EXTENSION AND VOLCANISM: TECTONIC DEVELOPMENT OF THE NORTHWESTERN MARGIN OF THE BASIN AND RANGE PROVINCE IN SOUTHERN OREGON

CHAPTER 1: INTRODUCTION TO PROBLEMS REGARDING TECTONISM OF THE NORTHWESTERN BASIN AND RANGE PROVINCE

This chapter summarizes principal research questions pertaining to the tectonic development of the northwestern corner of the Basin and Range Province in Oregon (NWBR) (Figure 1). This thesis takes a two-pronged approach to addressing these questions and is organized accordingly: (1) Assessment of the volcanic history of the NWBR through analysis of the style and composition of the products of magmatism in time and space within the province; and (2) Assessment of the deformational history of the NWBR through analysis of the structural development of the province. The primary goal of this thesis is to synthesis the results of these approaches, in hope that in doing so, a coherent model of the tectonic development of the NWBR will emerge.

Geophysical Characterization

The Basin and Range Province of the western United States has undergone a complex magmatic and structural history that reflects prolonged continental rifting since the early Tertiary. Seismic observations of the crust and uppermost mantle (Donath, 1962; Catchings and Mooney, 1988; Mooney and Braile, 1989; Allmendinger et al., 1987; Hearn et al., 1991) confirm this complexity and provide many of the physical constraints used to reconstruct the tectonic history of the region (Figure 1). Historic earthquakes (e.g., Qamar and Meagher, 1993) provide information about actively

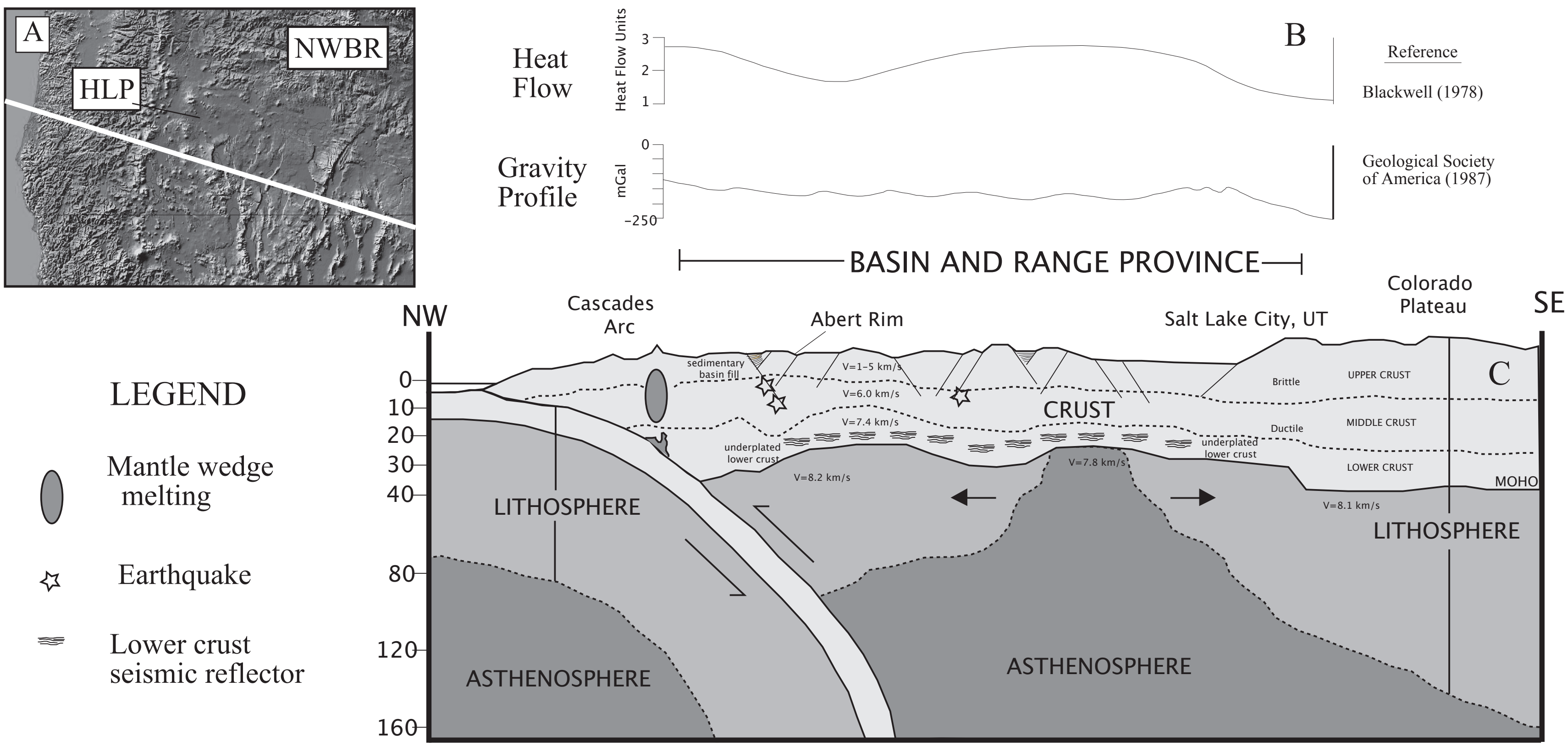

Figure 1. Physiographic and geophysical setting of the northwestern Basin and Range Province (NWBR) of southern Oregon. (A) DEM of NWBR illustrates declining relief of Basin and Range faults along-strike to the north and into the High Lava Plains (HLP). (B) Heat flow and gravity profiles accross the Basin and Range Province. (C) Schematic cross-section through the Basin and Range. Orientation of section shown by white line in panel A although entire section line not shown. 1.5x vertical exagerration for the uppermost 40 km of the section. Earthquake data from Qamar and Meagher (1993).

operating tectonic forces and the brittle-ductile transition within the crust. The addition of gravity and heat flow profiles provides a complimentary set of constraints, which collectively produce an image of the crust and uppermost mantle that displays these qualities: (1) a fairly uniform crustal thickness of 30-35 km, with an upper brittle part that is at most 16 km thick and a transition to ductile lower crust at ~20 km depth (2) asymmetrical rift grabens that are filled with 1.5-6 km of sedimentary and volcanic strata, (3) dense layering within the middle and lower crust thought to reflect ductile stretching and gabbroic underplating, (4) low-angle normal faults that extend to mid-crustal levels, (5) hot asthenosphere at depths ranging between 42-44 km, which lead to an elevated thermal state throughout the region, (6) a contemporary tectonic stress oriented ~N60˚W ± 20˚ that produces normal to right-oblique slip of as much as 6 mm/yr along faults (Pezzopanne and Weldon, 1993), (7) a bouguer gravity anomaly that lies between -150 to -200 mGals, and (8) high heat flow (2-2.5 HFU) particularly focused within the center and eastern margin of the province. These observations indicate the NWBR is a region of active continental rifting and that crust has been modified due to past episodes of extension and magmatism.

The NWBR: A Locus of Volcanism

Belts of intermediate composition magmatism within the interior of the Basin and Range Province broadly correlate with intervals of extreme Tertiary rifting (Armstrong and Ward, 1991). During the Quaternary magmatism has focused outward towards the margins of the Basin and Range province relative to a more central locus during the Tertiary (Christiansen and McKee, 1978). For these reasons, most volcanic rocks exposed within the NWBR are younger than Middle Miocene Steens flood basalt volcanism that essentially buried Early Tertiary and older rocks within a vast portion of southeastern Oregon (e.g., Johnson et al., 1998; Walker and MacLeod, 1991). Late Miocene mafic to bimodal basalt-rhyolite volcanism of the High Lava Plains (HLP) (Jordan et al., 2004) has obscured the older geology even more.

Isolated Early Miocene volcanoes of intermediate composition (andesite-dacite) are identified within the NWBR (e.g., Mathis, 1993; Thomas, 1981) and are intriguing targets for study because they possess promise for understanding the post-Laramide transition from Cretaceous subduction and calc-alkaline volcanism and plutonism to Late Miocene extension and primarily mafic volcanism within the Basin and Range Province. This transition is clear elsewhere in the Basin and Range but is not well established within the NWBR where the Late Miocene geologic history is complicated. For example, the region is likely affected by the Yellowstone hotspot (e.g., Jordan et al., 2004) or mantle flow produced by the northward motion of the Menodcino Triple Junction with respect to North America (Christiansen et al., 2002). Therefore, the coincidence of the High Lava Plains with the NWBR (Figure 1) is not well understood.

The NWBR: A Young Extensional Province

Continental deformation of the western margin of North America, due to Post-Laramide reorganization of the plate boundary (e.g., Christiansen and Yeats, 1991), is recorded by the formation of the vast Basin and Range extensional province (e.g., Wernicke, 1992) and the development and growth of intracontinental transform fault systems such as the San Andreas and Walker Lane fault systems (Figure 2) (Atwater and

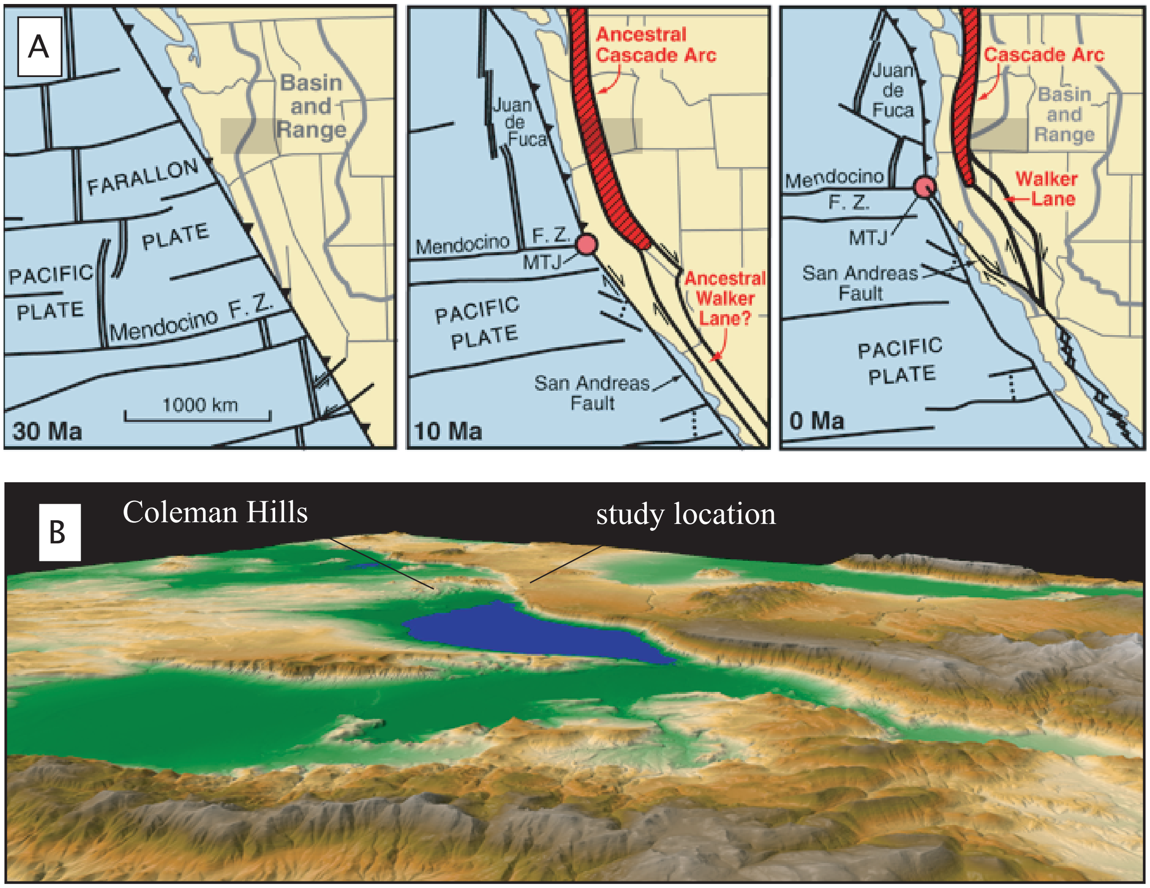

Figure 2. (A) Model reconstruction of the tectonic development of the western margin of the U.S. since ~30 Ma. Box indicates position of the NWBR and the ocus of this study. Based on work of Atwater and Stock (1998) and modified from Faulds et al. (2005). (B) Oblique DEM of the Lake Abert Basin and Abert Rim fault. View to NE. 2x vertical exaggeration. The junction of the Coleman Hills with Abert Rim is primary region of sampling and geologic mapping.

Stock, 1998; Faulds et al., 2005). Numerous models describe driving forces that facilitate expansion of the Basin and Range Province. These include: Subduction zone roll-back (Humphreys, 1994), clock-wise rotation of the Cascadia forearc (Wells and Heller, 1998), northward propagation of intracontinental transform faults (Faulds et al., 2005), and collapse of the overthickened Laramide crust due to excess gravitational potential energy (Humphreys and Coblentz, 2007).

Active Basin and Range extension was established in the NWBR sometime after 12 Ma based on previous work in the area (Dilles and Gans, 1995; Surpless et al., 2002; Colgan et al., 2004). Along-strike propagation of the Walker Lane transfers extensional strain to the north, which may correlate with the arrival of extension in southern Oregon. The NWBR is characterized by two principal sets of faults that strike NW and NNE and cut Late Cenozoic volcanic units. The temporal development of these faults has not been established.

The Abert Rim fault (Figure 2B) is the type of structure where questions about timing and style of Basin and Range faulting can be addressed. The Abert Rim fault is one of the major structures in Oregon (the trace is > 100 km) and systems of NW-striking faults interact with the NNE-striking Basin and Range fault at the north end of Lake Abert, a large playa that lies in the hanging wall of the fault. Topographic and presumably stratigraphic separation on the fault declines along-strike to the north and the area is characterized by a protracted Miocene volcanic history.

RESEARCH QUESTIONS

1. What are causes for a change form calc-alkaline to mafic/bimodal magmatism within the NWBR?
2. Are intermediate Early Miocene volcanoes within the NWBR part of the ancestral Cascades volcanic arc?
3. When did extension arrive in southern Oregon, and what were the tectonic controls on its arrival?
4. How did extension expand into the NWBR? Along-strike propagation from the south? Across-strike propagation from the east? Both?
5. What is the relative temporal development of NW- vs. NNE-striking faults of the NWBR?
6. Are the patterns of Late Miocene faults of the NWBR formed solely in response to regional stress or are their orientations affected by an older tectonic fabric?

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CHAPTER 2

TRANSITION FROM INTERMEDIATE TO BIMODAL VOLCANISM IN THE NORTHWESTERN BASIN AND RANGE PROVINCE: COMPOSITIONAL EVOLUTION AND TECTONIC IMPLICATIONS

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ABSTRACT

Volcanic rocks exposed at the north end of Lake Abert in southern Oregon preserve an Early Miocene volcano incompletely buried by Late Miocene volcanic units. Exposure of Early Miocene volcanic centers in southern Oregon are uncommon and chemical and geologic description of them adds to an understanding of the transition from subduction-related to rift-related volcanism along the western margin of North America. Early Miocene volcanic units of the Coleman Hills consist primarily of intermediate rocks (SiO_2 = 55-65 wt. %) that intrude and overlie a core of rhyolite domes and associated pyroclastic deposits (SiO_2 = 70-72 wt. %).

Trace element concentrations suggest that the Early Miocene rocks were not generated within an active arc but instead formed in a back-arc region that had been metasomatized by prior subduction. Volcanic rocks of the Coleman Hills exhibit isotopic ratios that indicate generation in a crustal environment, such as elevated $^{208}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{206}Pb/^{204}Pb$ and lower $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$, relative to the onlapped Late Miocene volcanic section. $^{87}Sr/^{86}Sr$ ratios are the same for intermediate compositions of the Coleman Hills and Late Miocene lavas although rhyolite of the Coleman Hills has much higher values (0.7051 vs. 0.7037) suggesting that they are the product of crustal anatexis

INTRODUCTION

The geologic history of the Basin and Range Province in southeastern Oregon (Figure 1A) is difficult to unravel because exposures older than 16.6-15.3 Ma (Hooper et al., 2002) are largely covered by flood basalts associated with Steens Mountain (e.g., Johnson et al., 1998) and by post-10 Ma bimodal basalt-rhyolite volcanism of the High

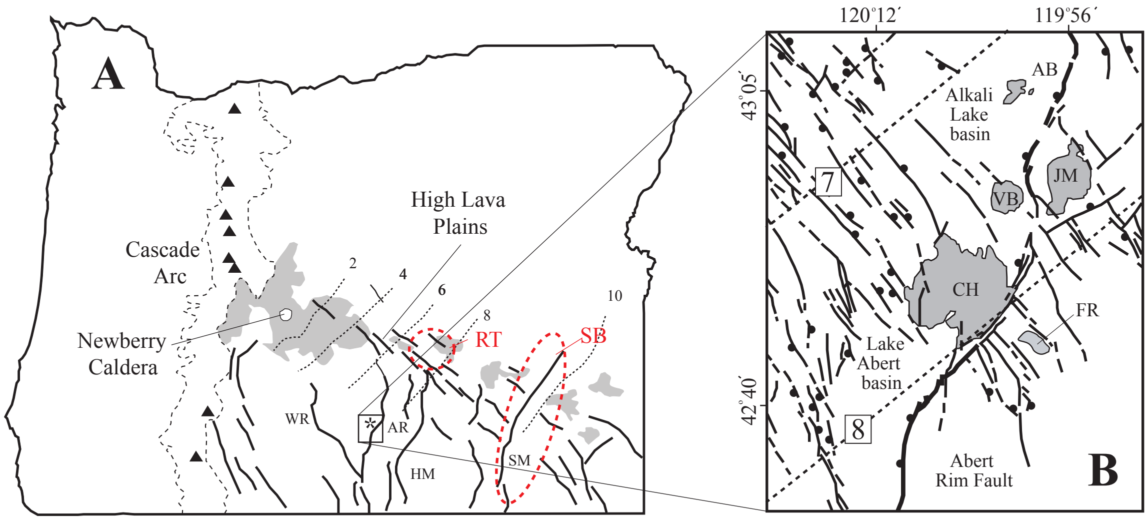

Figure 1. (A) regional volcano-tectonic setting of the Basin and Range margin in southern Oregon and (B) detailed structral fabric of the study area. (A) Quaternary mafic volcanism of the Cascade Arc to the west and the High Lava Plains (HLP) to the north border Basin and Range extension accross southern Oregon. Primary source of Middle Miocene Steens Basalts (SB) and Late Miocene Rattlesnake Tuff (RT) are shown in red. Prominent regional escarpments are labeled: WR-Winter Rim; AR-Abert Rim; HM-Hart Mountain; SM-Steens Mountain. The HLP is defined by a track of Quaternary basalts (shade) where isochrons (thin stippled line) show an age-progressive westward trend for the onset of silicic volcanism (in Ma) after Jordan et al., 2004. (B) The Coleman Hills (CH) are one of many volcanic centers (shaded polygons) associated with the convergence of NW-striking structures and the NE-striking Abert Rim Fault. AB- Alkali Butte; VB- Venator Butte; JM- Juniper Mountain; FR=Flint Ridge.

Lava Plains (HLP) (e.g., Walker and Nolf, 1981; Jordan et al., 2004). Prior to ~16 m.y., much of the Basin and Range Province was characterized by sweeping belts of intermediate composition magmatism, broadly related to extreme extension (e.g., Stewart and Carlson, 1974; Armstrong and Ward, 1991). Since then volcanism has focused to the margins of the extensional province (Christiansen and McKee, 1978). The widely distributed Middle Tertiary calcalkaline magmatism of the Basin and Range Province has been principally attributed to (a) shallow subduction followed by delamination of the slab from the base of the lithosphere with attendant mantle upwelling (Coney and Reynolds, 1977) and (b) extreme extension of thickened Laramide crust via low-angle detachment faulting (e.g., Armstrong and Ward, 1991; Wernicke, 1992).

The transition from Middle Tertiary calcalkaline magmatism to Late Tertiary and Quaternary, bimodal basalt-rhyolite magmatism is not well established in the northwestern corner of the Basin and Range Province, in southeastern Oregon. This region has seen little geologic study compared with much of the Basin and Range Province despite a complex tectonic setting and protracted post-Laramide volcanic history (e.g., Christiansen and Yeats). The Late Cenozoic geologic history of southeastern Oregon is complex with respect to tectonic influences. On the one hand, part of the transition from intermediate calc-alkaline to basaltic volcanism is similar to what is observed during evolution of the margins of the Basin and Range Province in general (e.g., Christiansen and McKee, 1978). On the other hand, the region is potentially influenced by the Yellowstone hotspot (e.g., Jordan et al., 2004) or mantle flow related to northward migration of the Mendocino Triple Junction (e.g., Christiansen et al., 2002). The Cascade Arc and High Lava Plains form the western and northern borders, respectively, to the extensional province in Oregon (Figure 1). The HLP has been interpreted as part of the Yellowstone hotspot system due to a westward age-progression in younger rhyolite volcanism (e.g., Draper, 1991; Jordan et al., 2004) that mirrors the eastward trend observed on the Snake River Plain (e.g., Pierce and Morgan, 1992).

This paper addresses the Coleman Hills, an Early Miocene volcanic complex associated with the Abert Rim, a major Basin and Range escarpment in southern Oregon (Figure 1B). Magmatism of the Coleman Hills volcanic complex provides important information about the tectonic transition from Middle Tertiary volcanism to Late Cenozoic extension within a young margin of the Basin and Range Province. The occurrence of the volcanic center at the intersection of NW- and NE-striking faults, characteristic of the Late Cenozoic structural fabric of the region, brings to question the role of older episodes of deformation in the evolution of younger extensional fault systems within the Basin and Range Province. The Coleman Hills provide insight into crustal processes that controlled the composition of magmas prior to Late Miocene block-style faulting of the Basin and Range Province. We here present new compositional and isotopic (Nd, Sr, Pb, and Hf) data from the Early Miocene section of the Coleman Hills and Late Miocene volcanic strata exposed in the vicinity of Lake Abert, OR. We consider the compositional and structural development of the Coleman Hills and environs with respect to the crustal development of the Basin and Range extensional province.