MONTANA STATE UNIVERSITY

Miocene calc-alkaline volcanism in southern Jackson Hole, Wyoming : evidence of subduction-related volcanism
by David Congdon Adams

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University
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Abstract:
Late Miocene lava flows in southern Jackson Hole are distinctly intermediate, calc-alkaline in composition in contrast to the bimodal basalt-rhyolite assemblages characteristic of most Neogene volcanic rocks in the Yellowstone Plateau-Snake River Plain region. Despite limited stratigraphic continuity between units, geochemical and petrographic analysis reveals strongly unifying and distinctive features. Silica variation diagrams are remarkably coherent, suggesting a co-genetic, if not co-magmatic, origin. As a whole, these rocks are significantly lower in K and Fe and higher in Ca and especially Mg than rocks of similar silica content from the Snake River Plain and Yellowstone. The basaltic andesites in particular are characterized by abundant olivine phenocrysts (Po 80-90) and extremely high Ni (200 ppm) and Cr (550 ppm) values. Within the suite, basaltic andesites and andesites (54-58% SiO2, with olivine and augite) differ from dacites (60-62% SiO2, aphyric or hornblende-rich) which differ from rhyodacites (66-69% SiO2, with hypersthene and rounded andesine) and rhyolites and obsidian (73-75% SiO2). Both geochemical and petrographic features suggest involvement of varying degrees of crustal contamination and/or magma mixing, especially in the more silicic rocks.

Low 143Nd/144Nd ratios in this suite clearly distinguish it from the Yellowstone-Snake River Plain volcanics and suggest the absence of asthenospheric input, precluding melt generation due to convective heat transfer. A possible melting mechanism is suggested by the high Ba/Nb values of these rocks, a feature considered diagnostic of involvement of subducted slab-derived hydrous flux in melt generation. It is proposed that a fragment of subducted slab detached as the Cascade subduction zone was disrupted by the inception of the Yellowstone mantle plume was buoyed and transported eastward, where its descent and dehydration beneath western Wyoming produced calc-alkaline magmas by solidus depression in the lithospheric mantle and lower crust.

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ABSTRACT

Late Miocene lava flows in southern Jackson Hole are distinctly intermediate, calc-alkaline in composition in contrast to the bimodal basalt-rhyolite assemblages characteristic of most Neogene volcanic rocks in the Yellowstone Plateau-Snake River Plain region. Despite limited stratigraphic continuity between units, geochemical and petrographic analysis reveals strongly unifying and distinctive features. Silica variation diagrams are remarkably coherent, suggesting a co-genetic, if not co-magmatic, origin. As a whole, these rocks are significantly lower in K and Fe and higher in Ca and especially Mg than rocks of similar silica content from the Snake River Plain and Yellowstone. The basaltic andesites in particular are characterized by abundant olivine phenocrysts (Fo 80-90) and extremely high Ni (200 ppm) and Cr (550 ppm) values. Within the suite, basaltic andesites and andesites (54-58% SiO_2, with olivine and augite) differ from dacites (60-62% SiO_2, aphyric or hornblende-rich) which differ from rhyodacites (66-69% SiO_2, with hypersthene and rounded andesine) and rhyolites and obsidian (73-75% SiO_2). Both geochemical and petrographic features suggest involvement of varying degrees of crustal contamination and/or magma mixing, especially in the more silicic rocks.

Low $^{143}Nd/^{144}Nd$ ratios in this suite clearly distinguish it from the Yellowstone-Snake River Plain volcanics and suggest the absence of asthenospheric input, precluding melt generation due to convective heat transfer. A possible melting mechanism is suggested by the high Ba/Nb values of these rocks, a feature considered diagnostic of involvement of subducted slab-derived hydrous flux in melt generation. It is proposed that a fragment of subducted slab detached as the Cascade subduction zone was disrupted by the inception of the Yellowstone mantle plume was buoyed and transported eastward, where its descent and dehydration beneath western Wyoming produced calc-alkaline magmas by solidus depression in the lithospheric mantle and lower crust.

CHAPTER 1

INTRODUCTION

Overview

Cenozoic volcanism in the interior regions of the western United States has been extensive and has exhibited a wide range in geochemical character (Lipman, 1992; Luedke and Smith, 1978a-e). In their seminal papers, Christiansen and Lipman(1972) and Lipman et al. (1972) identified two general tectono-magmatic associations: an early calc-alkaline, predominantly andesitic episode attributed to shallow subduction of the Farallon Plate and a later period of basaltic, bimodal, or "fundamentally basaltic" volcanism associated with regional extension. They also noticed broad spatial trends in the timing of the transition from one association to the other, attributed to the gradual replacement of the coastal subduction zone with a transform boundary. However, owing to the fairly ambiguous nature of the geochemical nature of the later group, this transition is not always clear, especially in the northern portions of the region, where subduction presently continues off the Oregon and Washington coasts. Many volcanic fields elsewhere in the western United States also do not fit neatly into either category (e.g. the Jemez in New Mexico (Perry et al., 1987)).

Christiansen and Lipman (1972) purposely refrained from proposing a petrogenetic explanation for these tectonic-geochemical relationships and never implied any paleostress aspects to the earlier subduction-related trend. Subsequent workers, however, have assumed a "compressional" tectonic character for subduction environments and claim to identify the timing of a shift from "compressional" to extensional tectonism in particular locales (Barnosky, 1984; McDowell and Fritz,1995). It is not clear that Lipman and Christiansen intended a paleostress interpretation for this geochemical transition, and they also acknowledged the difficulty in applying these concepts to individual areas as opposed to regions.

Stress in volcanic arcs can range from tensional in the backarc to compressional in the arc and forearc. Present-day stress fields in the Pacific Northwest also show a dominant component of dextral shear oblique to the arc axis (Zoback and Zoback, 1989). Indeed, the arc and forearc regions of any subduction environment may experience extension if the rate of slab rollback exceeds that of plate convergence (Royden, 1993).

The association of compressional paleostress with intermediate volcanism stems from early theories in which basaltic melts would be trapped in crustal magma chambers, as contraction closed available conduits. In such chambers, differentiation and crustal assimilation produces andesitic magmas. Extensional paleostrain would allow basaltic melts to pass unaffected through the crust (Hildreth, 1981; Norman and Leeman, 1989). Subsequent experimental work on andesites (Green 1973,1982; Eggler, 1972,1974; Eggler and Burnham, 1973) has suggested that certain conditions of partial melting (such as high water content) are perhaps more important than fractionation in the genesis of andesitic volcanism, especially as regards arc magmatism. In certain circumstances such as the Mogollon-Datil volcanic field (Cather, 1990), such a relationship between stress and volcanism may be realistic. However, in no way should the mere presence of extensional tectonism be taken as evidence precluding the possibility of subduction-related volcanism as some authors seem to suggest (Hooper et al., 1995).

Continued work on Cenozoic andesitic volcanism in the western United States has shown that, in many areas, lavas of intermediate composition can be generated by magma mixing (McMillan and Dungan,1988; Gerlach and Grove, 1982) or crustal assimilation (Gans et al., 1989) without necessarily requiring subduction of oceanic crust and that shifts in gross geochemistry may be a normal part of open-system magmatic evolution. Significant amounts of basalt can also occur in areas such as the Cascades, where subduction is indisputably the dominant tectonic process (Leeman et al., 1990; McBirney et al., 1974). Studies of bimodal volcanism have emphasized the primary importance of upwelling of asthenospheric mantle in areas of both significant (Suneson and Lucchitta, 1983) and minimal extension (Leeman, 1982a).

It thus appears that intermediate composition volcanism need not indicate subduction and that basaltic or bimodal volcanism need not preclude it. Instead, detailed study of each particular case is required, especially given the tectonic complexity of the western United States and the heterogeneity of its lithosphere, both crust and mantle (Menzies et al., 1983; Menzies, 1989; Lum et al., 1989). As pointed out by Arculus and Johnson (1978), there has often been an overemphasis on generalized models thereby ignoring the valuable information to be gained from the unique aspects of individual case histories. In this regard, it is also preferable that traditionally accepted geochemical subduction signatures (Gill, 1981) be critically examined to ascertain their applicability in this more or less intracontinental setting (Arculus, 1987).

Subduction Geochemistry

Crucial to Christiansen and Lipman's (1972) division of Cenozoic volcanism in the western United States, and the spatio-temporal trends displayed thereby, is not the distinction between extensional and compressional tectonism nor intermediate and basaltic or bimodal lavas. *Instead, it is the presence or absence of subduction-related volcanism.*

Following Christiansen and Lipman's 1972 paper, considerable work has been done on the geochemical aspects of subduction as expressed in arc magmas. Major and trace element contents in subduction-related volcanic rocks have been summarized by Jakes and White (1973), Ewart (1982), and Pearce (1982). Isotope systematics have been summarized by Hawkesworth (1982). Based on these features, various discriminant diagrams have been developed to distinguish arc magmas from those of other tectonic settings.

Primary among these features is the general depletion in subduction-related lavas of high field strength elements (HFSE, e.g., Ti, Hf, Nb, Ta) relative to large ion lithophile elements (LILE, e.g., Rb, Cs, Ba, K). These two groups show similarly incompatible behavior in crystal fractionation processes; however, LILE partition much more readily into a hydrous phase (Pearce and Norry, 1979; Tatsumi et al., 1986). Some workers (Eggler, 1987) have found little or no LILE vs. HFSE fractionation in hydrous systems. However, Eggler's findings involve the derivation of fluid-crystal partitioning data from the combination of fluid-melt and melt-crystal partitioning data; whereas Tatsumi directly observed fluid-crystal partitioning in the dehydration of spiked synthetic serpentine. Gill (1981) asserted that "a Ba/Ta ratio greater than 450 (Ba/Nb > ~25) is the single most diagnostic characteristic of arc magma." Although HFSE depletion has also been attributed to the stabilization, in either the slab or mantle wedge, of a residual phase such as rutile (Ryerson and Watson, 1987) or fractionation of other minor mineral phases (Saunders et al., 1980), the most widely accepted explanation is the enrichment and melting of the overlying mantle wedge by a flux derived from a descending and dehydrating oceanic crustal slab (Hooper and Hawkesworth, 1993). The question remains of the relative content of hydrous fluid versus silicate melt in this slab-derived flux (Arculus, 1987). Ratios such as K/Ti (Kempton et al., 1991) and Nb/Ta (Stolz et al., 1996) have been used to determine the relative importance of these two metasomatic modes.

Although such features have been used to assign an arc setting to rocks as old as the Precambrian (Pearce and Cann, 1973), in Tertiary volcanics of the western United States, they are often briefly acknowledged and then dismissed usually due to excessive distance from and/or non-alignment with potential coastal subduction zones (Robyn, 1979;

Goles, 1986; Gans et al., 1989). In the case of many recent studies, consideration of the process of initial melt generation is essentially ignored in favor of concentrating on subsequent aspects of magma evolution.

What then would constitute sufficient evidence of subduction-related volcanism in the interior of the western United States? Ratios such as Ba/Nb, although compelling, can be of dubious significance in the more alkalic provinces, where, for reasons other than slab dehydration, LILE values can be extreme (Dudas, pers. comm.). More importantly, much of the lithospheric mantle underlying the western U.S. may have experienced one or more episodes of subduction-related metasomatism; thus the geochemical characteristics of subduction may be *inherited* rather than the result of contemporaneous slab dehydration.

It is clear that in addition to evidence of slab dewatering metasomatism, evidence of *melt generation* by hydrous flux depression of solidus temperatures must also be established. The other options for melting the lithosphere are adiabatic decompression due to rapid extension, heat input from the asthenosphere, or increase in burial depth due to tectonic crustal thickening. Decompression melting requires substantial rates of crustal extension (McKenzie and Bickle, 1988; White and McKenzie, 1989) that are seldom encountered outside of mid-ocean ridges or continental rift zones, where "passive" upwelling of asthenosphere can occur. Upwelling of asthenospheric mantle also occurs without major extensional tectonism in association with mantle plumes, or "hot spots", which melt the lithosphere by conductive and/or convective thermal input.

The question of the relative amount of incorporation of asthenospheric mantle material in melts generated in the Cenozoic in the western United States is a very important one, as it can provide constraints on the possible mechanisms of initial melting. In other words, in regions where the geochemical signature of the asthenospheric (i.e. convecting) mantle can be distinguished, the absence of said signature would tend to preclude melting mechanisms that require heat input by advection of hot asthenospheric material. Lachenbruch and Sass (1978) pointed out that "the ultimate source of high heat flow in the Basin and Range province must be upward convective transport in the asthenosphere." Under these conditions, McKenzie and Bickle (1988) have shown that the first point of intersection of the geotherm with solidus (i.e. melting) will always occur at the transition from the conductive to the adiabatic geotherm at the base of the thermal boundary (i.e. within the asthenosphere).

Some workers (Christiansen and McKee, 1978; Dudas, 1991; Hooper et al., 1995) have suggested that melting entirely within the lithosphere could be induced by extension, perhaps with some degree of conductive pre-heating from the asthenosphere. However, decompression is the vital component of this process; thus the lithosphere would need to undergo either extensive removal of crustal overburden (increasing heat loss due to steepening of the conductive geotherm) or diapiric upwelling. The latter would require, at the outset, a density contrast, presumably thermally induced, between the diapir and its surrounding material. As much of the material above the developing diapir would be of increasingly lower- density crustal nature, it is not clear how extension could trigger this process. In any event, as outlined earlier, an asthenospheric melt would already be present due to extension-induced upwelling (McKenzie and Bickle, 1988); thus any lithospheric melting would more likely be the result of direct contact with intruding or underplating asthenospheric melts, most probably leading to some asthenospheric signature in the resulting magmas. This positive relationship between amount of extension and asthenospheric input has been noted in Rio Grande Rift lavas (Perry et al., 1987).

Leeman (1982b) has proposed a purely lithospheric source for the Snake River Plain tholeiitic basalts and the associated rhyolites in a setting involving minimal extension but dominated by high heat flow from an upwelling mantle plume (Leeman, 1982a). Once again, deriving sufficient heat from hot, convecting asthenospheric mantle to melt the lithosphere in such large volumes without asthenospheric admixture seems improbable. In fact, Menzies (1989) includes a small amount of OIB (ocean island basalt) type mantle as a component of these magmas, acknowledging the inevitability of some asthenospheric admixture during heat transfer. Based on low seismic velocities to depths of 250 km. and a high ^3He flux at Yellowstone, Hildreth et al. (1991) also suggested sublithospheric magma contributions.

The prevailing model for melt generation in volcanic arcs does not involve the asthenosphere as a source of heat; rather it is solidus depression due to slab-derived hydrous fluxes that initiates melting. Nonetheless, in the majority of arc settings, the nature of the mantle wedge in which the melting occurs is convecting, asthenospheric mantle. Only in situations in which the descending slab is directly overlain by lithospheric mantle would the resulting melt contain no evidence of asthenospheric input. Some workers have suggested that a convecting mantle wedge is necessary in order to transport mantle metasomatized by shallow slab-derived fluxes to deeper, hotter levels appropriate for melting (Tatsumi, 1989). Indeed, areas in the Andean arc where shallow subduction is apparently taking place and where the slab is interpreted to be in direct contact with the lithosphere (Sacks, 1983) are distinctly non-volcanic. Nevertheless, this lack of volcanism could just as well be due to the lack of correct pressure and temperature conditions for slab dehydration or lithospheric melting as due to the absence of asthenospheric mantle per se.

In summary, in areas such as Yellowstone and the surrounding region where an asthenospheric signature can be determined with a reasonable amount of certainty, lavas lacking that signature strongly suggest the possibility of the involvement of slab-derived fluids in the melting of the lithosphere.

Regional Setting

Northwest Wyoming and the surrounding region has experienced a complex magmatic and tectonic history during the Cenozoic. Sevier and Laramide-style contractional tectonism spanned a period from the late Cretaceous to the Eocene, during which extensive calc-alkaline and alkalic volcanism produced the Challis, Absaroka, and Central Montana volcanic provinces. These provinces, and the Sevier and Laramide orogenies themselves, have been attributed to the shallow subduction of the Farallon Plate beneath the western portion of the North American Plate (e.g. Lipman et al., 1972; Snyder et al., 1976). Other workers (Fitton et al., 1991; Hooper et al., 1995) have suggested that the geochemical subduction signature of these lavas is inherited from the metasomatized mantle of the accreted arc terranes which make up most of the western U.S., including portions of the Archaean Wyoming craton (Dudas, 1991).

Since the early Miocene the region has been dominated by a northeast-propagating system of explosive, rhyolitic volcanism followed by extrusion of basalt without any intermediate lavas (Pierce and Morgan, 1992). The present locus of explosive activity is in Yellowstone National Park and vicinity, where caldera-forming eruptions have occurred at 2.0, 1.3, and 0.6 Ma (Hildreth et al., 1991; Christiansen, 1995). To the west, the distribution of various widespread ash-fall tuffs suggest the presence of earlier calderas; in the vicinity of Rexburg, Idaho, 6.6 to 4.3 Ma (Morgan et al., 1984; Morgan and Hackett, 1988; Morgan, 1992); and in the general vicinity of Twin Falls, Idaho, ~10 to ~8 Ma (Leeman, 1982c). The system can be traced back as far as the McDermitt volcanic field (~16 Ma.) in the Owhyee Mountains in eastern Oregon (Pierce and Morgan, 1992).

Although the region has, during the Neogene, been experiencing a very general, eastward-propagating front of "Basin and Range" extension (Rodgers et al., 1990), it appears that the developing magmatic system has also confined the distribution of extensional tectonism to a parabolic or "bow wave" pattern (Anders et al., 1989; Anders and Sleep, 1992). In addition, a sequence of initial regional uplift followed by subsidence can be seen associated with the eastward migration of explosive rhyolitic activity (Fritz and Sears, 1993; Smith and Braile, 1994).

The interpretations of the Snake River Plain-Yellowstone province and this eastward-propagating magmatic system are numerous, but only one substantially explains the tectonic, geochemical, and isotopic evidence. Interpreting the Plain as an eastward-propagating extensional rift (Myers and Hamilton, 1964) is contrary to overwhelming evidence of an extensional direction parallel to the axis of the Plain (Allmendinger, 1982; Kuntz et al., 1992). Reactivation of an ancient plain of weakness (Eaton et al., 1975; Mabey et al., 1978) or characterization as a "leaky transform" between regions of differing rates of extension (Christiansen and McKee, 1978) may explain the overall geometry of the province but fail even to begin to consider the localization or the nature of the region's magmatism.

Only a model involving a deep-seated upwelling of asthenospheric mantle or "mantle plume" fully treats the time-transgressive nature of the magmatism (Armstrong et al., 1975), its large volume and geochemical features (Leeman, 1982c), regional heat flow (Brott et al., 1981; Blackwell, 1989), the deep-mantle signature of the He^3/He^4 ratios (Craig et al., 1978; Kennedy et al., 1987), and regional uplift and subsidence (Fritz and Sears, 1993; Pierce and Morgan, 1992). For this reason, the subcrustal mechanism responsible for the Snake River Plain-Yellowstone volcanic province will herein be referred to as a mantle plume rather than some other, more coy and obfuscatory term.

Under the mantle plume model, a broad plume "head" produced a regional epeirogenic uplift and possibly affected volcanic activity as far east as Colorado (Leat et al., 1991). This plume head may have produced (Draper, 1991; Geist and Richards, 1993), strongly influenced (Hooper, 1990; Hooper and Hawkesworth, 1993), or had no effect on the Columbia River Basalts (Carlson and Hart, 1987; Hart and Carlson, 1987). The more narrowly focused plume "tail" subsequently produced the eastern Snake River Plain and Yellowstone Plateau as the North American plate drifted to the west-southwest over the essentially stationary plume (Pierce and Morgan, 1992). Basaltic melts derived from the ascending, superheated mantle caused extensive anatexis in the lower crust. These rhyolitic melts not only led to explosive, caldera-forming eruptions by the formation and catastrophic draining of upper crustal magma chambers, but they also served as a low-density cap blocking the ascent of the denser basalts (Leeman, 1982c; Anders and Sleep, 1992). Only around the periphery of the province or after the rhyolite had cooled sufficiently to allow brittle fracture, could the less viscous basalt exploit the resulting conduits and reach the surface (Hildreth et al., 1991; Kuntz, 1992). This bimodal magmatism, rhyolite followed by basalt with no intermediate compositions, dominates the province; although some "hybrid" ferrobasalts and ferrolatites (Leeman, 1982d) and evidence of basalt-rhyolite mixing (Wilcox, 1944) do exist.

In the area of southern Jackson Hole, Wyoming, approximately 70 km south of Yellowstone National Park, there exist, however, scattered outcrops of late-Miocene intermediate lava flows. Not only are these volcanics distinctly not bimodal, but, as will be shown in subsequent chapters, their major and trace elements and isotopic ratios also indicate that they can in no way be derived from the magmas of the Yellowstone-Snake River Plain system. In addition, nowhere in the literature, to the author's knowledge, is there mention of a similar Neogene volcanic suite in the region. These lavas, herein referred to as the Jackson Hole volcanic complex (JHV), are apparently unique.

CHAPTER 2

STUDY AREA

Structural Overview

Jackson Hole, in northwestern Wyoming, is a north-trending, flat-bottomed valley approximately 12 km wide by 75 km long. (Figure 1) It is flanked on the east, from north to south, by the Pinyon Highlands, Leidy Peak Highlands, Gros Ventre Range, and Hoback Range. On the west it is flanked from north to south by the Teton Range and Snake River Range.

For most of its length, the valley is a half graben which constitutes the downdropped hanging-wall block of the east-dipping Teton normal fault. At its southern end, the half graben is reversed, with the master fault, the west-dipping Hoback normal fault, lying on the eastern side of the valley. The transition between the two half grabens coincides with two opposing WNW-trending thrust faults which mark the boundary between two major structural provinces. To the north, the Teton and Gros Ventre Ranges and the intervening valley occupy the hanging wall of the Cache Creek thrust, a thick-skinned, basement-cored, Laramide-style contractional fault. To the south, the Snake River and Hoback Ranges and intervening valley occupy the hanging walls of several

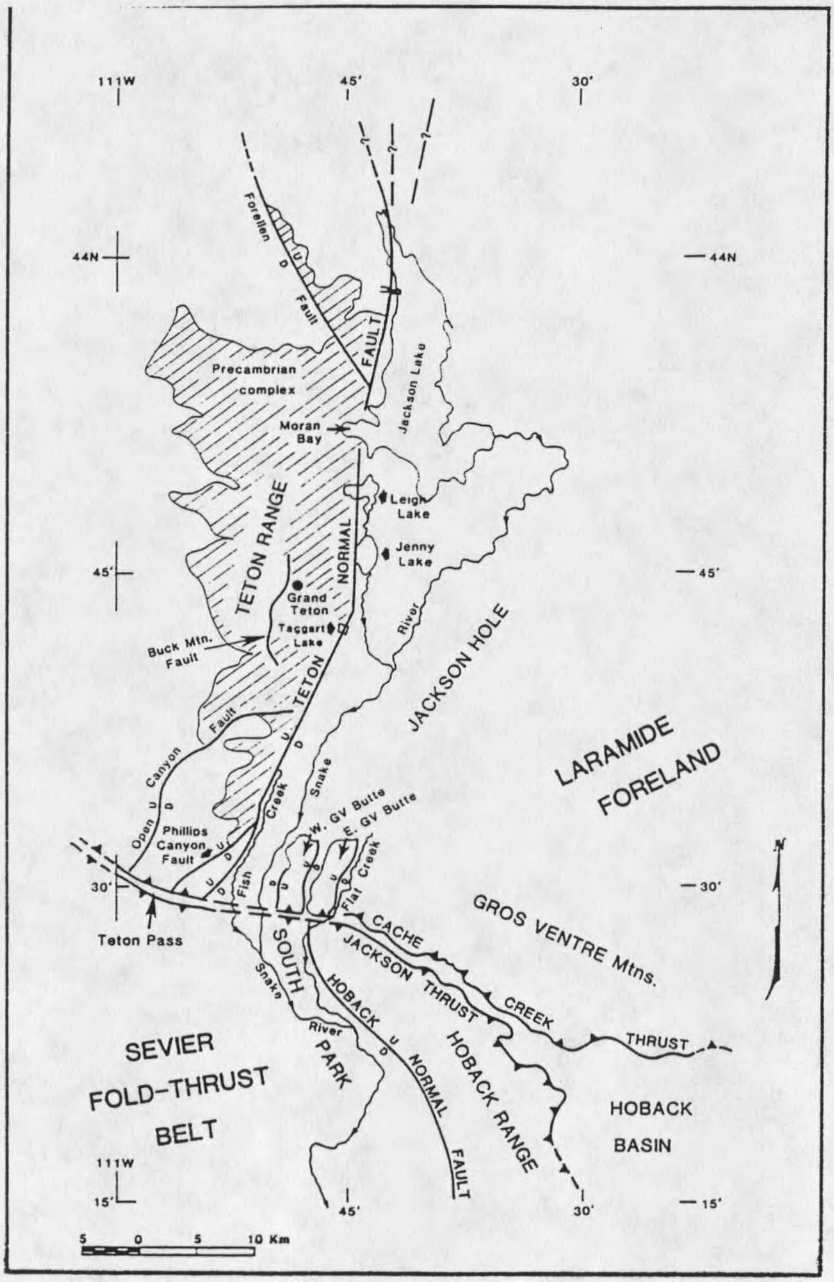

Figure 1. Structural index map of the Teton Range, reprinted from Lageson (1992).

imbricates of thin-skinned, Sevier-style thrusts, the Jackson-Prospect thrust being the northernmost. The episode of contractional tectonism that produced these structures lasted from late Cretaceous to perhaps early Eocene. The extensional tectonism which produced the Teton and Hoback faults and Jackson Hole itself commenced in the middle Miocene and continues to the present day (Byrd et al., 1994).

Considerable disagreement exists as to whether the Teton normal fault is confined to the Cache Creek thrust plate (i.e., soles into the Cache Creek decollement) or if it continues south of the province boundary (traced approximately by Wyoming Hwy. 22) into the region of the Sevier-style Snake River Range. It is of note that the Teton fault appears, as it approaches the edge of the Cache Creek thrust plate to the south, to shift from a single master fault, or fault zone, to a more distributed extensional system of normal faults. These faults, as mapped from west to east, are the Open Canyon fault, the Phillips Canyon fault, the Teton fault, and the faults bounding the east sides of the West and East Gros Ventre Buttes (Figure 1). Also present are several east-west faults, the Rendezvous Peak fault, the Warm Springs fault, and the Cache Creek fault, which may have served as transform structures accommodating differential extension in the area. It is this area of distributed extension that contains the bulk of the Jackson Hole volcanic complex.