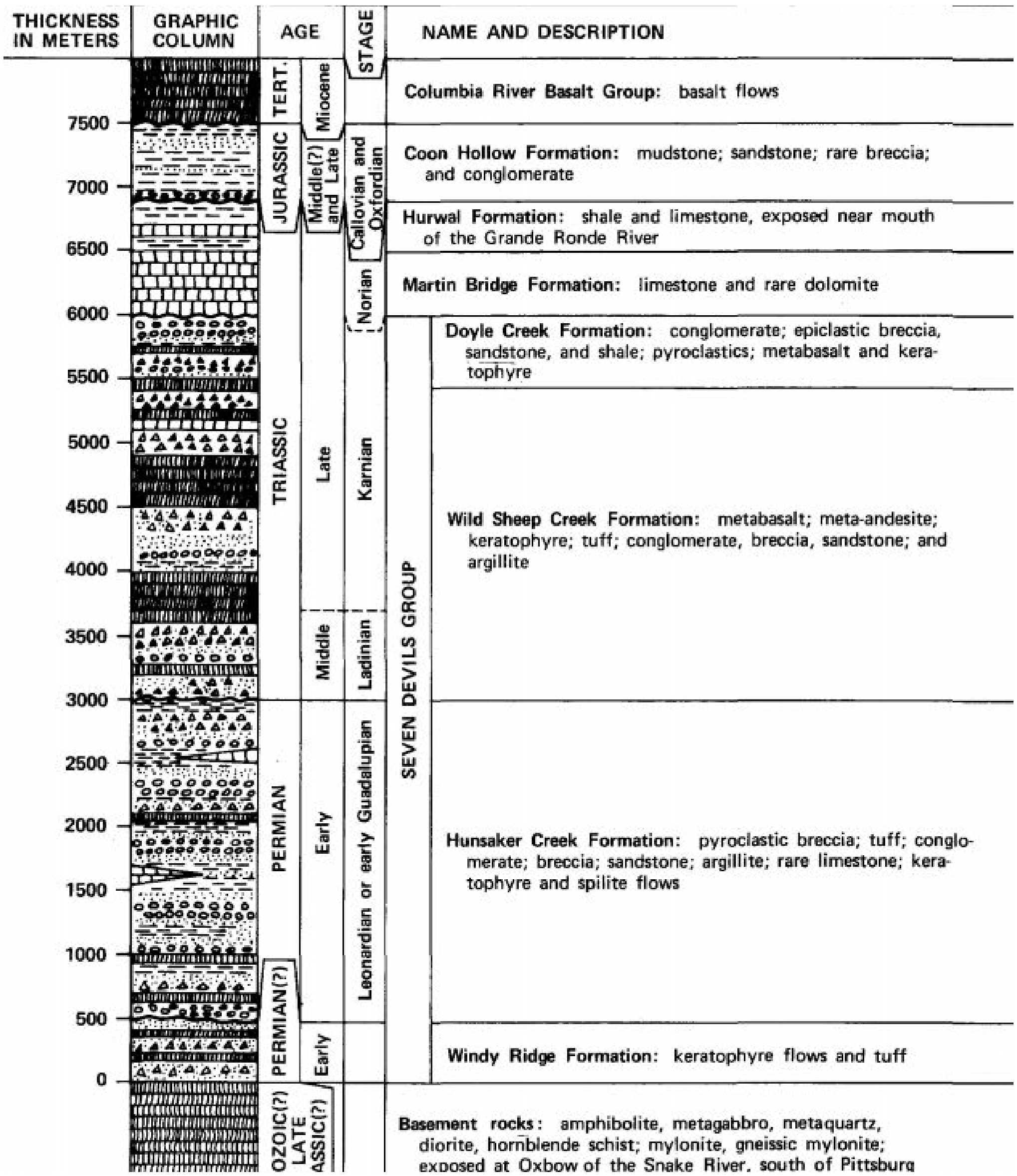


Figure 7. Generalized stratigraphic column of the Seven Devils Mountains (west side of Heavens Gate quadrangle). (Vallier, 1977).

(Vallier, 1977). The unit thickness nearest Hunsaker Creek canyon is estimated to be between ~2500 meters to ~780 meters (Vallier, 1977). On the Heavens Gate quadrangle, the Hunsaker Creek Formation occurs in a northeast-southwest trend that makes up the center of a large anticline. Fabric varies on the quadrangle from weak to strongly foliated, with stronger foliations more apparent in the volcaniclastic brecciated greenstone.

Wild Sheep Creek Formation (Triassic). Conformably overlying the Hunsaker Creek Formation is the Wild Sheep Creek Formation, named and described by Vallier (1977). The Wild Sheep Creek Formation is exposed throughout much of the quadrangle to the west of the Rapid River. The Wild Sheep Creek Formation is inferred to be ~680 meters thick to the southwest (Nandi, 2018), but the section is truncated by faults and may be thicker here in the quadrangle due to the plunging antiform that dominates the structure of the area. The Wild Sheep Creek Formation is primarily composed of porphyritic plagioclase-rich greenstone facies. Volcaniclastic facies include basaltic andesite and polymictic volcaniclastic breccia. Breccia clasts are composed of basaltic greenstone, limestone, argillite, and siltstone. Throughout the Wild Sheep Creek Formation, lenses of marble and limestone are present in this quadrangle. Marble and Limestone lenses are present in repeating pinched sections in the middle of the Wild Sheep Creek Formation and follow the antiform pattern that dominates the western half of the quadrangle. The marble and limestone are interbedded, ranges from light tan to dark blue grey in color. Volcaniclastic rocks within the formation are dark gray-green on fresh surfaces while weathered sections are brown to greenish black.

Marble within Volcaniclastic Greenstone (Triassic). Marble and limestone are exposed as discontinuous pods throughout the metavolcaniclastics of the Wild Sheep Creek Formation.

Outcrop scale folds are present just north of the quadrangle as shown in Figure 8. Limestone ranges from crystalline to micritic. In places, the carbonate is recrystallized and intensely deformed, exhibiting banding. Where mappable, marble/limestone intervals are shown as Triassic undifferentiated marble. Marble and limestone are interbedded with dark quartzite and ranges from light tan to dark blue grey in color.

Undifferentiated Wallowa Terrane Rocks (Cretaceous). Mapped in the quadrangle as undifferentiated this unit may contain these facies that may correlate to the Coon Hollow Formation. Rock types in the Coon Hollow Formation are primarily black and dark brown mudstones with minor siltstones and sandstones (Vallier, 1977). There are rare beds of conglomerate and breccia in the sequence (Vallier, 1977). In the Heavens Gate quadrangle, this unit also contains a siliceous tuff-like unit within the volcaniclastics pictured in Figure 9.

Morrison Ridge Thrust Sheet (Triassic)

Undifferentiated Marble (Triassic). Marble units are present throughout the stratigraphy. Undifferentiated marble consists of gray to blue marbles, limestones, and contains minor interbedded greenstone. In places these marbles correlate to the Martin Bridge limestone and Martin Bridge Formation (Hamilton, 1963; Lund, 2004). Exposed along the Rapid River, and striking north to south throughout the cross section, are marbles of the Martin Bridge Formation. The limestone ranges from crystalline to micritic. Calcite veins present are in both limestone and marble (Fig. 8). Thin talc schists and a dark blue to black quartzite are also intercalated throughout the marble units. Limestones are thinly bedded; however, the thickness of the limestone and marble along the river is around 700 feet based on constructed cross sections.

Figure 8. Outcrop scale fold in Wild Sheep Creek Formation carbonates, and slickenlines on a small-scale fault within the Wild Sheep Creek volcaniclastics. Folded rocks are carbonate limestone and marbles of the Wild Sheep Creek Formation. Slickenlines in greenschist volcaniclastic rocks near Heavens Gate lookout (bottom). Outcrop scale fold.

Lucile Slate (Triassic). Except where cut out by thrust faulting, the Lucile Slate overlies the Martin Bridge Limestone. The Lucile Slate is a light- to dark-gray, graphitic phyllite and slate with interbedded fine-grained quartzites. The Lucile Slate is present near the Rapid River in the quadrangle, and trends north-south. The phyllitic rocks in this unit outcrop poorly, with small phyllite/slate float common near small, rubbly outcrops. Crenulation cleavage is present in some outcropped exposures. The thickness of the Lucile Slate in the Heavens Gate quadrangle is around 800 feet based on cross section construction.

Pollock Mountain Thrust Sheet

Pollock Mountain Amphibolite (Triassic-Cretaceous). Present in the eastern sections of the map, the amphibolite is exposed on hillsides to the east of the Rapid River. There appear to be two main variations, one with approximately equal amounts of hornblende and plagioclase, and one which occurs discontinuously and is dominated by hornblende (70-90%) with lesser quantities of plagioclase. Euhedral to subhedral almandine garnet occur on average at nearly 0.5 – 1 cm sizes; however, they can be found in much larger sizes, up to 10 cm, within the Pollock Mountain Amphibolite. When present, garnets are often ringed with plagioclase feldspar. The Pollock Mountain Amphibolite exhibits fissile weathering. In places, the amphibolite is intercalated with post-kinematic, light colored quartz veins. Peak metamorphic conditions in the Pollock Mountain plate are estimated to be 8–11 kbar and 650-700 °C (Selverstone et al., 1992; McKay 2011). Garnet growth occurred in the rock between 141-124 Ma (McKay et al., 2017).

Cold Springs Orthogneiss, Migmatite, and Tonalite Undifferentiated (Triassic-Cretaceous). The course- to fine-grained felsic orthogneiss is intercalated with isolated zones of migmatite and fine-grained, undeformed tonalite and quartz diorite. The Cold Springs orthogneiss (Fig. 9) exhibits a strong fabric, and includes biotite, quartz, hornblende, and plagioclase feldspar as primary constituents. Migmatites occur locally within the orthogneiss but are absent from the adjacent Pollock Mountain Amphibolite, which is intercalated with the Cold Springs orthogneiss. The protolith of the orthogneiss is interpreted to be Triassic (~206 Ma) based on U-Pb zircon and which was overprinted by Cretaceous metamorphism at 141 Ma (10ID42; McKay et al., 2017). Pegmatite veins and leucosomes are discontinuously present within the Cold Springs orthogneiss. An undeformed tonalite intrudes the Pollock Mountain Amphibolite and Cold Springs orthogneiss and is likely genetically similar to other Cretaceous intrusions in the vicinity, including the Deep Creek and Echols Mountain pluton (Jeffcoat et al., 2013). Given the intercalated and discontinuous nature of the migmatite and undeformed tonalite, and frequent observation in association with the orthogneiss, this unit is presented as an undifferentiated Triassic-Cretaceous orthogneiss, migmatite, and tonalite.

Riggins Group (Jurassic-Permian)

Fiddle Creek Schist (Permian-Jurassic). The Fiddle Creek Schist is a fine- to medium-grained, garnet-muscovite- schist with minor metaconglomerate, quartzite, and a garnet-biotite-schist. Along the Rapid River in the center of the quadrangle, the Fiddle Creek Schist strikes roughly southwest-northeast and is poorly exposed at the surface. Based on cross section construction, the Fiddle Creek Schist is approximately 500 feet thick within the quadrangle. The primary schist unit includes minor amounts of plagioclase, and retrograde chlorite (Vallier, 1977)

Figure 9. Cold Springs orthogneiss, siliceous tuffaceous unit, calcite banding within marble/limestone of the Wild Sheep Creek formation. Cold Springs orthogneiss (upper left). Siliceous tuff (upper right) possibly correlative to the Coon Hollow Formation. Taken along the west fork Rapid River trail (113). Calcite veins and deformation bands in marble unit within the Wild Sheep Creek Formation (lower middle).

and is light gray to green in color. Metaconglomerates are monomictic, with meta-tonalite clasts. Clasts range in size from 4 to 12 cm. Garnet sizes increase with a shift to the biotite-garnet schist and are around 1 cm in diameter on average. The Fiddle Creek Schist is distinguished from the Lightening Creek Schist by a higher percent of white mica and quartz, a lower percentage of biotite and chlorite, and the presence of metaconglomerates in the Fiddle Creek Schist.

Lightning Creek Schist (Permian-Jurassic). The Lightning Creek Schist is a fine- to medium-grained biotite-chlorite schist and is light to dark gray and green in color. Within the unit moderate amounts of quartz are present. Lightning Creek Schist exposures are limited to the north eastern extent of Heavens Gate quadrangle (Gray 2013). In the Heavens Gate quadrangle, the Lightning Creek Schist is around 500 feet thick based on cross section construction. Garnet, biotite, and chlorite are present in the schistose units (Lund, 2004). A few beds of foliated calcite marble, a few feet thick at most, are intercalated with greenschist facies in the upper part of the formation near the type section by the town of Riggins (Vallier, 1977).

Squaw Creek Schist (Jurassic). Fine- to medium-grained, pelitic biotite-garnet schists are present running north-south on the eastern side of the quadrangle. The Squaw Creek Schist is distinctly quartz rich compared to other nearby lithologies. The unit is exposed at the surface in wide swathes, likely due to fault splays which thicken it at the surface. Garnet is present in discontinuous zones. Amphibole grains are present and are randomly oriented. Some sections exhibit serpentinization, particularly to the northeast near Riggins. Squaw Creek Schist weathers to a reddish brown and exposures are heavily weathered and friable. The Squaw Creek Schist locally contains minor quartzite and marble as well as talc schists. Interbedding relationships with the marble and quartzite suggest that foliation (S_1) may be parallel to original bedding (S_0). In the eastern portion of the map area garnet growth in the Squaw Creek Schist occurred at ~124

Ma (McKay et al., 2017). In the Riggins quadrangle to the northeast, preliminary detrital zircon dating yields an age of approximately 200 Ma as shown in a following section. Based on cross-section construction the Squaw Creek Schist is at a minimum of 1000 feet in thickness in the quadrangle, however, internal fault splays may have tectonically thickened the unit near Wild Horse Saddle on the quadrangle.

Intrusive Rocks- Cretaceous tonalite and quartz diorite (Early Cretaceous?)

Medium- to course-grained, biotite rich tonalite to quartz diorite units intrude the Pollock Mountain Amphibolite and Cold Springs orthogneiss in the eastern-central region of the map (Plate 1). Units are white to gray in color and are made up of primarily plagioclase feldspar, hornblende, biotite, and quartz. Some sections exhibit a weak fabric of aligned hornblende and biotite. The units with weak fabrics may correlate to the compositionally similar Echols Mountain and Deep Creek plutons, suggesting a Cretaceous age. U-Pb zircon from a quartz diorite and tonalite in the Deep Creek pluton records a 123 Ma age (Jeffcoat et al., 2013). Some sections of the tonalite and quartz diorite are more heavily altered than others and exhibit a more friable texture, particularly those cut by the fault on Forest Road 624. Exposures are heavily jointed throughout the quadrangle. Based on U-Pb, partial melting occurred around 125 Ma with tonalite intrusions emplaced at 114 Ma (K. Johnson, pers. comm).

Columbia River Flood Basalt- Imnaha Basalt (Miocene)

The Imnaha Basalt of the Columbia River Basalt Group is present mostly in the southeast corner of the Heavens Gate quadrangle and continues into the Pollock Mountain 7.5-minute quadrangle to the south. In the Heavens Gate 7.5-minute quadrangle, the Imnaha Basalt is a medium to coarsely grained porphyritic basalt flow with olivine and plagioclase phenocrysts dominating. These phenocrysts range on average from 1-9 mm in diameter (Lund, 2004). The unit weathers into a reddish brown or gray hue. Vesicular textures can be found in float on the quadrangle. The Imnaha Basalt is Miocene in age, at 15.4 Ma (McKee et al., 1981; Hooper et al., 2002) and can be observed at all elevations at which basalt is present within the quadrangle, despite the Imnaha Basalt typically covering lower elevation areas (Vallier, 1977). Elsewhere, the Grande Ronde Basalt of later flows covered the majority of the Seven Devils Region (Vallier, 1977). The basalt in this region originated from vents and dikes along the Oregon-Idaho border (Hooper and Swanson, 1990), and much thicker sections of it can be observed to the west of the Heavens Gate quadrangle across the Oregon border. In the Heavens Gate quadrangle, the Imnaha Basalt ranges from 500 to 1000 feet thick, based on topography.

Quaternary Deposits

Alluvium and low terrace deposits (Quaternary) composed of unconsolidated Holocene and Pleistocene deposits of gravel, sand, clay, and silt are present in the quadrangle. Thick terrace deposits occur along the Rapid River especially in the north east corner of the map, near the fish hatchery. Terrace deposits contain pebble to boulder size clasts, clasts are aligned in some areas. Clast composition includes greenstone, tonalite, and basalt. Quaternary deposits are not displayed in cross section due to thicknesses less than 50 feet.

GEOLOGIC STRUCTURES

The Heavens Gate 7.5-minute quadrangle contains strata terrane that have been folded into a northeast plunging anticline, as well as three major thrust faults which juxtapose increasingly higher-grade metamorphic rocks atop lower grade rocks in the foot wall. Structures in the quadrangle, from west to east, include a large northeast plunging anticline that exposed the Hunsaker Creek Formation in the core of the anticline and Wild Sheep Creek Formation and overlying Wallowa strata rocks in the eastern limb and hinge line to the north. Several smaller scale folds and faults (outcrop scale) are present on the quadrangle in the volcaniclastics and carbonates of the Wild Sheep Creek Formations (Fig. 8). The metasedimentary and metavolcanic rocks of the western region of the Heavens Gate 7.5-minute quadrangle, known as the Heavens Gate plate (McKay et al., 2017), are unconformably overlain by Early Cretaceous rocks possibly correlative with the Coon Hollow Formation. The overlying lower greenschist facies rocks of the Lucille Slate and Martin Bridge Formations are juxtaposed onto the Seven Devils Group along the northeast-southwest trending, southeast dipping thrust fault known as the Morrison Ridge fault. Structurally above the Lucille and Martin Bridge units lies the Riggins Group. These midcrustal schist to amphibolite grade facies are exposed east of the Rapid River and above the north-south trending Rapid River thrust fault. The Riggins Group is bound to the east by the Pollock Mountain thrust fault which contains rocks of the Pollock Mountain Amphibolite and Cold Springs orthogneiss in the hanging wall, thrust over the Riggins Group rocks in the footwall in the southeastern corner of the Heavens Gate 7.5-minute quadrangle.

STRUCTURAL ANALYSIS

Methods

To investigate map scale structures, foliations were plotted for each thrust sheet in the region, and poles to foliation were calculated and displayed (Fig. 10-13) using Stereonet 10 (Allmendinger, 2018). Poles to foliation and bedding planes are shown, with contours to show density of orientations. Each stereonet has a significance level of 3 sigma. Each of the thrust sheets' plots show western movement along east dipping planes.

Results

Pollock Mountain thrust sheet. The average foliation for this thrust sheet is 050°/22° SE. The highest density of poles to foliation plots in the northwest quadrant, however there appears to be a general clustering of data across both northern quadrants (Fig. 10).

Rapid River thrust sheet. The highest density of data for poles to foliation for this thrust sheet fall within the northwestern quadrant, with nearly all the data falling in the western quadrants (Fig. 11). The average foliation for this thrust sheet was 014°/27° SE.

Morrison Ridge thrust sheet. The highest density of poles to foliation here fall in the western quadrants. The mean orientation of foliation within this thrust sheet is 359°/22° NE (Fig. 12).

Seven Devils/Wallowa rocks beneath the Morrison Ridge thrust fault. The poles to foliation here show two distinct groupings, representing the large-scale fold in the Seven Devils units (Fig. 13). One grouping of poles is in the southeastern quadrant with a trend of 124° and a plunge of approximately 12 degrees. The other high-density regions are in the northwest

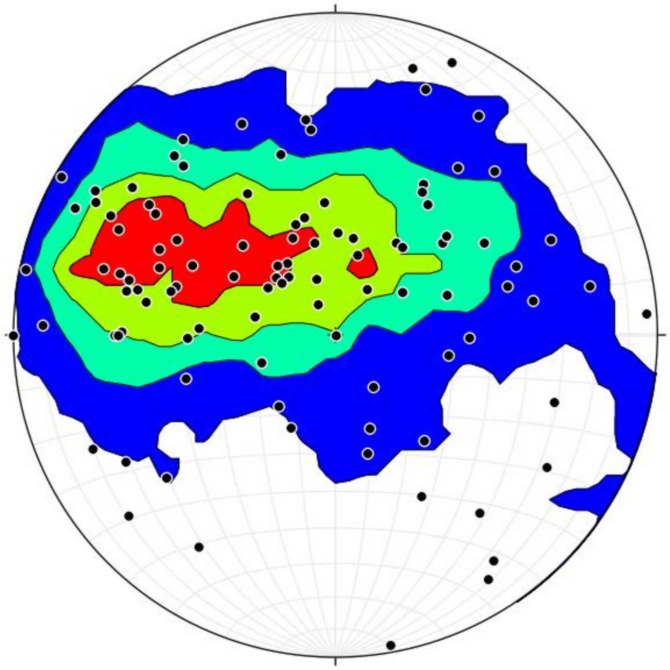


Figure 10. Poles to foliation with density contours for the Pollock Mountain thrust sheet. Red indicates high density, blue indicates low density. Poles are represented by black points.

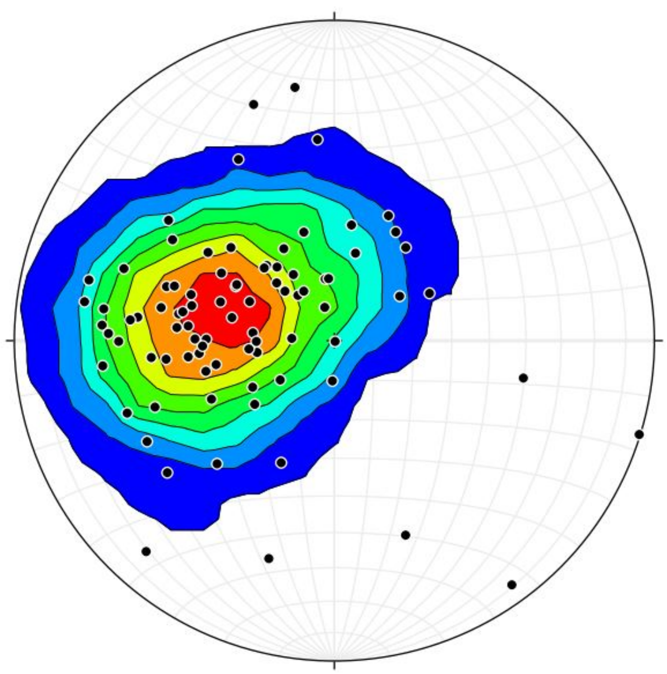


Figure 11. Poles to foliation with density contours for the Rapid River thrust sheet. Red indicates high density, blue indicates low density. Poles are represented by black points.

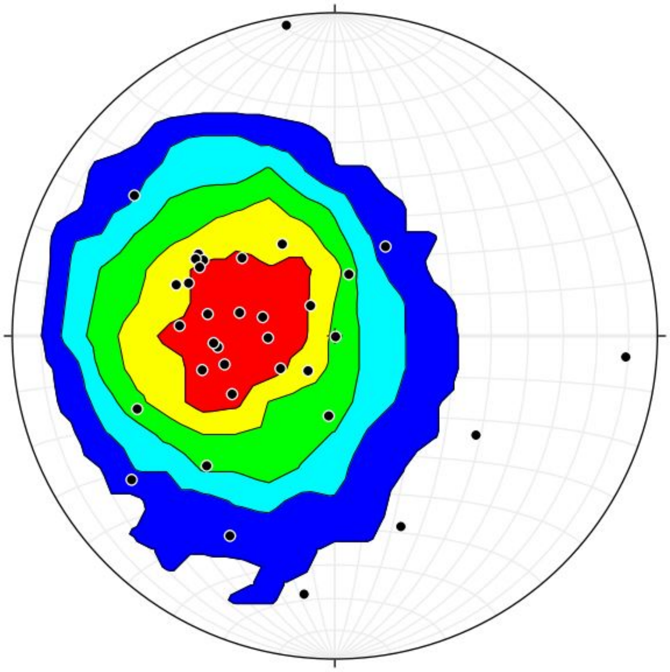


Figure 12. Poles to foliation with density contours for the Morrison Ridge thrust sheet. Red indicates high density, blue indicates low density. Poles are represented by black points.

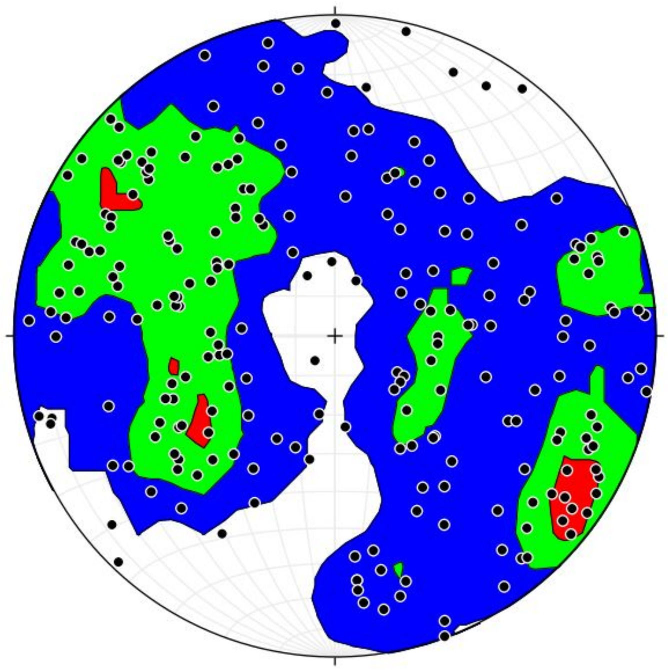


Figure 13. Poles to foliation with density contours for the Seven Devils thrust sheet. Red indicates high density, blue indicates low density. Poles are represented by black points.

quadrant and southwest quadrants and have plunge and trends of 48°/237° and 302°/22°. Average foliations for the limbs of the folds are 016°/44° SE and 194°/72° NW.

GEOCHRONOLOGY

The methods used in this study combine field relations and structural measurements observed during geologic mapping of the Heavens Gate quadrangle with geochronology to determine the timing of burial, exhumation, and faulting in the Heavens Gate 7.5-minute quadrangle.

Methods

Geochronology refers to the techniques concerned with dating rock formations and geologic events. One branch of geochronology involves the use of radioactive isotopes and their half-lives to date these rocks and events (Dalrymple, 1991). Common types of radioactive isotope dating include uranium to lead (U-Pb), rubidium to strontium (Rb-Sr), potassium to argon (K-Ar), Samarium to Neodymium (Sm-Nd), and thorium to lead (Th-Pb) (Dalrymple, 1991). The methods used in this study are U-Th-Pb dating of the mineral zircon. The basis of radiometric dating involves a radioactive parent isotope which decays to a stable daughter isotope at rates that can be measured experimentally (Dalrymple, 1991). With this known rate of decay, the time that has elapsed since the rock (or mineral) has formed can be calculated. Zircon also readily incorporates trace elements making it useful for geochemical tracers and is relatively insoluble in melts and fluids allowing it to preserve multiple generations of information in a single grain (Cherniak and Watson, 2003).

Deposition Ages vs Ages of Metamorphism. When dating the mineral zircon, it is important to distinguish whether ages represent original growth of the zircon in an igneous system, or if the zircon experienced multiple phases of growth, including metamorphic crystallization of zircon on older zircon cores. Single zircon crystals can retain isotopic evidence for multiple magmatic and or metamorphic events (Cherniak and Watson, 2003). For this reason, the interpretations of U-Pb dates from zircons with a polyphase growth history necessitate careful consideration of domains from single crystals (Gatewood and Stowell, 2012). Care must also be taken in cases where the zircon grain grew during an igneous or metamorphic event taking several million years, as P-T conditions may not be accurately reflected (Gatewood and Stowell, 2012). To determine whether the zircon grains are recording magmatism or periods of partial melting and metamorphism, we look to the ratio of Uranium and Thorium (U/Th or Th/U). Zircon data from Gatewood and Stowell (2012) show that young and discordant zircon have high U/Th ratios (>10) (extremely low Th/U ratios), suggesting crystallization with metamorphic fluids, or mixing between low and high U/Th Proterozoic and Cretaceous rims respectively, making them metamorphic zircon. This combination of U/Th ratios with U-Pb age dating could have useful applications in providing insight into the tectonic history of a region (McKay et al., 2018). Zircon data from western Idaho should therefore tentatively be able to tell us if the grain has recorded a metamorphic event, based on U/Th ratios and the grains correlation with garnet Sm-Nd ages.

Analysis. Geochronology samples were prepared at Missouri State University and analyzed at the University of Arkansas with a single collector iCAP Quadropole ICP-MS. Samples selected for analysis were first thoroughly cleaned to avoid any contamination with detrital zircon that may have come in contact with the rock since its collection. Following cleaning, samples were broken down in a rock crusher, and then pulverized to sand sized particles in a disk mill. A Franz magnetic separator was used to remove high magnetic susceptibility minerals. Separation of the mineral zircon from less dense minerals such as quartz and feldspar was achieved through the use of heavy liquids. Lithium sodium tungstate (LST) was used with a density of 2.85 g/cm^3 which allows minerals such as zircon (density of 4.65 g/cm^3) to sink. Zircons were then hand-picked from the remaining grains and mounted on double sided tape mounts. Laser ablation of sample grains was conducted using a beam diameter of ~25 μm. The ablated material was then removed from the ablation chamber by means of a carrier gas which was then passed through the plasma of the inductively coupled plasma-mass spectrometer (Gehrels et al., 2008). This superheated material carried by the gas was then accelerated and passed through a magnet which separates out the isotopes it is carrying, and these were picked up by the collector and analyzed (Gehrels et al., 2008). Data was acquired beginning with a single period of time with no laser firing to measure background intensity, followed by periods of laser firing, and once more without laser firing, to allow all the sample material to travel through the system and prepare for the next analysis, much like the process detailed in Gehrels et al. (2008). Upon completion of analysis the data was reduced at Missouri State University and the signatures were displayed using software called Density Plotter (Vermeesh, 2012). Weighted mean ages were calculated in Isoplot (Ludwig, 2003).

Results

Zircon from three tonalites (Figs. 14-15) (17IDMB443, 17IDMB506, and 18IDSD162a), one orthogneiss (Fig. 16) (17IDMB427), a schist member of the Riggins Group (Fig. 17) (17IDSN528), and a siliceous unit in undifferentiated clastic strata above the Seven Devils Group (Fig. 18) (18IDSD51) were analyzed to bracket localized deformation. Weighted mean ages are calculated for all samples using Isoplot (Ludwig, 2003; Vermeesh, 2012). The mean squared weighted deviation (MSWD), also known as the reduced chi-squared statistic, is

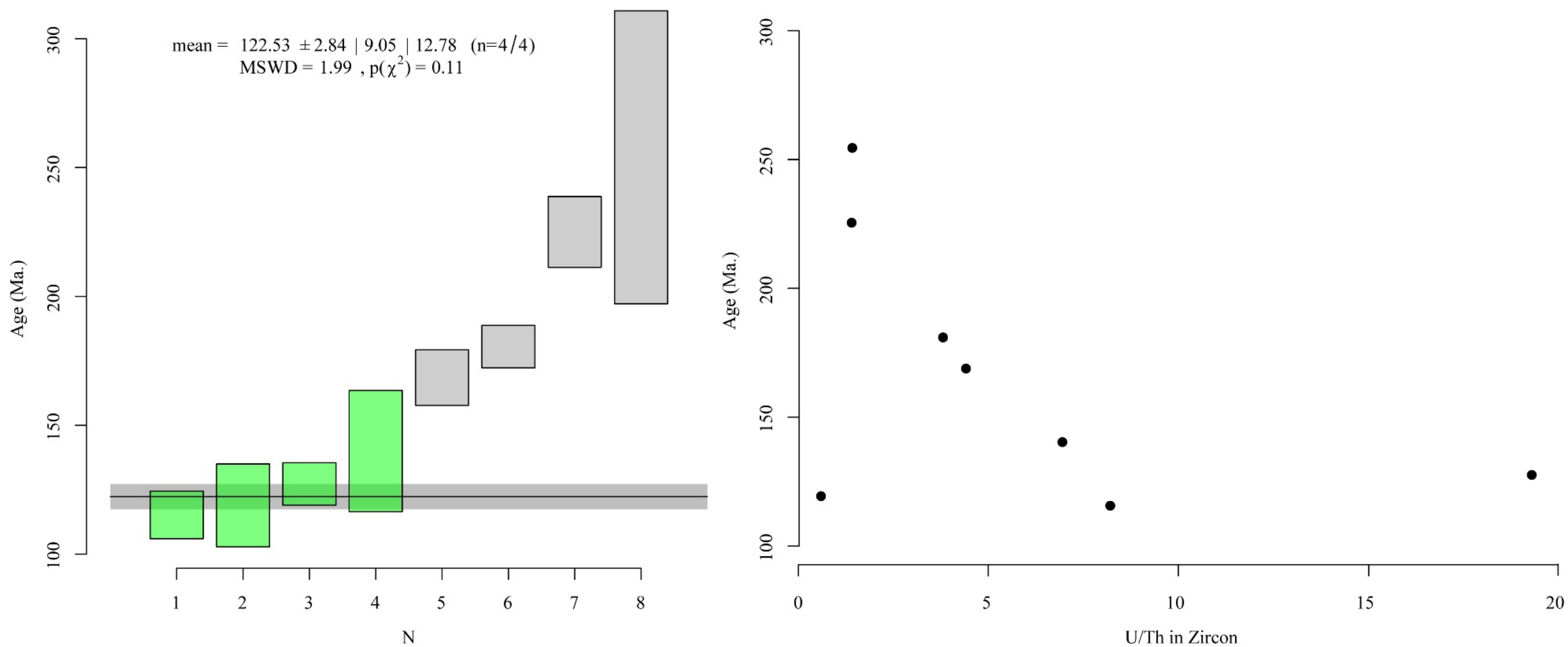


Figure 14. Weighted mean age for samples 17IDMB443 and 17IDMB506. Sample size 4 zircon grains out of 8. Four zircon were inherited by the intruding tonalite melt. The youngest zircon exhibit low U/Th ratios, while older, recycled zircon show higher (>5) coeval with metamorphism.

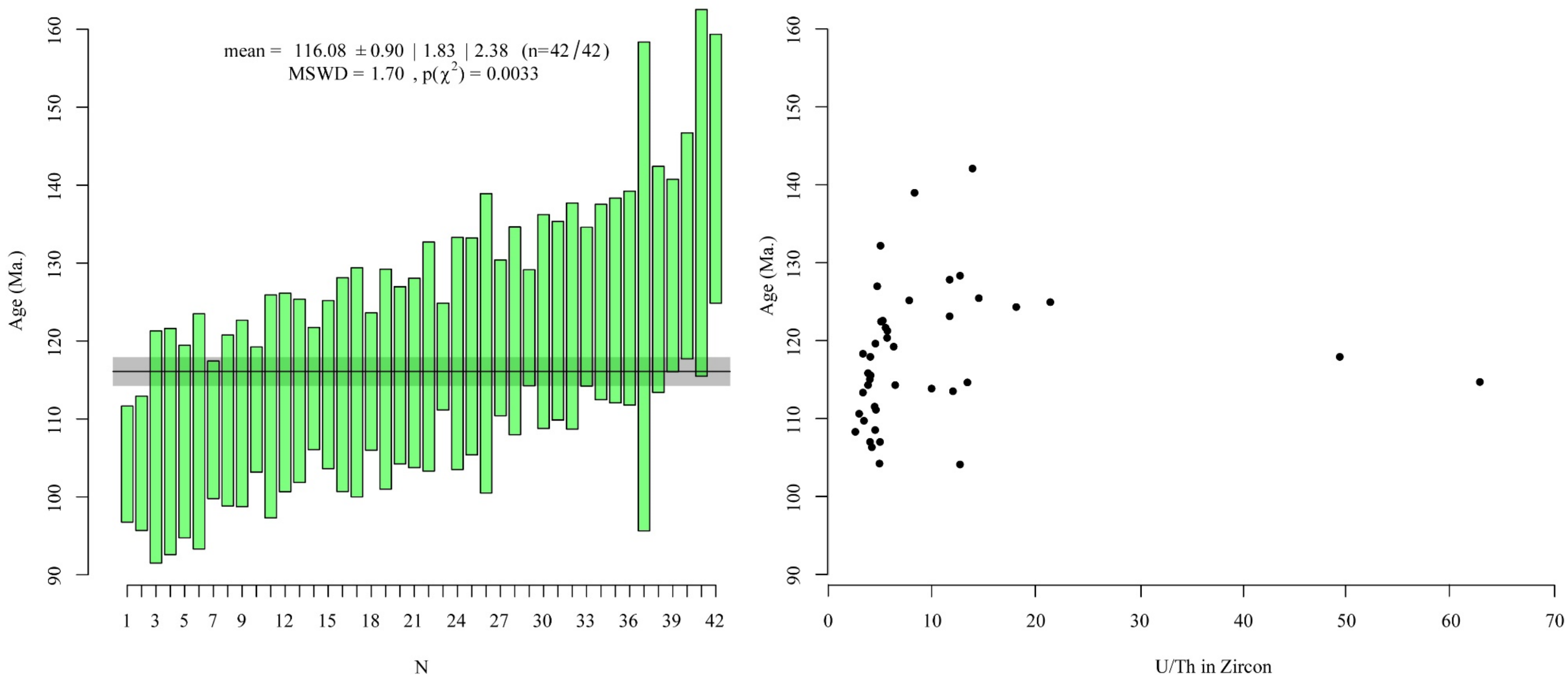


Figure 15. Weighted mean age for sample 18IDSD162a. Sample size 42 zircon grains. Population of 116 Ma zircon represent intrusion of tonalite and quartz diorite bodies.

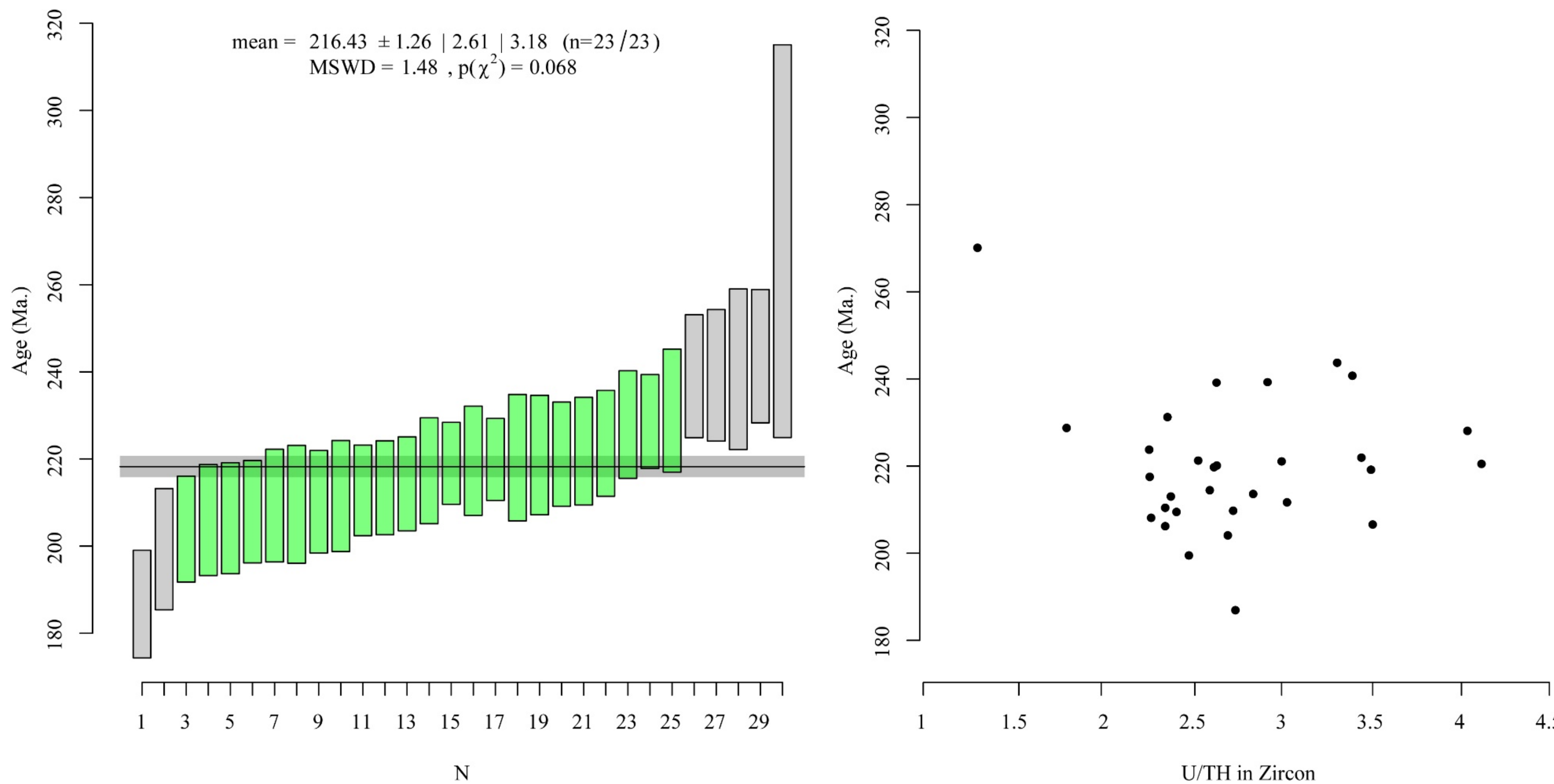


Figure 16. Weighted mean age for sample 17IDMB427. Sample size 23 zircon grains, 7 zircon grains excluded as they were likely inherited from the surrounding rock.

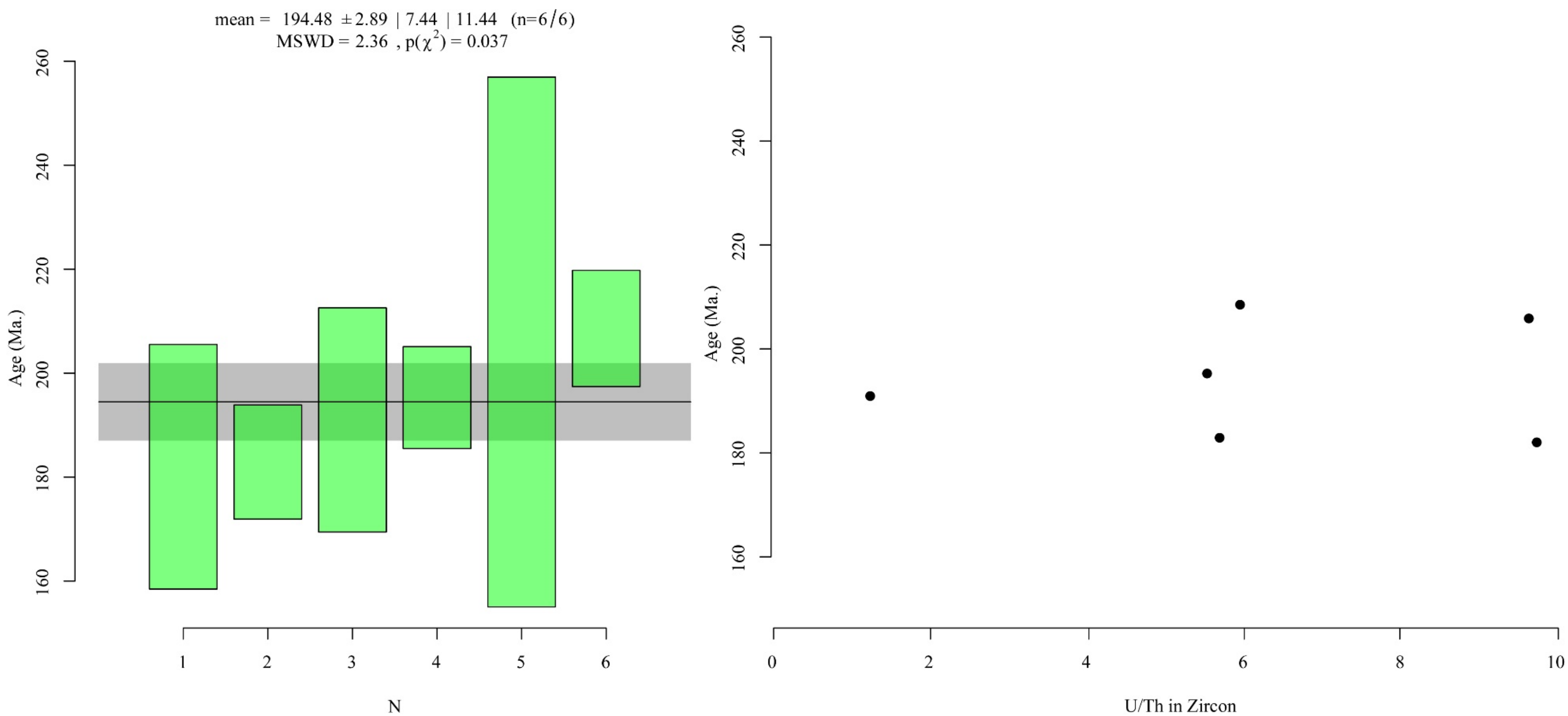


Figure 17. Weighted mean age for sample 17IDSN528. Sample size 6 zircon grains. High (>5) U-Th ratios may be representative of metamorphism in the unit.

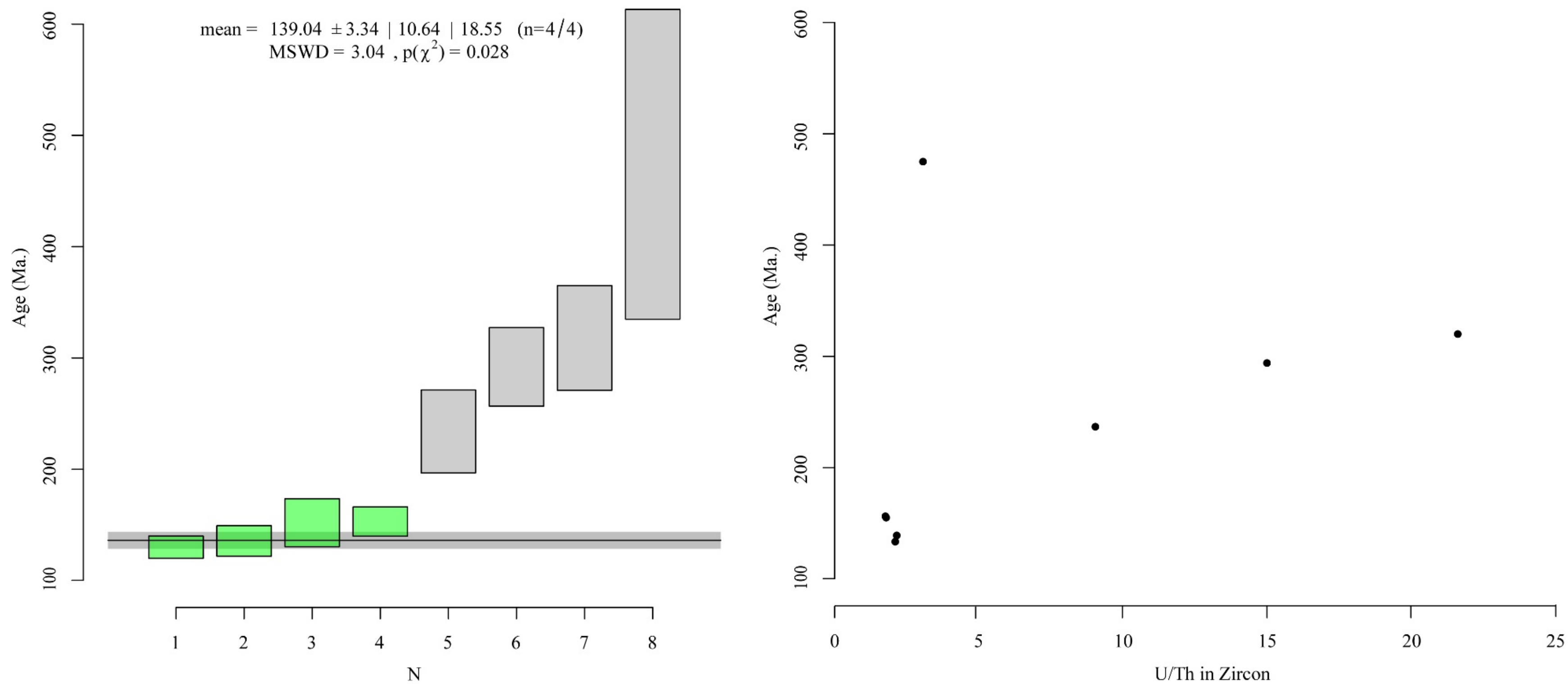


Figure 18. Weighted mean age for sample 18IDSD51. Sample size 8 zircon grains. Four zircons are excluded from the mean age as they were inherited and represent xenocrysts. High (>5) U/Th ratios suggest inheritance of older, metamorphic zircon from the surrounding units.

reported to assess the degree of coherence within a given dataset. As MSWD values approach 1.0, the scatter in the data represent scatter predictably within a single age population, given the known analytical uncertainties. Values less than 1.0 suggest analytical uncertainties are less than predicted for a single population, while values greater than 1.0 suggest mixing of two or more age populations. Complete data for each sample can be found in Appendix A.

17IDMB443 and 17IDMB506. These samples are tonalite that intruded the Pollock Mountain thrust sheet and Seven Devils Group, respectively (Brown, pers. comm., 2018). Four zircon grains were recovered from each sample. Given the similar compositions and proximity to one another (approximately 2 km), these have been grouped as belonging to the same intrusive event and are therefore considered together for age determination. Out of eight analyzed zircon, U-Pb ages for four grains are >160 Ma and are interpreted as xenocrysts (168.5, 180.5, 225, 254) inherited from an older population as the tonalite intruded the surrounding rock. The four youngest zircon grains form a population with a weighted mean age of 122.53 ± 2.84 Ma [MSWD=1.99].

18IDSD162a. This unmetamorphosed tonalite intrudes the Pollock Mountain thrust sheet. The particular sample locality is within the Heavens Gate quadrangle and included exposures of both Pollock Mountain Amphibolite and unmetamorphosed tonalite, providing spatial context between nearby units. Of 47 grains, 42 are between 142.1 and 104.2 Ma, and produce a weighted mean age of 116.08 ± 0.90 Ma with an MSWD of 1.7. Five, older zircon (219, 303, 382, 394, 605) were excluded from the age calculation as they were significantly older, possibly xenocrysts recycled from earlier magmatism.

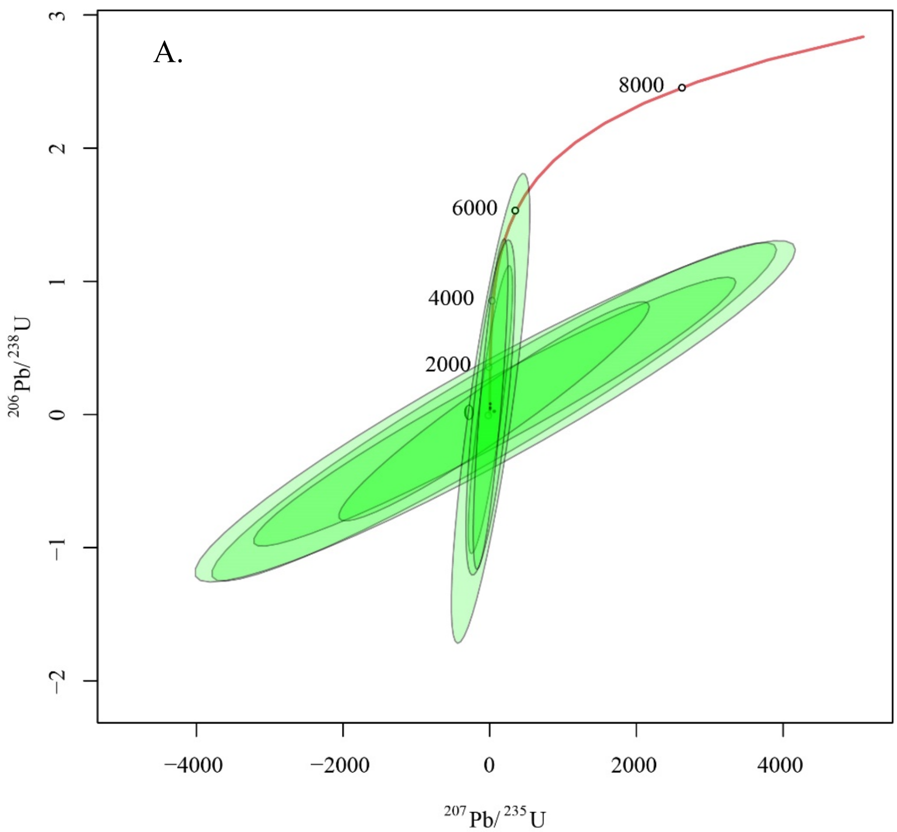
17IDMB427. A sample of the Cold Springs orthogneiss was collected from the Pollock Mountain quadrangle (Brown, pers. comm., 2018). Ages for this sample came from 23 zircon, at 216.43 ± 1.26. The MSWD was 1.48.

17IDSN528RS. The Squaw Creek Schist, a member of the Riggins Group, was sampled from above the Salmon River in a well constrained section near Riggins, Idaho (Nandi, 2018). As a fine-grained, mafic micaceous schist, the zircon yield for this sample was low. Six zircon grains were analyzed producing an age of 194.48 ± 2.89 Ma with an MSWD of 2.36.

18IDSD51. A fine-grained, gray, siliceous unit within the greenstone and clastic facies unconformably overlying the Seven Devils Group, possibly the Coon Hollow Formation, that, we interpret as a metamorphosed volcanic tuff was collected from just east of the Rapid River in the Heavens Gate 7.5-minute quadrangle. The sample yielded 8 grains, four of which are > 234 Ma, outside of uncertainty of the youngest 4 grains, and excluded from age calculation and likely represent xenocrystic or detrital contamination. The weighted mean age of the youngest three grains is 139.04 ± 3.34 Ma [MSWD =3.04].

DISCUSSION

Sample 18IDSD51, a siliceous tuff, which potentially is correlative to the Coon Hollow Formation and overlies the Seven Devils Group helps constrain the start of deformation in the Seven Devils Group. The mean weighted age given by the four of the eight zircon grains in the sample is 139.04 ± 3.34 Ma. There are three possible interpretations for this sample: First, the 139 Ma age obtained from this sample may be a result of metamorphism, possibly occurring concurrently with the Pollock Mountain thrust plate. However, this explanation is unlikely as the U/Th ratios for each of zircon used to calculate an age in the sample have very low U/Th ratios (<5) (Fig. 18). The second interpretation for this age is that the zircon used in the dating of this sample experienced lead loss at some point following deposition. Despite having high error, the four zircon grains used to assign an age to the unit are concordant (Fig. 19), which is atypical of grains that have experienced Pb loss. The four youngest ages are also of moderate U concentration (<1000 ppm) and do not young with age, another trait of Pb loss affected grains. Ages of each zircon grain versus the uranium content in parts per million are shown in Figure 19B. Uranium content (ppm) for the four zircon grains used to give an age are all similar making it unlikely the zircon has been altered. This rules out lead loss as an explanation for the age obtained from the tuff. The final interpretation for the ages given is that the tuff was deposited at this time and post 139 Ma folding and faulting generated the structures present in the region. This interpretation is not consistent with the proposed timing of deformation in the thrust sheet by Lamaskin et al. (2015), who proposes that the timing of folding and faulting had to occur pre-160 Ma. There is no evidence for multiple deformational events as proposed by Lamaskin et al. (2015) in the Heavens Gate quadrangle, as the tuff (interpreted as Coon Hollow Formation)



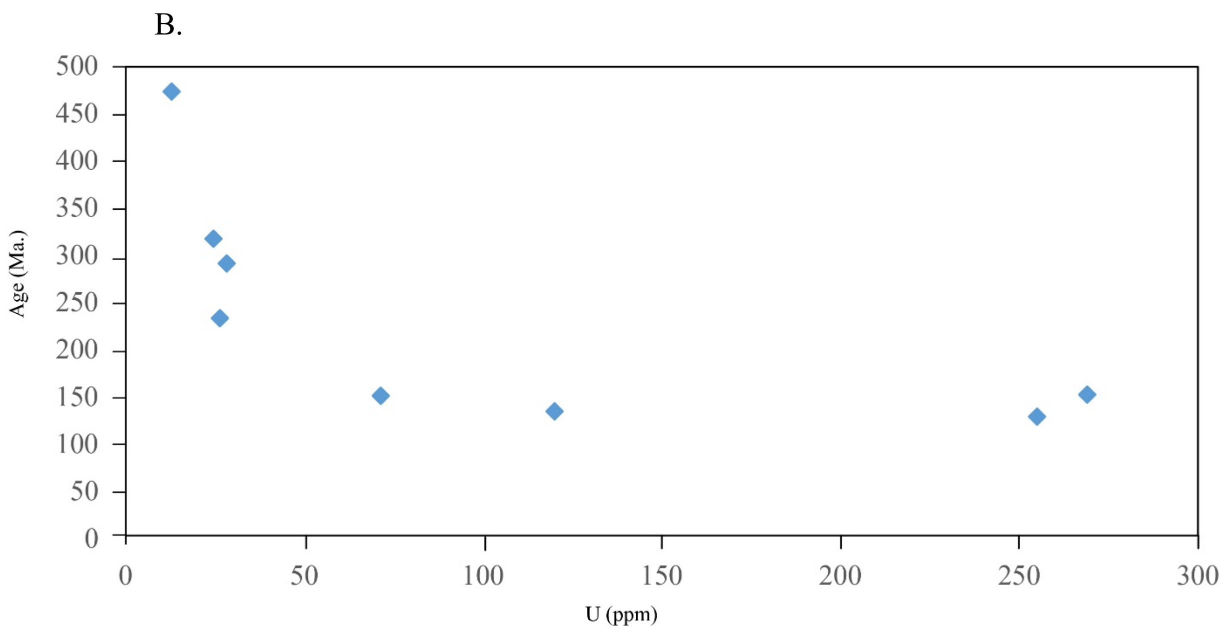


Figure 19 A, B. Concordia plot and age vs uranium concentration for sample 18IDSD51. Concordia plot (top), Age vs Uranium concentration (ppm) (Bottom). Concentrations of uranium decrease as the age increases. Concordia plot shows high error.

shares similar structure with the Seven Devils rocks it abuts, and there is no discernable angular unconformity separating it from the Seven Devils Group rocks below. For these reasons, it seems reasonable that the 139 Ma age for the tuff represents deposition prior to a folding and faulting deformational event.

Timing of Folding and Thrust Fault Development

Along the western portion of the Heavens Gate 7.5-minute quadrangle, rocks of the Wallowa terrane (Seven Devils Group and overlying strata) are folded, with a large anticline dominating the area, placing the Hunsaker Creek Formation in the center of Wild Sheep Creek Formation rocks. Additionally, several smaller scale folds are contained within the Wild Sheep Creek Formation. Folds plunge to the north east and are truncated to the east by the Morrison Ridge fault, suggesting that folding in the Wallowa-affinity rocks predates development of the Morrison Ridge fault. The presence of a fine-grained tuff with a 139 Ma U-Pb zircon age brackets folding within the Seven Devils Group and overlying strata to post-139 Ma. Based on reconnaissance mapping, Gray (2016) suggests low-angle thrusting between the Seven Devils Group and carbonate Martin Bridge Formation along the Morrison Ridge fault postdates the 130 Ma emplacement of the Fish Hatchery stock, which is compatible with post-139 Ma folding of the Seven Devils Group and associated strata.

The movement of the Morrison Ridge thrust fault can be bracketed further. The relationship between the Fish Hatchery stock and the thrust fault separating volcaniclastics of the Heavens Gate plate from the carbonates of the Morrison Ridge thrust plate, constrains faulting to post-130 Ma (Gray, 2016), while to the south the Echols Mountain pluton intrudes the Morrison Ridge fault on the Pollock Mountain 7.5-minute quadrangle (Brown, pers. Comm., 2018; Nandi, 2018). The Echols Mountain is likely an extension of the Deep Creek pluton, which is 123 Ma (Jeffcoat et al., 2013). Therefore, the Morrison Ridge thrust fault was likely active between 130-123 Ma.

West of the Morrison Ridge thrust sheet are two additional thrust faults; the Rapid River and Pollock Mountain thrust faults (from west to east). These split the region into thrust sheets which each contain rocks of differing characteristics. The easternmost thrust fault, the Pollock Mountain thrust fault, separates mid-crustal orthogneiss and amphibolites within the Pollock Mountain thrust plate in the east, and the rocks of the Rapid River thrust to the west. The differences in the makeup of these rocks and thrust sheets are due to the differences in formation conditions for each. The Rapid River thrust fault places the mid-crustal garnet—mica schists of the Riggins Group above the Lucile Slate in the footwall of the thrust. The Fiddle Creek Schist, Lightning Creek Schist, and Squaw Creek Schists are thrust fault slices within this east-dipping, west-directed thrust fault system. Overriding all these units is likely a splayed thrust sheet of Squaw Creek Schist, which tectonically thickens the unit at the surface.

The units within the Pollock Mountain thrust sheet record peak metamorphic conditions of temperatures of 650°-700°C and at a minimum of 7.5 kbar of pressure (Zen and Hammarstrom, 1984; Selverstone et al., 1992; Bollen, 2015; McKay et al., 2017). This slightly contrasts with those rock units within the Rapid River thrust plate, which experienced peak metamorphism at ~650°C, and at 7-9 kbar (Bollen, 2015; McKay et al., 2017).

In the Heavens Gate quadrangle, a tonalite that was emplaced at 116 Ma (Fig. 15) is truncated to the north and east by the Pollock Mountain thrust fault, implying the fault is either synchronous with or post-dates pluton crystallization. (McKay et al., 2017). Hornblende cooling ages record 118 Ma cooling and exhumation of the Pollock Mountain thrust plate (Lund and

Snee, 1988; Getty et al., 1993), therefore suggesting that exhumation of the Pollock Mountain plate and movement along the Pollock Mountain thrust fault are synchronous (McKay et al., 2017). The Pollock Mountain plate needs to have been buried to approximately 32 km, its maximum depth, by 117 Ma, with burial and metamorphism beginning between 141-137 Ma based on initial garnet growth (McKay et al., 2017). This exhumation of the Pollock Mountain plate likely played a role in the loading of the Rapid River plate down to 7-9 kbar (McKay, 2011; McKay et al., 2017). Garnet growth in the Rapid River plate records metamorphism overlapping with the Pollock Mountain plate, beginning at 124 Ma and continuing until at the minimum, 113 Ma (McKay et al., 2017). This timescale works with an Early Jurassic depositional age given for the Squaw Creek Schist at 194.48 ± 2.89 Ma. from U-Pb zircon dating. Any metamorphism occurring in the region would have had to occur after this time. Hornblende cooling ages of 109-107 Ma (Lund and Snee, 1988) track exhumation of the Rapid River thrust plate, implying movement towards the surface along the fault plane at this time.

Model for Deformation During Arc-Continent Collision

The earliest evidence for thrust fault development in the Heavens Gate 7.5-minute quadrangle is the ~123 Ma intrusion of the Echols Mountain pluton that cuts across the Morrison Ridge thrust fault., recording pre-123 Ma faulting in the western portion of the Salmon River suture zone. Activation of the Pollock Mountain thrust fault began likely by 118 Ma, which uplifted and exhumed the Pollock Mountain plate in the hanging wall, while burying the Rapid River plate in the footwall to mid-crustal metamorphic conditions. The Rapid River thrust fault was likely not active until after peak metamorphism of the Rapid River plate at 113 Ma. These spatiotemporal trends suggest out-of-sequence thrust fault development in a mid-crustal shear zone, where early faulting developed at the shallowest structural levels (the pre-123 Ma Morrison Ridge thrust fault) in the west, then shifted eastward to the mid-crustal, high geothermal gradient rocks of the Pollock Mountain plate, resulting in the 117 Ma Pollock Mountain thrust fault. The final sequence of thrust faulting occurred between these two faults and at mid-crustal conditions, within the Rapid River thrust fault. The complex nature of the Rapid River thrust fault suggests that thrust faulting and crustal thickening played a role in the Cretaceous metamorphism that occurred in the Salmon River suture zone.

Crustal Shortening

To estimate the magnitude of crustal shortening that the Salmon River suture zone underwent in the Paleozoic, horizontal transport distances were calculated across the region. The Morrison Ridge thrust fault juxtaposes rocks in the hanging wall that experienced ~9 kbar of pressure (McKay, 2011), while the Deep Creek pluton in the footwall was emplaced into the Seven Devils Group at 2.4-2.8 kbar of pressure (Jeffcoat et al., 2013). To account for the ~6.4 kbar pressure discrepancy present along the fault requires transport of the high pressure, hanging wall from mid-crustal conditions to upper crustal levels, resulting in significant uplift and shortening. Shortening was calculated using the equation for hydrostatic pressure: $P = \rho * g * d$, where P is the pressure, ρ is the density of the crust, *g* is gravity (9.8 m/s^2) and d is the depth below the surface. Once depth was calculated, fault geometries were inferred to estimate horizontal tectonic transport (Table 1). Assuming crustal densities from Simmons et al. (2007) (Table 1) an initial fault angle of approximately 15 degrees, like those found in local analogues in Idaho and Wyoming thrust belts (Armstrong and Oriel, 1965), shortening over the Salmon River suture zone during Cretaceous metamorphism is estimated to be between 72.6 and 86.1

Table 1. Crustal shortening and exhumation rates: parameters, distance, and percent

Plate	Density (g/cm3)	Depth (km) Pressure(kbar) Max (6.4)	Min (5.4)	Avg (5.9)	Horizontal Transport (km) Pressure(kbar) Max (6.4)	Min (5.4)	Avg (5.9)	Exhumation (mm/yr)
Seven Devils	2.7	23.9	20.1	22.0	89.1	75.2	82.2	
Rapid River	2.8	23.5	19.8	21.7	87.8	74.0	80.9	1.57
Pollock Mountain	3.0	21.9	18.5	20.2	81.8	69.0	75.4	0.95
Average	2.8	23.1	19.5	21.3	86.1	72.6	79.4	
					Shortening %			
Morrison Ridge - Rapid River					91.9			
Morrison Ridge - Pollock Mountain					86.8			
Morrison Ridge - Pollock Mountain					83.5			

Table 1. Metamorphic pressures calculated from McKay et al. (2017) for the Pollock Mountain and Rapid River thrust sheets, and Jeffcoat et al. (2013) for the Deep Creek pluton were used to calculate depth based on the densities for various rock types. Calculations for depth were completed using hydrostatic pressure equation, p=Pgh, where p = pressure, P = rho, g = gravity constant, h = depth. Shortening for the region is shown in km while percent shortening is shown in table 1B. Modern surface width estimates for calculating percent shortening were measured in google earth between Heavens Gate road and Allison Creek, a distance of 13.1 km; Heavens Gate road and the sample location of ID26 from McKay et al. (2017), a distance of 6.4 km; and the boundary just west of the Rapid River for the Martin Bridge limestone and Seven Devils group rocks to Patrick Butte, a distance of 17 km. These distances were used respectively to calculate Morrison Ridge – Rapid River, Morrison Ridge –Pollock Mountain minimum, and Morrison Ridge – Pollock Mountain maximum percentage of shortening. The rates of exhumation are shown in mm per year.

km. The percent shortening for the region was calculated first between the Morrison Ridge plate and the Rapid River plate using the minimum pressure estimates for shortening (Fig. 20). The modern distance between these plates was measured to be 6.4 km, from the Heavens Gate road to the sample location for ID26 from Mckay et al. (2017). These measurements resulted in a percent shortening of 91.9. Percent shortening was also calculated between the Morrison Ridge and Pollock Mountain plates at two locations: (1.) between the Heavens Gate road and Allison Creek; and (2.) between the boundary of the Morrison Ridge thrust plate just west of the Rapid River and Patrick Butte. The distances between these points were 13.1 and 17 km respectively.

The three locations where distance was measured are shown in Figure 20. The shortening calculated at each of these locations was 86.8 (1.) and 83.5 percent (2.). Shortening amounts and percentages are shown in Table 1 for a variety of conditions and variables.

The lateral transport and crustal thickening that resulted from the compressional forces driving metamorphism between 141 Ma and 108 Ma in the Salmon River suture zone amounted to shortening of nearly 90% of the region's original distance. The shortening estimates presented here are similar to the shortening estimates proposed by Giorgis et al. (2008) that were required to account for the compressed geochemical boundary between arc and continental affinity rocks. These estimations call for as much as 80-90 km of shortening (Giorgis and Tikoff, 2004; Giorgis et al., 2005; Giorgis et al., 2008). Activation of the western Idaho shear zone has been hypothesized to be responsible for much of the shortening that occurred throughout the Salmon River suture zone (McClelland et al., 2000; Tikoff et al., 2001; Giorgis et al., 2008). It is possible that the amount of shortening required to provide the compressed geochemical boundary and feldspar finite strain analysis found by Giorgis et al., (2008) could have been accommodated in

Figure 20. Distances across the Salmon River suture zone thrust sheets, aerial imagery. Imagery from google earth showing the distances measured across the Salmon River suture zone thrust sheets. Yellow line corresponds to the distance between the Rapid River and Morrison Ridge thrust (6.4 km) between the Heavens Gate road and the sample location for ID26 from McKay et al. (2017). Orange line corresponds to the minimum distance between the Pollock Mountain and Morrison Ridge thrusts (13.1 km) between the Heavens Gate road and Allison Creek. Red line represents the maximum distance between the Pollock Mountain and Morrison Ridge thrusts (17 km) between the Martin Bridge-Seven Devils group boundary west of the Rapid River to Patrick Butte.

the Salmon River suture zone. This would imply that the western Idaho shear zone is not the major zone of shortening in the Blue Mountain province, rather the Salmon River suture zone represents this, with the western Idaho shear zone serving to activate the periods of shortening.

Exhumation Rates

Exhumation rates have been calculated for the Pollock Mountain and Rapid River plates. Peak pressures for both the Rapid River and Pollock Mountain plates are assumed to be ~9 kbar (Selverstone et al., 1992; McKay, 2011) and are assumed to have been exhumed from crustal depths similar to rocks in the Seven Devils Mountains at ~2.6 kbar by the end of accretionary orogenesis. Therefore, the minimum exhumation required to account for current structural juxtaposition is ~6.4 kbar. These values are shown in Table 1 based on McKay et al. (2017). Densities used are the same as those shown in Table 1. If metamorphism in the Pollock Mountain plate began at 141 Ma (McKay et al., 2017), and exhumation was complete by 117 Ma (McKay et al., 2017), the Pollock Mountain plate was exhumed at a minimum rate of 0.95 mm per year. The duration of metamorphism in the Rapid River plate has been constrained to ∼15 m.y. by early garnet growth (124-113 Ma; McKay et al., 2017) and postmetamorphic cooling of hornblende (109 Ma; Lund and Snee, 1988). Using these age estimates, exhumation rates of 1.57 mm per year would be required for the Rapid River plate. Exhumation rates of approximately 1-2 mm per year are consistent other Cordilleran accretionary orogens, including the north Cascades which were loaded at a rate of 1-3 mm per year (Gatewood and Stowell, 2012). Loading rates of 1 mm/yr calculated by McKay et al. (2017) for the Rapid River plate are consistent with the rates of exhumation calculated here for the Pollock Mountain plate, supporting the theory that thrust fault-driven exhumation of the Pollock Mountain plate resulted in tectonic loading and burial of the Rapid River plate.

CONCLUSIONS

Geologic mapping within the Salmon River suture zone coupled with geochronology demonstrates the distribution of geologic units in the Heavens Gate 7.5-minute quadrangle and brackets the timing of tectonic deformation recorded in the Salmon River suture zone. By integrating structural relationships, geochronology data, and pressure estimates, estimates for crustal shortening and exhumation can be calculated for accretionary orogenesis in the Blue Mountains province. A visual representation of the timing of these events is shown in Figure 21.

1. Deposition of a 139 Ma siliceous tuff (Coon Hollow Formation?) within Wallowa terrane strata in the footwall of the Morrison Ridge thrust fault. Therefore, the Wallowa-affinity rocks to the west were folded between 139 and 123 Ma. The Morrison Ridge fault truncates this structure and was active between 130 and 123 Ma.
2. The Pollock Mountain thrust fault cuts a 117 Ma tonalite pluton, suggesting movement during or after ca. 117 Ma.
3. Age controls to the north of the quadrangle suggest that metamorphism and deformation of the Riggins Group has been constrained to ~15 m.y. by early garnet growth beginning by 124 Ma and ending around 109 Ma as constrained by post-metamorphic cooling of hornblende ages.
4. These age controls suggest that thrust fault development in the Salmon River suture zone is out-of-sequence. Faulting was active in the west (Morrison Ridge thrust fault), which overlaps with late mid-crustal metamorphism of the Pollock Mountain plate in the east. The second phase of deformation resulted in exhumation of the Pollock Mountain plate and burial of the Rapid River plate along the Pollock Mountain thrust fault beginning at ~124 Ma. In the central portions of the quadrangle, metamorphism of the Rapid River plate ended coeval with uplift and exhumation along the Rapid River thrust fault at ~109 Ma.
5. Shortening estimates suggest ~ 80 km of tectonic transport between [what] and 83.5% and 91.9% shortening [between what!] The calculated shortening is approximately the magnitude required to account for the compression observed in the geochemical boundary between the North American cratonic rocks and the units of the western Idaho shear zone.
6. Exhumation of the midcrustal metamorphic rocks at rates of 0.97 mm/year to 1.38 mm/year for the Pollock Mountain plate and 1.71 mm/year to 2.15 mm/year for the Rapid River plate are similar to rates of thrust fault loading, suggesting that (a) burial and metamorphism may be controlled by thrust faulting, (b) exhumation was controlled by thrust fault movement.

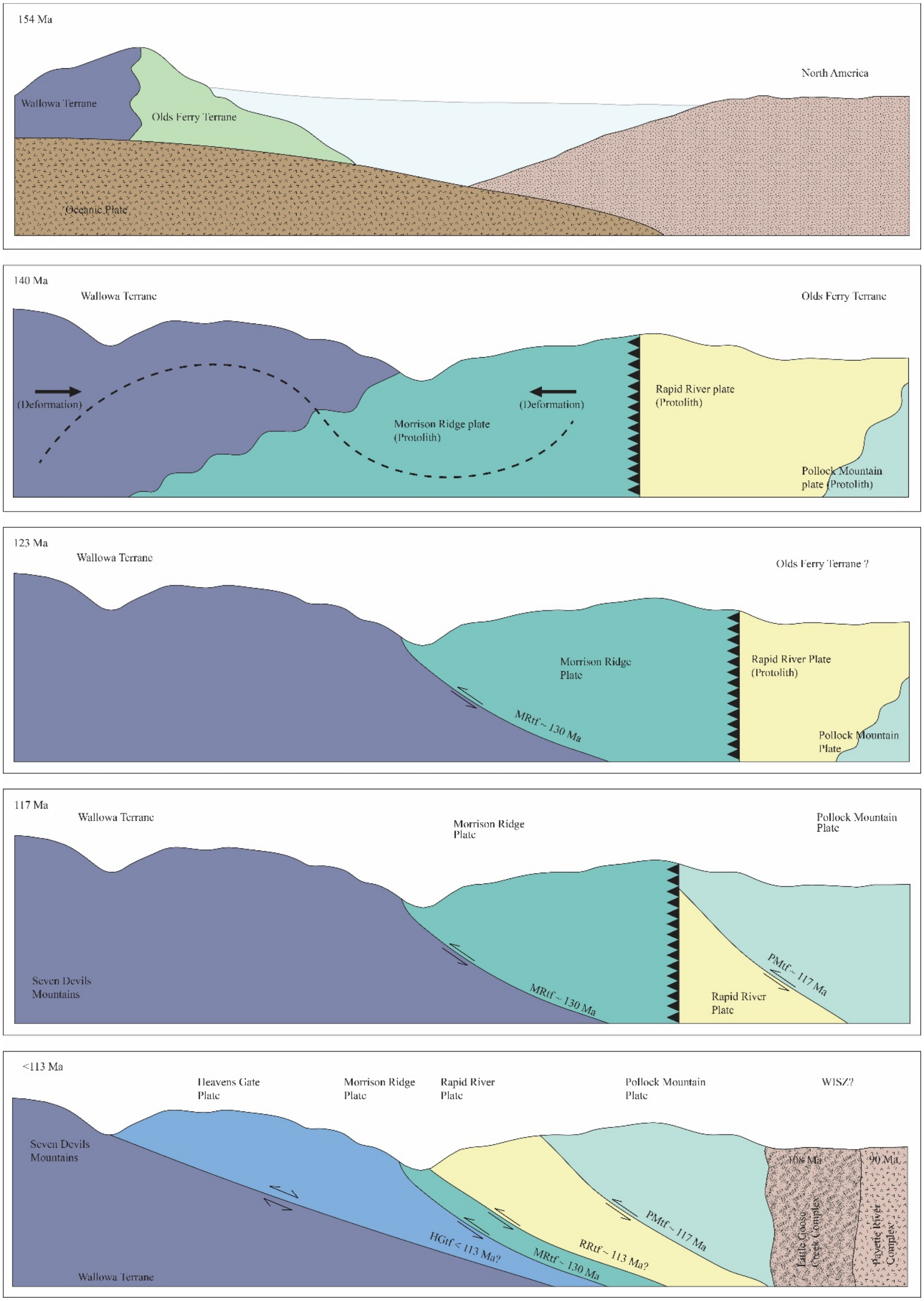


Figure 21.) Schematic timeline showing the timing of thrusting and deformation in the Salmon River suture zone from 154Ma to <113 Ma. Not to scale.

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APPENDIX A. U-PB ZIRCON AGES

Analysis	U/Th	$^{207}Pb/^{235}U$ Age (Ma)	± (Ma)	206Pb/238U Age (Ma)	± (Ma)	$^{207}Pb/^{206}Pb$ Age (Ma)	± (Ma)	Best Age (Ma)	± (Ma)
17IDMB506.13	8.21	168	17	115.2	4.7	750	230	115.2	4.7
17IDMB506.25	0.597	171	28	118.9	8.2	610	390	118.9	8.2
17IDMB506.24	4.41	166	17	168.5	5.5	110	200	168.5	5.5
17IDMB506.16	3.81	186	7.1	180.5	4.2	238	91	180.5	4.2
17IDMB443.02	19.3	133	12	127.2	4.2	150	190	127.2	4.2
17IDMB443.06	6.95	400	63	140	12	2280	310	140	12
17IDMB443.23	1.398	222	17	225	7	170	170	225	7
17IDMB443.20	1.42	1327	85	254	29	-45000	57000	254	29
17IDMB427.06	2.74	206	13	186.7	6.3	390	130	186.7	6.3
17IDMB427.20	2.48	224	13	199.3	7.1	440	140	199.3	7.1
17IDMB427.22	2.697	204	14	203.9	6.2	140	150	203.9	6.2
17IDMB427.21	2.347	219	13	206	6.5	320	140	206	6.5
17IDMB427.24	3.51	201	13	206.4	6.5	110	150	206.4	6.5
17IDMB427.18	2.268	217	15	207.9	6	270	160	207.9	6
17IDMB427.08	2.41	253	19	209.3	6.6	550	180	209.3	6.6
17IDMB427.03	2.727	211	15	209.6	6.9	180	160	209.6	6.9
17IDMB427.19	2.347	213	14	210.2	6	180	150	210.2	6
17IDMB427.27	3.03	244	11	211.5	6.5	555	92	211.5	6.5
17IDMB427.25	2.379	220	15	212.8	5.3	240	150	212.8	5.3
17IDMB427.09	2.84	235	17	213.4	5.5	420	160	213.4	5.5
17IDMB427.02	2.597	235	17	214.3	5.5	360	170	214.3	5.5
17IDMB427.15	2.259	228	17	217.3	6.2	290	170	217.3	6.2
17IDMB427.17	3.5	233	13	219	4.8	320	130	219	4.8

Appendix A Continued. U-Pb Zircon Ages

Analysis	U/Th	$^{207}Pb/^{235}U$ Age (Ma)	± (Ma)	206Pb/238U Age (Ma)	± (Ma)	$^{207}Pb/^{206Pb}$ Age (Ma)	± (Ma)	Best Age (Ma)	± (Ma)
17IDMB427.16	2.62	277	15	219.6	6.4	750	120	219.6	6.4
17IDMB427.05	2.636	236	11	219.9	4.8	350	110	219.9	4.8
17IDMB427.29	4.12	208	21	220.3	7.4	10	210	220.3	7.4
17IDMB427.07	3	228	18	220.9	7	240	180	220.9	7
17IDMB427.11	2.532	213	13	221.1	6.1	100	140	221.1	6.1
17IDMB427.30	3.447	232	13	221.8	6.3	310	130	221.8	6.3
17IDMB427.13	2.256	230	15	223.6	6.2	250	160	223.6	6.2
17IDMB427.10	4.04	286	18	227.9	6.3	690	160	227.9	6.3
17IDMB427.01	1.793	254	12	228.6	5.5	440	110	228.6	5.5
17IDMB427.04	2.36	228	13	231.1	7.2	180	130	231.1	7.2
17IDMB427.28	2.634	228	17	239	7.2	100	170	239	7.2
17IDMB427.12	2.92	229	15	239.2	7.7	110	150	239.2	7.7
17IDMB427.26	3.395	231	20	240.6	9.4	80	180	240.6	9.4
17IDMB427.14	3.311	226	15	243.6	7.8	40	140	243.6	7.8
17IDMB427.23	1.294	682	60	270	23	2330	320	270	23
18IDSD162a.40	12.7	105.4	6.1	104.2	3.8	180	140	104.2	3.8
18IDSD162a.39	4.93	107	13	104.3	4.4	70	230	104.3	4.4
18IDSD162a.20	4.19	100	20	106.4	7.6	-120	350	106.4	7.6
18IDSD162a.05	4.97	99	24	107.1	7.4	-300	390	107.1	7.4
18IDSD162a.19	4.02	103	20	107.1	6.3	-150	350	107.1	6.3
18IDSD162a.28	2.61	96	18	108.4	7.7	-170	330	108.4	7.7
18IDSD162a.26	4.52	110	12	108.6	4.5	20	210	108.6	4.5
18IDSD162a.01	3.435	108	15	109.8	5.6	-20	280	109.8	5.6
18IDSD162a.25	2.976	115	17	110.7	6.1	60	270	110.7	6.1
18IDSD162a.31	4.59	116	12	111.2	4.1	120	210	111.2	4.1
18IDSD162a.03	4.47	147	25	111.6	7.3	440	350	111.6	7.3

Appendix A Continued. U-Pb Zircon Ages

Analysis	U/Th	$^{207}Pb/^{235}U$ Age (Ma)	± (Ma)	206Pb/238U Age (Ma)	± (Ma)	$^{207}Pb/^{206}Pb$ Age (Ma)	± (Ma)	Best Age (Ma)	± (Ma)
18IDSD162a.06	3.35	136	19	113.4	6.5	330	300	113.4	6.5
18IDSD162a.35	12	132	16	113.6	6	330	270	113.6	6
18IDSD162a.13	9.95	150	14	113.9	4	610	190	113.9	4
18IDSD162a.43	6.44	128	19	114.4	5.5	140	280	114.4	5.5
18IDSD162a.45	3.83	131	30	114.4	7	-80	410	114.4	7
18IDSD162a.38	13.4	184	24	114.7	7.5	860	330	114.7	7.5
18IDSD162a.15	62.8	112.5	9.6	114.8	4.5	150	200	114.8	4.5
18IDSD162a.04	3.99	107	20	115.1	7.2	-160	310	115.1	7.2
18IDSD162a.11	4.08	115	19	115.6	5.8	-60	290	115.6	5.8
18IDSD162a.22	3.83	110	19	115.9	6.2	-110	330	115.9	6.2
18IDSD162a.08	4.05	106	21	118	7.5	-240	310	118	7.5
18IDSD162a.27	49.3	120.3	8.7	118	3.5	180	160	118	3.5
18IDSD162a.14	3.337	101	20	118.4	7.6	-290	340	118.4	7.6
18IDSD162a.32	6.3	117	22	119.3	7.1	-100	340	119.3	7.1
18IDSD162a.36	4.54	110	30	119.7	9.8	-300	430	119.7	9.8
18IDSD162a.17	5.66	107	15	120.4	5.1	-150	260	120.4	5.1
18IDSD162a.02	5.68	251	33	121.3	6.8	1250	350	121.3	6.8
18IDSD162a.47	5.53	112	11	121.7	3.8	-50	190	121.7	3.8
18IDSD162a.37	5.07	118	20	122.5	7	0	320	122.5	7
18IDSD162a.12	5.26	118	18	122.6	6.5	-70	280	122.6	6.5
18IDSD162a.21	11.7	95	19	123.2	7.4	-400	310	123.2	7.4
18IDSD162a.07	18.1	119	14	124.4	5.2	20	230	124.4	5.2
18IDSD162a.47	21.4	115	19	125	6.4	-110	300	125	6.4
18IDSD162a.33	7.8	133	19	125.2	6.7	200	290	125.2	6.7
18IDSD162a.24	14.5	120	19	125.5	7	-50	270	125.5	7
18IDSD162a.16	4.7	86	32	127	16	-500	530	127	16

Appendix A Continued. U-Pb Zircon Ages

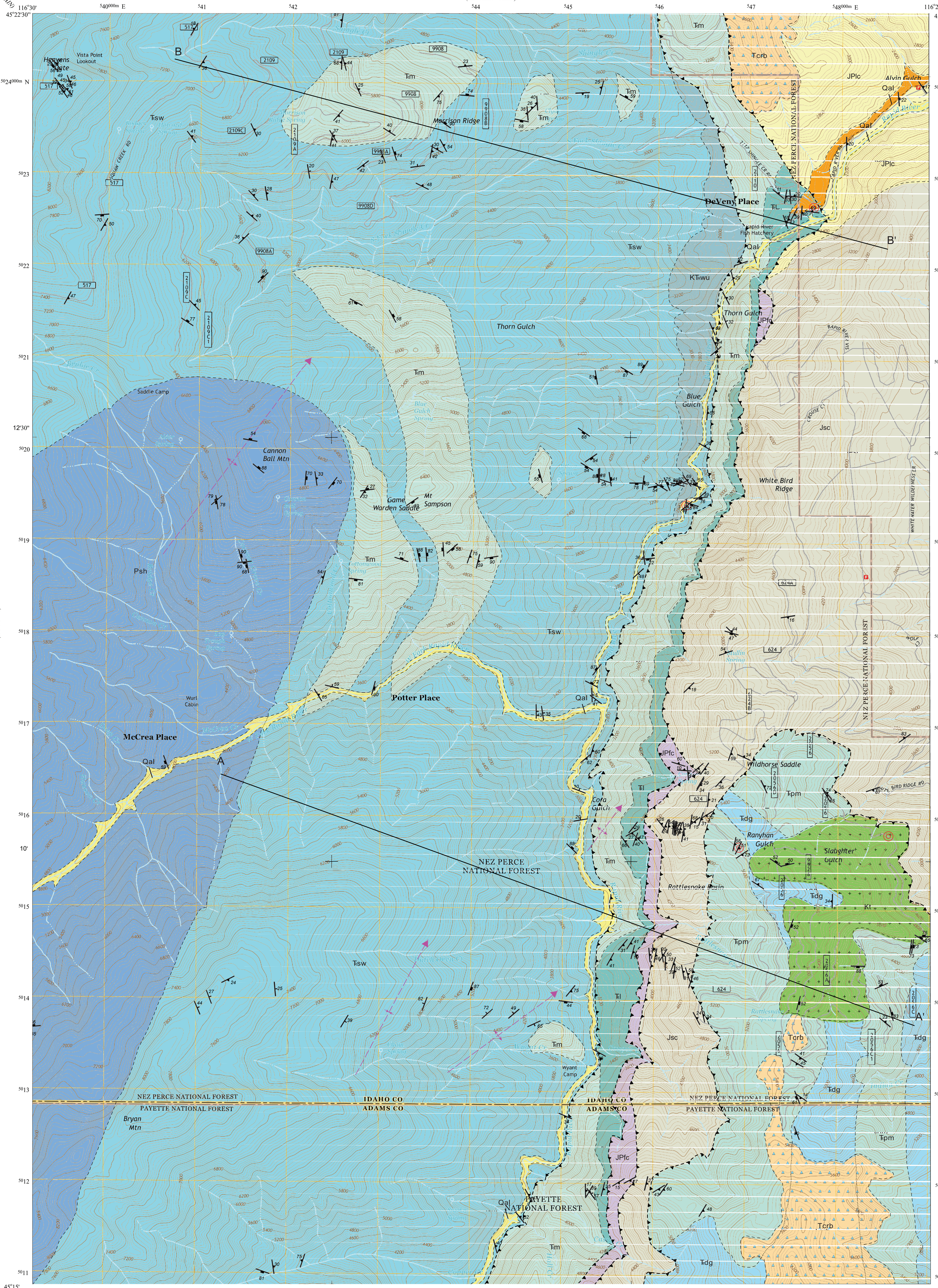
Analysis	U/Th	$^{207}Pb/^{235}U$ Age (Ma)	± (Ma)	206Pb/238U Age (Ma)	± (Ma)	$^{207}Pb/^{206}Pb$ Age (Ma)	± (Ma)	Best Age (Ma)	± (Ma)
18IDSD162a.09	11.7	148	22	127.9	7.4	260	310	127.9	7.4
18IDSD162a.27	12.7	122	17	128.4	6.3	0	280	128.4	6.3
18IDSD162a.44	5.04	133	24	132.2	7.4	-30	310	132.2	7.4
18IDSD162a.28	8.3	94	26	139	12	-570	410	139	12
18IDSD162a.15	13.9	129	22	142.1	8.8	-120	320	142.1	8.8
18IDSD162a.29	16.7	1144	55	219	17	4130	180	219	17
18IDSD162a.42	10.72	1330	120	303	39	4090	180	303	39
18IDSD162a.48	25	1825	76	382	29	4630	290	382	29
18IDSD162a.10	12.5	1802	66	394	29	4650	280	394	29
18IDSD162a.30	11.8	2200	150	605	83	4880	330	605	83
18IDSD51.08	2.098	121	13	130	5.1	-30	220	130	5.1
18IDSD51.06	2.156	113	19	135.6	7	-230	300	135.6	7
18IDSD51.03	1.784	148	29	152	11	-30	370	152	11
18IDSD51.04	1.757	131	15	153	6.7	-120	230	153	6.7
18IDSD51.05	9.04	1227	68	234	19	4280	270	234	19
18IDSD51.09	14.99	1444	67	292	18	4230	160	292	18
18IDSD51.10	21.6	1673	61	318	24	4700	200	318	24
18IDSD51.02	3.06	1950	160	474	71	5030	440	474	71

GEOLOGIC MAP AND CROSS SECTIONS OF THE HEAVENS GATE 7.5' QUADRANGLE, IDAHO COUNTY, IDAHO

by

Samuel G. DeYoung, Matthew P. McKay, Jordan Cruzan, Sage Muttel, and Tessa Mills

2019



Base topographic map U.S Geological Survey 2004. Shaded elevation from 10 m DEM.

Projection: Idaho coordinate system, west zone (Transverse Mercator). 1983 North American Datum.

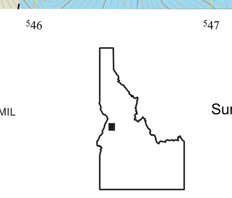
1000- meter Universal Transverse Mercator grid ticks, zone 11.

Map rotated -0.355 degrees clockwise for display.

Map version 10-25-2018.

SCALE 1:24,000

CONTOUR INTERVAL 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1983



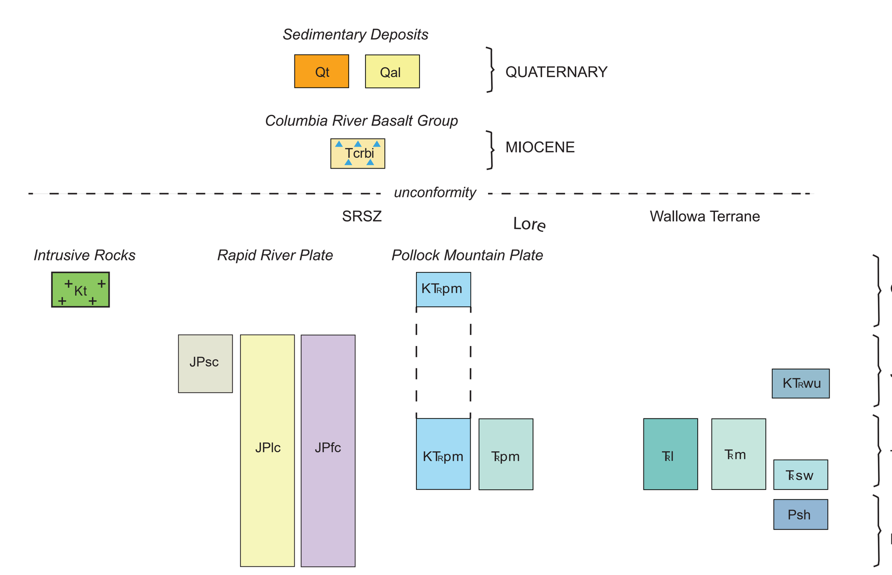
QUADRANGLE LOCATION

Field work conducted in Summer 2018.

Produced in cooperation with the U.S. Geological Survey National Cooperative Geologic Mapping Program, USGS Award No. G18AC00128.

Digital database by Sam DeYoung

CORRELATION OF MAP UNITS



SYMBOLS FOR GEOLOGIC MAP

- Contact, located very approximately
- Contact, concealed beneath mapped units
- Thrust fault, concealed beneath mapped units
- Thrust fault, located very approximately, saw teeth on hanging wall
- Trace of syncline axis, located approximately, arrow showing direction of plunge
- Trace of anticline axis, located approximately, arrow showing direction of plunge
- Strike and dip of bedding (S_0)
- Vertical bedding
- Strike and dip of metamorphic foliation (S_1, S_2)
- Joint and fracture set
- Geochronology sample location

SYMBOLS FOR CROSS SECTIONS A-A' & B-B'

- Stratigraphic contact
- Fault showing relative movement
- Metamorphic foliation

DESCRIPTION OF MAP UNITS

Qal — **Alluvium deposits (Quaternary)—**Unconsolidated Holocene and Pleistocene deposits of gravel, sand, clay, and silt. Quaternary deposits are not displayed in cross section due to thicknesses less than 50 feet.

Qt — **Low terrace deposits (Quaternary)—** Thick terrace deposits occur along the Rapid River especially in the north east corner of the map, near the Fish Hatchery. Terrace deposits contain pebble to boulder size clasts, clasts are aligned in some areas. Clast composition includes greenstone, tonalite, and basalt. Quaternary deposits are not displayed in cross section due to thicknesses less than 50 feet.

Tcrb — **Imnaha Basalt (Miocene)—**Imnaha Basalt of the Columbia River Basalt Group is present mostly in the southeast corner of the Heavens Gate quadrangle approximately ~1000 feet thick and continues into the Pollock Mountain quadrangle to the south. In the quadrangle, the Imnaha Basalt is a medium to coarsely porphyritic basalt flow with olivine and plagioclase phenocrysts dominating. Fewer are course hornblende phenocrysts in the unit. The unit weathers into a reddish brown or gray hue. Vesicular texture can be found in float, and is a result of olivine phenocrysts weathering away.

INTRUSIVE SUITES

Kt — **Cretaceous tonalite and quartz diorite (Early Cretaceous?)—**Medium- to course-grained, biotite rich tonalite to quartz diorite units intrude the Pollock Mountain Amphibolite and Cold Springs Orthogneiss in the eastern-central region of the map. Units are white to gray in color, and are made up of primarily plagioclase feldspar, hornblende, biotite, and quartz. Some sections exhibit a weak fabric and are perhaps genetically linked to the Echols Mountain pluton, suggesting a cretaceous age. Some sections are more heavily altered than others and exhibit a more friable texture, particularly those cut by the fault on forest service road 624. Exposures are heavily jointed.

EASTERN SALMON RIVER BELT

Rapid River plate

Jsc — **Squaw Creek Schist (Jurassic)—**Fine- to medium grained, pelitic biotite-garnet schists. Present running north-south on the eastern side of the quadrangle. Exposed at the surface in wide swathes, likely due to fault splays which thicken it at the surface. Garnet is present in discontinuous zones. Amphiboles are present and are randomly oriented. Unit is very quartz rich. Some sections exhibit serpentinization, particularly to the northeast near Riggins. Squaw Creek Schist weathers to a reddish brown and exposures are heavily weathered and friable. Locally contains minor quartzite and marble as well as talc schists. Interbedding relationships with these suggest that S_1 may be parallel to original bedding (S_0). In the eastern portion of the map garnet growth in the Squaw Creek Schist occurred ~124 Ma (McKay et al., 2017). In the Riggins quadrangle to the north east, preliminary (Table 1.) detrital zircon dating yields an age of approximately 200 Ma.

JPlc — **Lightening Creek Schist (Jurassic-Permian)—**Fine- to medium grained biotite-chlorite schist. Light to dark gray and green in color. Moderate amounts of quartz present. Exposures limited to north eastern extent of Heavens Gate Quadrangle (Gray 2013). Local garnet, kyanite, and staurolite containing occurrences present as well as localities of marble.

JPfc — **Fiddle Creek Schist (Jurassic-Permian)—**Fine to medium grained, muscovite, quartz, garnet schist with minior metaconglomerate, quartzite, and biotite, garnet schist. Found in the center of the quadrangle, striking roughly southwest-northeast, and is poorly exposed at the surface. Primary schist unit includes minor amounts of plagioclase, and retrograde chlorite. Light gray to green in color as schist. Metaconglomerate is monomictic and clasts are tonalitic in composition. Clasts range in size from four to twelve inches. Garnets increase in size with a shift to the biotite-garnet schist, and are around 1 cm in diameter on average. Distinguished from Lightening creek by an increase in white mica and quartz, less biotite and chlorite, as well as metaconglomerate's absence in the Lightening Creek Schist.

Pollock Mountain plate

Tdg — **Cold Springs Orthogneiss and migmatite (Triassic-Cretaceous)—**Course- to fine-grained felsic orthogneiss intercalated with a fine grained, undeformed tonalite and quartz diorite. Pegmatitic veins and leukosomes present discontinuously and in small areas. Undeformed portions of the units intrude the surrounding Cold Springs orthogneiss and Pollock Mountain Amphibolite. Orthogneiss exhibits a strong fabric, and includes biotite, quartz, hornblende, and plagioclase feldspar as primary constituents. Migmatites occur locally and are not observed to form a coherent partial melt zone or spatial trend. The protolith of the orthogneiss is interpreted to be Triassic (206 Ma) based on U—Pb zircon and was overprinted by Cretaceous metamorphism at 141 Ma (10ID42; McKay et al., 2017). Based on U—Pb, partial melting occurred around 125 Ma with tonalite intrusions emplaced at 114 Ma (K. Johnson, pers. comm). Sample ID's 17IDMB443, 17IDMB506, and 18IDSD162a are all unmetamorphosed tonalite and quartz diorites from within this unit. 17IDMB427 is the Cold Springs orthogneiss.

KTpm — **Pollock Mountain Amphibolite (Triassic)—**Garnet-Kyanite-tourmaline-quartz- biotite amphibolite. Present in the eastern sections of the map as continuous units at the surface, well exposed on hillsides to the east of the Rapid River. There appear to be two main variations, one with approximately equal amounts of hornblende and plagioclase, and one which occurs discontinuously and is dominated by hornblende (70-90%) with lesser quantities of plagioclase. Euhedral to subhedral almandine garnet occur on average at nearly 0.5 – 1 cm sizes, however they can be found in much larger sizes, up to 10 cm. Garnets are often ringed with plagioclase. Weathers fissile. In places interbedded with a light quartzite (post kinematic). P-T estimates and Sm-Nd geochronology suggest that the Pollock Mountain Amphibolite was buried to >7.5 kbar and ~700°C between 144 and 123 Ma (09ID03; 10ID23; Selverstone et al., 1992; Getty et al., 1993; and McKay et al., 2017).

WESTERN SALMON RIVER BELT

Tl — **Lucile Slate (Triassic)—**Light- to dark-gray graphitic phyllite and slate with interbedded fine-grained quartzites. Present near the Rapid River in the quadrangle, trending north and south. Outcrops poorly. In contact with terrace deposits to the north, and Martin Bridge limestone throughout the quadrangle. Crenulation cleavage present in some outcropped exposures.

Tm — **Undifferentiated Marble (Triassic)**—Undifferentiated marble consists of gray to blue marbles, limestones, with minor interbedded greenstone. In places, marble correlates to the Martin Bridge Limestone and Martin Bridge Formation (Hamilton, 1963; Lund, 2004). Exposed along the Rapid River, and striking north to south throughout the cross section are marbles of the Martin Bridge formation. Marble and Limestone are exposed a discontinuous pods throughout the metavolcaniclastics of the Wild Sheep Creek Formation. Limestone ranges from crystalline to micritic. Calcite veins present in both limestone and marble. Limestones are thinly bedded. Thin talc schists and a dark blue to black quartzite are also intercalated throughout the marble units.

WALLOWA TERRANE

KTwu — **Undifferentiated Clastics and Volcaniclastics (Triassic-Cretaceous)**—Undifferentiated Seven Devils unit. May correlate to some of the Hurwal or Coon Hollow Formations. Hurwal formation consists of two distinct lithologies, a metamorphosed argillaceous limestone and argillite below, and an upper unit consisting of metamorphosed musdstone and volcaniclastic rocks (Vallier, 1977). Rock types in the Coon Hollow formation are a primarily black and dark brown mudstone with minor siltstones and sandstones (Vallier, 1977). There are rare beds of conglomerate and breccia in the sequence (Vallier, 1977). In the Heavens Gate quadrangle, this unit also contains a siliceous tuff-like unit within the volcaniclastics (sample ID no. 18IDSD51).

Tm — **Marble within volcaniclastic greenstone (Triassic)**—Undifferentiated marble consists of gray to blue marbles, limestones, with minor interbedded greenstone. Marble and Limestone are exposed as discontinuous pods throughout the metavolcaniclastics of the Wild Sheep Creek Formation. Limestone ranges from crystalline to micritic. Calcite veins present in both limestone and marble. Limestones are thinly bedded. Thin talc schists and a dark blue to black quartzite are also intercalated throughout the marble units.

Tsw — **Wild Sheep Creek Formation (Triassic)—**The Wild Sheep Creek Formation conformably overlies the Hunsaker Creek Formation in the Heavens Gate quadrangle. The Wild Sheep Creek Formation is exposed throughout much of the quadrangle to the west of the Rapid River. It is inferred to be ~680 meters thick in the quadrangle to the south west (Nandi, 2018) but it may be thicker here due to the structural trend of the region (interpreted as a plunging antiform). The Wild Sheep Creek Formation is dark gray-green on fresh surfaces, and is composed of porphyritic plagioclase-rich greenstone facies that are basalt dominated with almost no quartz porphyry, basaltic andesite, and polymectic volcaniclastics which include basaltic greenstone, limestone, argillite, and siltstone as clasts. Lenses of marble and limestone are present within the unit in this quadrangle. Weathering colors the unit brown to greenish black.

Psh — **Hunsaker Creek Formation (Permian)—**The oldest stratigraphic unit exposed in the quadrangle, the Permian Hunsaker Creek formation was named and described by Vallier (1977) for exposures along Hunsaker creek, a Snake River tributary. This formation consists of siliceous greenstone facies (pyroclastic breccia and conglomerate) metavolcaniclastics with quartz clasts, and metabasalt flows with quartz porphyries. Clasts in the volcaniclastics are polymectic and include basalts, sedimentary rocks, and some plutonic rock. Brachiopod faunas reported in the Hunsaker Creek Formation constrain an Early Permian age (Vallier, 1977). Near Hunsaker Creek the unit is ~2500 meters to ~780 meters thick. The estimated thickness of the Hunsaker Creek Formation in the Purgatory Saddle quadrangle to the south west is ~2200 meters (Nandi, 2018)

INTRODUCTION

The Heavens Gate (7.5-minute) quadrangle is located in Idaho County, Idaho. Land use within the quadrangle is a mixture of National Forest and Privately-owned land. Two national forest service branches manage the land in the quadrangle with the northern regions of the quadrangle falling into the Nez Perce national forest, while in the south the Payette National forest manages the land. The Hells Canyon wilderness area exists to the west of the quadrangle. Access to the quadrangle is provided through a series of unnamed forest service roads. Access to the northern regions of the map are provided by forest service roads 2109 and 517. Forest service road 624 and 2056 provide access to the eastern-central sections of the map. Peaks in the quadrangle include Vista Point lookout (8429 feet), Mount Sampson (6462 feet), Cannon Ball Mountain (7178 feet), and Bryan Mountain (8358 feet). Trails are maintained by the U.S. Forest Service for recreational access. The closest cities to the quadrangle are Riggins (7.1 miles) to the northeast and New Meadows (33 miles) to the south. Historic land use in the region has been grazing as well as copper and gold mining. Abandoned mining pits are present in the Seven Devils unit, primarily near limestone units which have been intruded by plutons.

This report and accompanying map summarize the basic geology of the area. This will provide insight into the timing of accretion and deformation in the area. Relationships between the thrust sheets within the Salmon River Suture Zone (SRSZ) and ages for greenschist facies volcaniclastic sequences will be critical to interpreting the events which shaped the western margin of North America during the Mesozoic.

GEOLOGIC SETTING

The Heavens Gate (7.5-minute) quadrangle is located in the eastern Blue Mountain Province in Idaho. This edge marks the boundary of accreted terranes to the North American craton (Armstrong et al., 1977). These terranes exhibit the magmatism, metamorphism, and sedimentation which was occurring here from the late Paleozoic to the Mesozoic (Dickinson, 1979; Walker, 1986; Schwartz et al., 2010). These terranes are intruded by late Jurassic-Early Cretaceous plutonic complexes which are exposed below the accreted (primarily) Cenozoic rocks (Schwartz et al., 2010). The eastern edge of the quadrangle contains rocks from the Salmon River suture zone, a north and south trending zone (Lund and Snee, 1988) that marks the boundary between the volcanic rocks in the Blue Mountains province, and the units originating in the Precambrian in central Idaho (Gray and Oldow, 2005).

Within the quadrangle, Permian to Triassic sedimentation and subsequent Jurassic to Cretaceous metamorphism are evident in the Seven Devils Group. In addition, Cretaceous thrusting and deformation of the Salmon River suture zone rocks is recorded within the quadrangle. The rocks of the Heavens Gate quadrangle can be broken up into four thrust sheets, from east to west; Pollock Mountain, Rapid River, Morrison Ridge, and Seven Devils thrust sheets. Cretaceous plutons are present within the Pollock Mountain Thrust sheet.

PREVIOUS INVESTIGATIONS

Mining reports by multiple mine inspectors for hte state of idaho provide the earliest documentation of the rocks in the area around the Heavens Gate quadrangle. In the southern Seven Devils region, Livingston and Laney (1920) documented some of the earliest mining activities.

The earliest geologic mapping and documentation of the rocks in the Heavens Gate quadrangle produced was by Hamilton (1963) at a 1:125000 scale. Hamilton was the first to formulate any tectonic interpretations of the region, and hypothesized that metamorphism was occurring related to an intrusion of the 100-54 Ma Idaho batholith (Gaschnig et al., 2010). The Seven Devils volcanics mapped previously were only stratigraphically differentiated as the Seven Devils Group by Vallier (1967, 1977) in the Blue Mountains region later. The Seven Devils group was only mapped at a 1:125,000 scale by Lund (2004) until Nandi (2018) mapped the units at a 1:24,000 scale in the Purgatory Saddle quadrangle. The Salmon River suture zone (SRSZ) was mapped first by Aliberti (1988) and then Lund (2004) but at a large scale (1:125,000). The nearest published quadrangle, the Lucille 7.5-minute quadrangle (Lewis et al., 2011) maps the metamorphic rocks of the SRSZ at a 1:24,000 scale. There is a geologic transect map that covers the arc-continent boundary done by Gray (2013) and covers the top of the Heavens Gate quadrangle. This study provides structural fabrics for the various members of the Seven Devils group in detail, which can be compared to the structural data collected by this study to identify changes in the structural fabric throughout the region. Tectonic studies within the region determining accretion timing are generally split into two separate models, one of early and one of late collision. Structural relationships within terranes, U-Pb zircon ages of fault stitching plutons (Schwartz et al., 2010; 2011), and Garnet Sm-Nd ages of metamorphism (Getty et al., 1993; McKay et al., 2017), amongst others, have been conducted to attempt to determine what model of timing is more likely.

STRUCTURAL GEOLOGY

The Heavens Gate Quadrangle contains Permian-Triassic age strata originating in the Wallowa terrane that have been folded, potential folds in some mid crustal metamorphic rocks, as well as three major thrust faults which juxtapose increasingly higher grade metamorphic rocks atop lower grade rocks in the foot wall.

Along the western portion of the Heavens Gate quadrangle, rocks of the Wallowa terrane (Seven Devils) are folded, with a large anticline dominating the area, placing the Hunsaker Creek Formation in the center of Wild Sheep Creek Formation rocks. Additionally there are several smaller scale folds contained within the Wild Sheep Creek, with both anticlines and synclines being present. All folds discussed above plunge to the north east, and there is potentially some folding in the Martin Bridge Formation which is located across the Morrison Ridge Thrust Fault from the Seven Devils Rocks. If these faults continued across the fault boundary this means that they are predated by the fault and must have occurred later in the regions history.

Of the major thrust faults which traverse the quadrangle, all three are NNE-SSW striking, and east dipping. These split the region into thrust sheets which each contain rocks of differing characteristics.

The easternmost thrust, the Pollock Mountain thrust fault, separates mid-crustal orthogneiss and amphibolites within the Pollock Mountain thrust plate in the east, and the rocks of the Rapid River thrust to the west. The differences in the makeup of these rocks and thrust sheets are due to the differences in formation conditions for each. Those units within the Pollock Mountain thrust sheet formed with peak metamorphism occurring at temperatures of 700°C and at 7.5 kbar of pressure. This is in contrast to those rock units within the Rapid River thrust plate, which experienced peak metamorphism at ~650°C, and at >8 kbar. These differences in temperature and pressure suggest that the Pollock Mountain thrust fault may have played the role of a major crustal boundary as it seperates rocks from distinctly different metamorphic regimes. In the Heavens Gate quadrangle, The Pollock Mountain thrust fault cuts a 117 Ma tonalite pluton in the western portion of the map (McKay et al., 2017), and hornblende cooling ages record 118 ma cooling of the Pollock Mountain thrust plate suggesting displacement along the Pollock Mountain thrust fault ~118 Ma.

The Rapid River thrust fault places the midcrustal garnet-mica schists of the Riggins group above the Lucile slate in the footwall of the thrust. The Fiddle Creek, Lightning Creek Schist, and Squaw Creek Schists are thrust in slices by this west-directed thrust fault. Overriding all of these units is likely a splayed thrust sheet of Squaw Creek schist, which tectonically thickens the unit at the surface, accounting for the much thicker size of the unit. Hornblende cooling ages of 109-107 Ma (Lund and Snee, 1988) track exhumation of the Rapid River thrust plate, implying movement at this time.

The westernmost thrust, the Morrison Ridge thrust fault emplaces the lower greenschist facies rocks of the Lucille Slate and Martin Bridge Formation over top the Seven Devils Group. This thrust is cut by the by the Echols Mountain pluton, implying that the fault predates the plutonism. U-Pb zircon from a quartz diorite and tonalite int eh Deep Creek pluton records a 123 Ma age (Jeffcoat et al., 2013). If a similar age is assumed for the quartz diorite of the Echols Mountain pluton, movement along the Morrison Ridge fault must have occurred prior to 123 Ma.

Based on the age correlations above, it is apparent that the thrusting which occurred in the Heavens Gate quadrangle is out of sequence. The first activated thrust was the Morrison ridge fault, at pre-123 Ma, which was closely followed by the thrusting of the Pollock Mountain plate at around 118 Ma. This thrusting event is likely what loaded the Rapid River thrust plate to mid-crustal metamorphic conditions. The approximately 109 degree Ma Rapid River thrust fault was the final thrust fault to develop in the Salmon River suture zone. This occurred just before the uplift and extension of the rocks of the western Idaho shear zone (Giorgis et al., 2008; Schmidt et al. 2016).

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Table 1. Geochronology samples collected in the Heavens Gate quadrangle as of 2017

Sample ID	Reference	Isotopic system	Mineral phase	Age (Ma)	± (Ma)	MSWD	No. grains	Unit	Mapped unit
11ID58	McKay et al., 2017	U-Pb	Zircon	117.1	1.8	1.8	16 19	Tonalite	Kt
17IDSN528	*this study*	U-Pb	Detrital Zircon	193.9 189.2	4.6 3.6	2.4 1.0	6 (of 7) 4 (of 7)	Garnet, quartz biotite schist	JPsc
17IDMB427	*this study*	U-Pb	Zircon	216.4	1.3	1.48	23	Orthogneiss	Tdg
18IDSD162a	*this study*	U-Pb	Zircon	116	0.9	1.7	42	Tonalite	Kt
17IDMB506	*this study*	U-Pb	Zircon	116.1 176.1	4.1 3.0	0.15 3.01	2 (of 4) 2 (of 4)	Tonalite	Kt
17IDMB443	*this study*	U-Pb	Zircon	128.6 226.6	3.96 6.8	1.01 0.94	2 (of 4) 2 (of 4)	Tonalite	Kt
18IDSD51	*this study*	U-Pb	Zircon	139.04	3.34	24.5	7	Siliceous Tuff(?)	Tsu

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