Petrogenesis of Eocene calc-alkaline magmatism at Electric Peak and Sepulcher Mountain, Absaroka Volcanic Province, Montana and Wyoming
by Charles Roger Lindsay

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University

Abstract:
Electric Peak and Sepulcher Mountain represent the well-exposed intrusive and extrusive components of an early Eocene eruptive center in the Absaroka volcanic province of Montana and Wyoming. Geological field relationships, petrographic analysis, and mineral and whole rock geochemical compositions were used to investigate the petrogenesis of this eruptive center. The Electric Peak stock has an outcrop area of ~lkm3 and consists of six intrusive phases ranging in composition from quartz diorite to granite, representing multiple intrusions of compositionally distinct magmas. Stratigraphic constraints and Al-in-hornblende geobarometry indicate that these magmas stalled and solidified at a depth of ~3 km. Lava flows and dikes at Sepulcher Mountain are basaltic-andesitic to rhyolitic in composition and silicic rocks are peripheral to mafic rocks. Collectively, intrusive and extrusive rocks represent a medium- to high-K, calc-alkaline, comagmatic suite. Important geochemical characteristics of these rocks include high Ni and Cr concentrations in andesitic and dacitic rocks, lower rare earth element concentrations in evolved rocks relative to more mafic rocks, non-uniform Sr and Nd isotopic ratios, and strong relative depletions in high field strength elements relative to large ion lithophile elements. Although petrographic evidence permissive of magma mixing is limited, quantitative petrogenetic modeling demonstrates that intermediate composition rocks are hybrids formed by mixing of variably fractionated and contaminated mantle-derived mafic magmas with diverse composition crustal-derived silicic magmas and their differentiates. Chemical compositions indicate that mafic magmas were derived from ancient, enriched lithospheric mantle and that silicic magmas represent partial melts of amphibolitic crust leaving restites with variable modal mineralogy. The significance of these results is that a considerable crustal component was involved in generating Eocene calc-alkaline magmas in the Absaroka volcanic province.

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

Electric Peak and Sepulcher Mountain represent the well-exposed intrusive and extrusive components of an early Eocene eruptive center in the Absaroka volcanic province of Montana and Wyoming. Geological field relationships, petrographic analysis, and mineral and whole rock geochemical compositions were used to investigate the petrogenesis of this eruptive center. The Electric Peak stock has an outcrop area of ~1km^3 and consists of six intrusive phases ranging in composition from quartz diorite to granite, representing multiple intrusions of compositionally distinct magmas. Stratigraphic constraints and Al-in-hornblende geobarometry indicate that these magmas stalled and solidified at a depth of ~3 km. Lava flows and dikes at Sepulcher Mountain are basaltic-andesitic to rhyolitic in composition and silicic rocks are peripheral to mafic rocks. Collectively, intrusive and extrusive rocks represent a medium- to high-K, calc-alkaline, comagmatic suite. Important geochemical characteristics of these rocks include high Ni and Cr concentrations in andesitic and dacitic rocks, lower rare earth element concentrations in evolved rocks relative to more mafic rocks, non-uniform Sr and Nd isotopic ratios, and strong relative depletions in high field strength elements relative to large ion lithophile elements. Although petrographic evidence permissive of magma mixing is limited, quantitative petrogenetic modeling demonstrates that intermediate composition rocks are hybrids formed by mixing of variably fractionated and contaminated mantle-derived mafic magmas with diverse composition crustal-derived silicic magmas and their differentiates. Chemical compositions indicate that mafic magmas were derived from ancient, enriched lithospheric mantle and that silicic magmas represent partial melts of amphibolitic crust leaving restites with variable modal mineralogy. The significance of these results is that a considerable crustal component was involved in generating Eocene calc-alkaline magmas in the Absaroka volcanic province.

CHAPTER 1

INTRODUCTION

A widespread magmatic event affected northwestern North America during the Eocene, emplacing several large igneous provinces throughout the Cordillera and adjacent foreland (Figure 1). The genesis of this magmatic activity remains poorly understood as reflected by the numerous contrasting models that have been proposed to account for it (e.g. Lipman and Glazner, 1991; Lipman, 1992). As one of the largest volcanic fields in this region, the Absaroka volcanic province (AVP; Figure 1) is similarly difficult to place in a proper tectonomagmatic context. Understanding the magmatic processes involved in the evolution of individual eruptive centers is critical to unraveling the origin of the volcanic field as a whole. Therefore, this study investigates the petrogenesis of Electric Peak and Sepulcher Mountain, the well-exposed intrusive and extrusive components of a moderate-volume, calc-alkaline, early Eocene eruptive center in the AVP. Specifically, the goals of this study are to (1) document the compositional ranges of extrusive and intrusive rocks present; (2) characterize the relationship between intrusive rocks at Electric Peak and extrusive rocks at Sepulcher Mountain; and (3) evaluate the possible roles of different petrogenetic processes in producing the compositional diversity of these rocks.

Electric Peak and Sepulcher Mountain were chosen for this study for two reasons. First, there are few contemporary petrologic studies of calc-alkaline eruptive centers in the AVP (Hiza, 1999; Feeley et al., *in press*). Second, intrusive bodies at Electric Peak

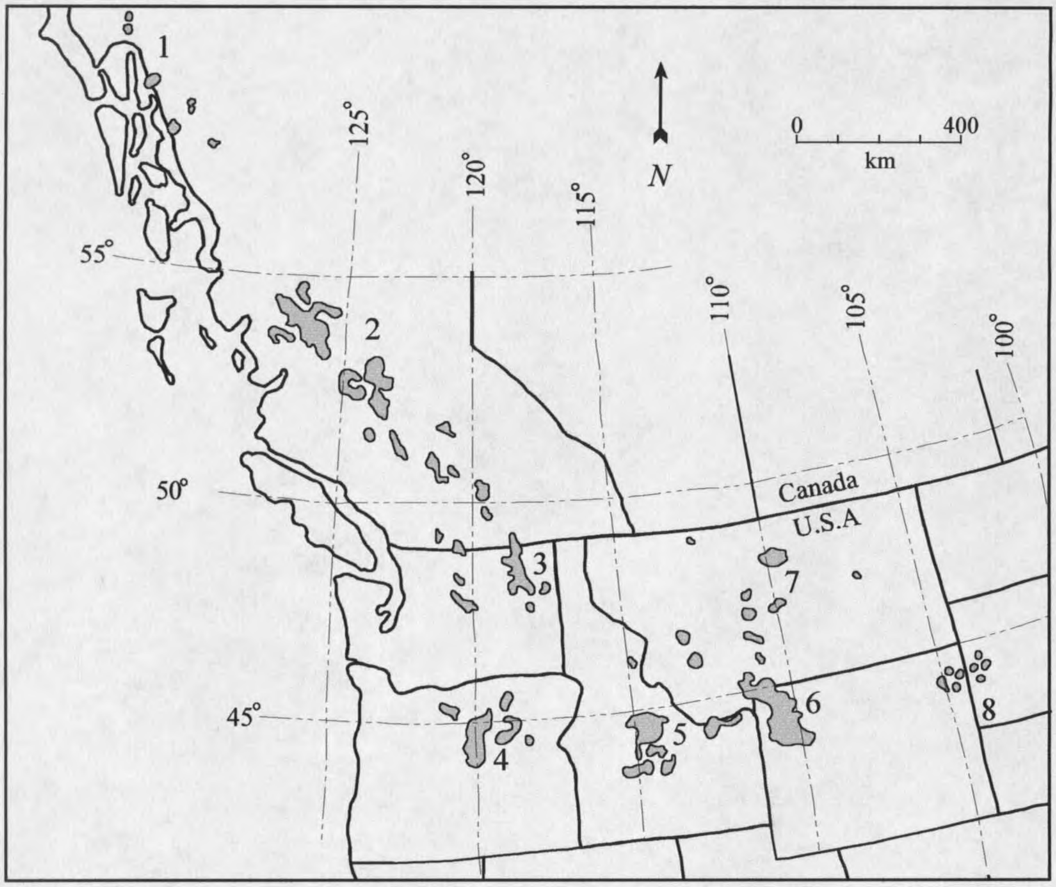

Figure 1. The northwestern United States and Canadian Cordillera showing the location of early- to middle-Eocene volcanic fields (adapted from Chadwick, 1985; Armstrong, 1988; Dudas, 1991; Norman and Mertzman, 1991; Luedke, 1994; and Morris et al., 2000). Numbers refer to: 1. Sloko volcanic province, 2. Francois Lake igneous complex, 3. Colville igneous complex, 4. Clarno volcanics, 5. Challis volcanic province, 6. Absaroka volcanic province, 7. Montana alkalic province, 8. Black Hills-Bear Lodge Mountains igneous centers.

are thought to represent subvolcanic intrusive bodies related to extrusive rocks at Sepulcher Mountain (Iddings, 1891; Smedes and Prostka, 1972), but no genetic relationship has been established, and thus they have never been formally included in the Absaroka Volcanic Supergroup (Smedes and Prostka, 1972).

Significance of Eocene Magmatism in the Northern Cordillera

Eocene igneous provinces are distributed throughout the northern Rocky Mountains forming a belt that stretches from southern Yukon to Wyoming. This belt is relatively narrow in British Columbia (~70-300 km) and is diffuse (~1400 km) in the northwestern United States between 43° and 48° north latitude (Figure 1). Collectively, these igneous provinces were originally interpreted as an early Tertiary magmatic arc (Lipman et al., 1972; Coney and Reynolds, 1977), analogous to those formed above modern subduction zones (e.g. the Cascade and Andean arcs). This "arc" is sometimes referred to as the "Challis Arc", although in this study it is termed the Eocene magmatic belt.

Two notable features of the Eocene magmatic belt are its width between 43° and 48° north latitude and the number of discrete igneous provinces located within this region (Figure 1). Three large (>15,000 km^3), roughly contemporaneous volcanic fields, the Clarno (~47-34 Ma; Vance, 1988; Urbanczyk and Lilligren, 1990), Challis (~51-40 Ma; Norman and Mertzman, 1991), and Absaroka (~55-38 Ma; Hiza, 1999; Lindsay et al., 2000; Feeley et al., *in press*) fields, are located across this region. Four smaller areas situated across this region were also strongly affected by Eocene magmatism. These include the Colville igneous complex, Montana alkalic province, and the Black Hills-

Bear Lodge Mountains igneous centers. Petrologic investigations of these igneous provinces over the last four decades have documented the chemical compositions of rocks present, allowing for general comparison.

Rocks with either calc-alkaline or alkaline-potassic geochemical affinities characterize Eocene igneous rocks across this region. Calc-alkaline rocks are volumetrically dominant and include intermediate (~54-65 wt % SiO_2), high-alumina (>15 wt % Al_2O_3), and low- to high-K (LeMaitre et al., 1989) compositions. These compositions are typical of rocks documented at the Challis (Norman and Mertzman, 1991) and Absaroka (Chadwick, 1970) volcanic fields as well as at the Colville igneous complex (Morris et al., 2000). Alkaline-potassic rocks are generally strongly silica undersaturated (Ne-normative, $\leq$30%), potassic ($K_2O/Na_2O \approx 1.0$-6.0), and predominately mafic, compositions typical of rocks documented across the Montana alkalic province and at the Black Hills-Bear Lodge Mountains igneous centers (Jenner, 1989).

Lipman et al. (1972) first recognized that the distribution of calc-alkaline and alkaline-potassic rocks across this region reflects generally increasing K_2O contents eastward across the region. Although rocks from a specific igneous province generally exhibit either calc-alkaline or alkaline-potassic affinities, both types also occur in close proximity at the Crazy Mountains in the Montana alkalic province (Dudás, 1991) and at the Independence volcano in the AVP (Meen and Eggler, 1987). In addition to exhibiting either calc-alkaline or alkaline-potassic affinities, widely distributed igneous rocks from across the Eocene magmatic belt display remarkable chemical similarities to each other and to rocks found at modern volcanic arcs.

Striking features shared to some extent by both calc-alkaline and alkaline rocks from the Eocene magmatic province are high abundances of large ion lithophile elements (LILE) relative to abundances of high field strength elements (HFSE). For example, extreme LILE abundances of Ba >1000 ppm, Sr >450 ppm, and Rb >60 ppm and HFSE abundances of Zr <200 ppm, Nb <20 ppm, Ta <2.0 ppm, and Ti <6000 ppm are typical of rocks from the Colville igneous complex, (Morris et al., 2000), Challis volcanic field (Norman and Mertzman, 1991), Absaroka volcanic province (Meen, 1987), and Montana alkalic province (Dudás, 1991). Enrichment in LILE relative to HFSE is considered a characteristic geochemical signature of arc-related igneous rocks (Pearce and Norry, 1979; Perfit et al., 1981). Specifically, values of Ba/Ta >450 and Ba/Nb >25 are considered diagnostic of subduction-related magmatism (Gill, 1981). In light of these parameters, a cursory interpretation of these compositions might suggest the involvement of a subduction-related component.

Petrogenetic hypotheses regarding the origin of these igneous rocks are both varied and controversial, and strikingly different tectonomagmatic models have been proposed for their origin. Recognition of the predominately calc-alkaline nature of rocks emplaced contemporaneously with subduction of the Farallon Plate beneath western North America led early workers to develop models that related these rocks to subduction. Eastward increasing potassium contents across the magmatic belt were thought to represent increasing depth to the subducting Farallon Plate and, therefore, increasing interaction of subduction-related magmas with continental crust (K-h relationship of Dickinson and Hatherton, 1967). Lipman et al. (1971) interpreted the changing compositions of rocks and distribution of igneous activity across the belt in relation to evolving subduction geometry between the North American and Farallon Plate and suggested that an "imbricate" double subduction zone was responsible for producing arc-like magmatism far inland from the Eocene trench. Further research modified this hypothesis, suggesting that changing plate convergence rates caused the dip of the subducted slab to shift from steep to shallow angles, resulting in temporally shifting loci of arc-like magmatism across a broad region (Bird, 1984; Ward, 1995). Eocene calc-alkaline and alkaline-potassic rocks from the Crazy and Highwood Mountains of the Montana alkalic province are currently interpreted to represent subduction-related magmas (O'Brien et al., 1991; du Bray and Harlan, 1996).

Other studies, although acknowledging that Eocene igneous rocks exhibit a "subduction-related geochemical signature", recognize a close spatial and temporal association between magmatism and large-scale crustal extension. This relationship is well documented at the Challis volcanic field (Norman and Mertzman, 1991) and Colville igneous complex (Morris et al., 2000) and has also been proposed for the AVP (Hiza, 1999). Petrogenetic models developed for these regions suggest that regional extension led to consequent decompression partial melting of the upper mantle and lower crust. The arc-like geochemical signature is interpreted as being inherited by Eocene magmas through interaction with, or derivation from, lithospheric mantle (Dudás, 1991) and continental crust (Morris et al., 2000) that was chemically "enriched" through pre-Eocene subduction-related magmatism. Alternatively, some researchers argue that Eocene magmatism across this region cannot be explained by simple subduction or extension related models and suggest that it may not be possible to identify a single causative melt-generation process or simple tectonomagmatic setting for Eocene magmatism in northwestern North America (Meen and Eggler, 1987; Dudás, 1991; Irving and O'Brien, 1991; MacDonald et al., 1992).

The compositional significance and origin of Eocene magmatic rocks in the AVP remain poorly understood. One of the outstanding problems in deciphering the regional significance of the AVP is that petrologic data have been obtained from only a small fraction of the magmatic rocks exposed. Most previous studies have concentrated on mineralized areas and nearly all geochemical data is based on small sets of major-element analyses from widely separated localities (Chadwick, 1970; La Pointe, 1977; Nelson et al., 1980). Thus, the relative contributions of mantle, crustal, and potentially subducted sources to parental magmas and their subsequent differentiation processes are not well known. This study presents new information on the petrogenesis of a calc-alkaline magmatic center in the AVP and contributes to studies whose ultimate goal is to better understand the origin and tectonic significance of this large-scale Eocene magmatic event.

CHAPTER 2

GEOLOGIC SETTING

Tectonic Setting

The AVP is bordered on the west by the Yellowstone Plateau, on the northwest by the Madison Range, on the northeast by the Beartooth Mountains, on the east by the Bighorn Basin, and on the south by the Wind River Basin. The volcanic province occupies the Absaroka basin, a shallow Laramide foreland basin (Sundell, 1993) that formed concurrently with surrounding basement-cored uplifts exposed in the Washakie, Gallatin-Madison, and Beartooth mountain ranges. The majority of these uplifts experienced episodic contractional deformation from late Cretaceous through middle Eocene time (Schmidt and Garihan, 1983; Winterfield and Conrad, 1983). The AVP rests unconformably on deformed Paleozoic to Mesozoic carbonate and clastic sedimentary strata and on high-grade metamorphic and igneous rocks of the Wyoming Province, an Archean granite-gneiss craton that underlies much of Wyoming, Montana, and southeastern Idaho. Seismic refraction studies indicate that the crust beneath the AVP at present is ~45-50 km thick (Prodehl and Lipman, 1989) and lithospheric thickness is estimated to be at least 170 km thick based on the presence of a weak low-velocity zone at 170-225 km depth (Iyer and Hitchcock, 1989). Although the composition of the deep crust beneath the AVP is poorly constrained, an amphibolitic to granulitic lower-crust is inferred through geochemical evidence (Meen and Eggler, 1989) and xenolith geothermobarometry (Joswiak, 1992).

Regional extension associated with crustal thinning and development of metamorphic core complexes occurred during the early-to-mid Eocene in northeastern Washington (Morris and Hooper, 1997), north-central Idaho (Wust, 1986; Janecke, 1992; Janecke and Snee, 1993), and westernmost Montana (Foster and Fanning, 1997). Although contemporaneous with magmatism in the AVP, little evidence is documented for major Eocene extensional faulting within or directly adjacent to the AVP. Both listric and normal faults have been recognized and mapped across the AVP, but they are not acknowledged as products of regional extension (Montagne and Chadwick, 1982; Sundell, 1993). It has also been suggested that the Heart Mountain detachment may be associated with regional extensional faulting (Hiza, 1999), but there is little conclusive evidence to support this relationship. The Heart Mountain detachment is a shallow-rooted, bedding-parallel, low-angle normal fault that accommodated transport of the hanging wall for a distance of 50 km or more (Hauge, 1993). It appears to represent a structure associated with large-scale, eastward-directed, gravitational sliding of a growing volcanic highland (Hauge, 1985) and not regional crustal extension.

Magmatism in the AVP occurred between 55 and 38 Ma (Hiza, 1999; Lindsay et al., 2000; Feeley et al., *in press*), apparently during a transitional period in the tectonic framework of the northern Rocky Mountains. The earliest eruptions occurred directly after, but possibly overlapping with the last phases of Sevier- and Laramide-style contractional deformation (Love et al., 1975; Sundell, 1993). Magmatism also coincided with the onset of regional crustal extension in the northern Rocky Mountains directly west of the AVP (Burchfiel et al., 1992; Janecke and Snee, 1993; Foster and Fanning, 1997). Thus, magmatism in the AVP occurred during period critical to understanding the tectonomagmatic framework of the northern Cordillera in the early Tertiary period.

Physical Volcanology of the AVP

Encompassing an area of approximately 23,000 km^2 with a maximum thickness of 1500 m, the AVP is one of the most voluminous Eocene volcanic fields in the northern Cordillera (Steven et al., 1972). The inferred depositional setting for the AVP is an approximately 90 km wide belt of large stratovolcanoes, shield volcanoes, and dike swarms flanked by coalescing alluvial aprons (Sundell, 1993). Volcaniclastic rocks are volumetrically dominant and include volcaniclastic sandstone, siltstone, claystone, conglomerate, and breccia (Smedes and Prostka, 1972). Intercalated primary volcanic rocks increase in abundance near eruptive centers and include effusive lava flows, flow breccias, and domes as well as pyroclastic flow and fall deposits. Hypabyssal intrusive bodies are common at many of the eruptive centers and include dikes, sills, ring dikes, cone sheets, plugs, stocks, and laccoliths (Parsons, 1969).

Smedes and Prostka (1972) defined the Absaroka Volcanic Supergroup to include all volcanic rocks within the AVP as well as associated outliers erupted or deposited during the Eocene. They defined three stratigraphic divisions: the Washburn, Sunlight, and Thorofare groups. Rocks exposed at Sepulcher Mountain represent the type section for the Sepulcher Formation, the western member of the Washburn Group. The aerial distribution of these groups (Figure 2) and stratigraphic divisions are, however, currently under revision (e.g. Sundell and Eaton, 1982; Hiza, 1999).

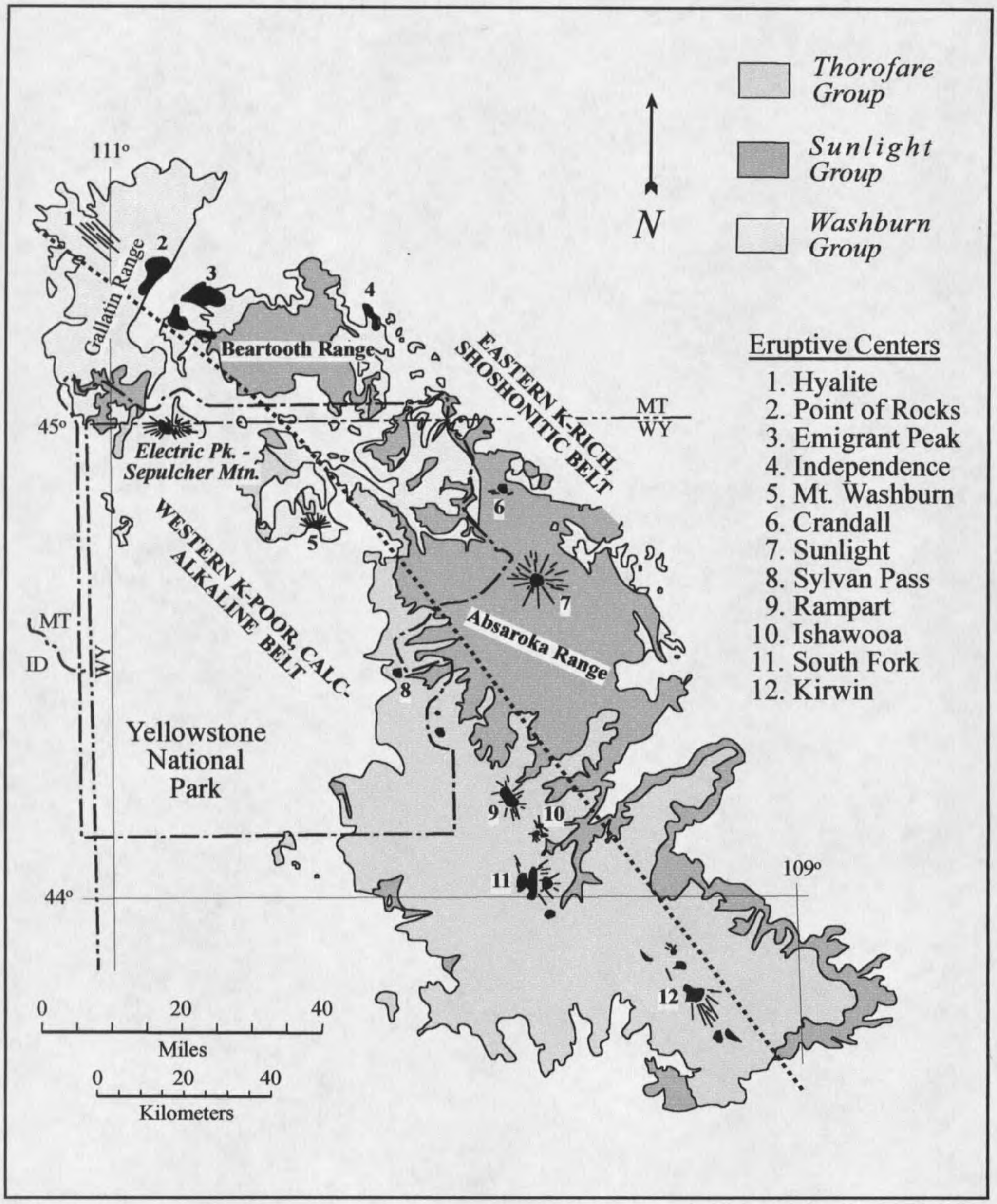

Figure 2. Generalized geologic map of the Absaroka volcanic province showing spatial extent of the major stratigraphic divisions of the Absaroka Volcanic Supergroup (modified from Smedes and Prostka, 1972; Chadwick, 1970) and location of the Electric Peak - Sepulcher Mountain eruptive center. Other eruptive centers discussed in the text are numbered for reference. Thick dashed line shows the approximate division between western potassium-poor and eastern potassium-rich belts (after Chadwick, 1970). Single dot-dashed line is the boundary of Yellowstone National Park.

Eruptive styles within the AVP were varied and are represented by Plinian airfall deposits (Sundell and Eaton, 1982), Hawaiian-style dike-fed lava flows and lava lakes (Nelson and Pierce, 1968), as well as deposits from Vesuvian-, Strombolian-, and Pelean-style eruptions (Wilson, 1964; Rubel, 1971; LaPointe, 1977). In addition, the Castle Rocks "chaos" is interpreted to be the deposit of a stratovolcano sector collapse that was one hundred times larger than that of the 1980 Mt. St. Helens eruption (Sundell, 1985). Although significantly eroded, edifice types likely included composite cones, shield volcanoes, silicic domes, small Mt. Mazama-sized calderas, and dike swarms. Paleo-relief was likely greater than 3,000 m between the highest terrain (stratovolcanoes) and adjacent lowlands (alluvial aprons) based on compositional and morphological differences in fossil fauna and flora (Fritz, 1982; Yuretich, 1984).

Across-Strike Geochemical Variations

Thirteen distinct eruptive centers are presently recognized in the AVP and are aligned along two sub-parallel belts (Figure 2). Chadwick (1970) interpreted these lineaments as Precambrian structures that were reactivated during the Laramide Orogeny. On the basis of major element compositions from ~50 rocks from nine eruptive centers, Chadwick (1970) demonstrated that the two sub-parallel belts of eruptive centers exhibit significant compositional differences with respect to potassium content and differentiated a western "K-poor" calc-alkaline belt and an eastern "K-rich" shoshonitic belt (Figure 2). These across-strike variations in potassium content are similar to those observed at many subduction-related volcanic arcs (e.g. Gill, 1981; Tatsumi and Eggins, 1995) although the petrogenetic origin of these variations in the AVP is unclear.