Neogene-Quaternary Tectonics and Volcanism of Southern Jackson Hole, Wyoming and Southeastern Idaho

David R. Lageson
Department of Earth Sciences, Montana State University, Bozeman, MT 59717
David C. Adams
Department of Earth Sciences, Montana State University, Bozeman, MT 59717
Lisa Morgan
U.S. Geological Survey, Box 25046, MS-966, Federal Center, Denver, CO 80225
Kenneth L. Pierce
U.S. Geological Survey, Box 25046, MS-980, Federal Center, Denver, CO 80225
Robert B. Smith
Department of Geology and Geophysics, 717 W.C. Browning Building, University of Utah, Salt Lake City, UT 84112

INTRODUCTION

This field trip guide focuses on the region south of the Snake River Plain between Pocatello, Idaho and Jackson, Wyoming (Fig. 1). Our intent is not to rewrite the excellent geologic field guides that have already been published (e.g., Love and Reed, 1971; Love and Love, 1983; Love and Love, 1988; Love, 1989; Smith and Downs, 1989; Smith et al., 1990; Pierce and Good, 1992; Good and Pierce, 1996), but rather to synthesize regional tectonic relations and present new information relative to the magmatic and structural history of the region. We refer the interested reader to the extant field guides for details and information on this region not covered herein. Furthermore, we have elected not to write this field guide in the traditional ìroad logî format that has been so popular with societal guidebooks in the past, namely because landmarks and roads can change with time. Therefore, we have summarized the geology between major localities, referring to incremental or lapsed mileage as little as possible.

Four aspects of Neogene-Quaternary tectono-volcanic history that have received recent study by one or more co-authors are highlighted in this field trip. The first aspect concerns late Miocene lava flows in southern Jackson Hole that are distinctly intermediate calc-alkaline in composition in contrast to the bimodal basalt-rhyolite assemblages characteristic of most Neogene volcanic rocks of the Snake River Plain ñ Yellowstone region (Adams, 1997). The second aspect involves a reinterpretation of large slide blocks found primarily within the Grand-Swan Valley of southeast Idaho. We (Morgan and Lageson) suggest an alternative hypothesis to the slow ìcreepî model of emplacement (Boyer and Hossack, 1992), namely that some slide blocks may have been emplaced catastrophically during large magnitude earthquakes associated with large-volume silicic eruptions in the Heise volcanic field immediately to the northwest. The Teton Range and Jackson Hole are spotlighted for the third aspect of this field trip, including the Holocene history of the Teton fault, the contemporary deformation of Jackson Hole and the evolution of the Teton fault (Smith et al., 1993; Byrd et al., 1994), and the Quaternary glacial record of Jackson Hole (Pierce and Good, 1992). Lastly, the fourth aspect involves the identification and documentation of a large lineament that extends across southeast Idaho from the Snake River Canyon (near Alpine) to Pocatello, called the ìsoutheast Idaho lineamentî (Lageson, 1998). This lineament appears to be a reactivated, deep-seated tear fault in the Sevier orogenic belt that has compartmentalized Neogene extension across the region.

Lageson, D.R., Adams, D.C., Morgan, L., Pierce, K.L., and Smith, R.B., 1999, Neogene-Quaternary tectonics and volcanism of southern Jackson Hole, Wyoming and southeastern Idaho, *in* Hughes, S.S., and Thackray, G.D., eds., Guidebook to the Geology of Eastern Idaho: Pocatello, Idaho Museum of Natural History, p. 115-130.

Itinerary Summary

This field trip entails two very full days with an over-night stay in Jackson Hole, Wyoming. The itinerary is as follows (Fig. 1):

Day 1:

- Pocatello to Idaho Falls via I-15
- Idaho Falls to Swan Valley via Hwy 26
- Swan Valley to Victor via Hwy 31
- Victor to Jackson via Hwy 33 & 22
- Local stops in Jackson Hole

Day 2:

- Local stops in Jackson Hole
- Jackson to Alpine via Hwy 26 (Snake River Canyon)
- Alpine to Freedom via Hwy 89 & 34
- Freedom to Grays Lake to Soda Springs via Hwy 34
- Soda Springs to I-15 to Pocatello

DAY 1: POCATELLO, IDAHO TO JACKSON, WYOMING

Pocatello to Idaho Falls via Interstate 15

From Pocatello to Idaho Falls, Interstate 15 (I-15) curves to the northeast around the north end of the Pocatello, Portneuf, and Blackfoot Ranges and traverses Hellís Half Acre lava field. These ranges, in addition to the Big Hole ñ Snake River Range northeast of Idaho Falls, all lie within ìneotectonic belt IVî (Pierce and Morgan, 1992) and/or ìzone IIî of Smith and Braile (1993). Neotectonic belt IV, which exists only on the south side of the Snake River Plain, is characterized by muted range-front escarpments >500 m high with no planar triangular facets and the absence of range-front fault scarps in surficial deposits. These observations imply little or no Quaternary seismogenic activity (i.e., major range-front displacement occurred in the Neogene) and that range-bounding faults have either ceased movement or slip rates have substantially decelerated since the Neogene. In the regional context of the Yellowstone hotspot, belt IV is interpreted to be a ìcompleted phaseî of range-front fault development in the wake

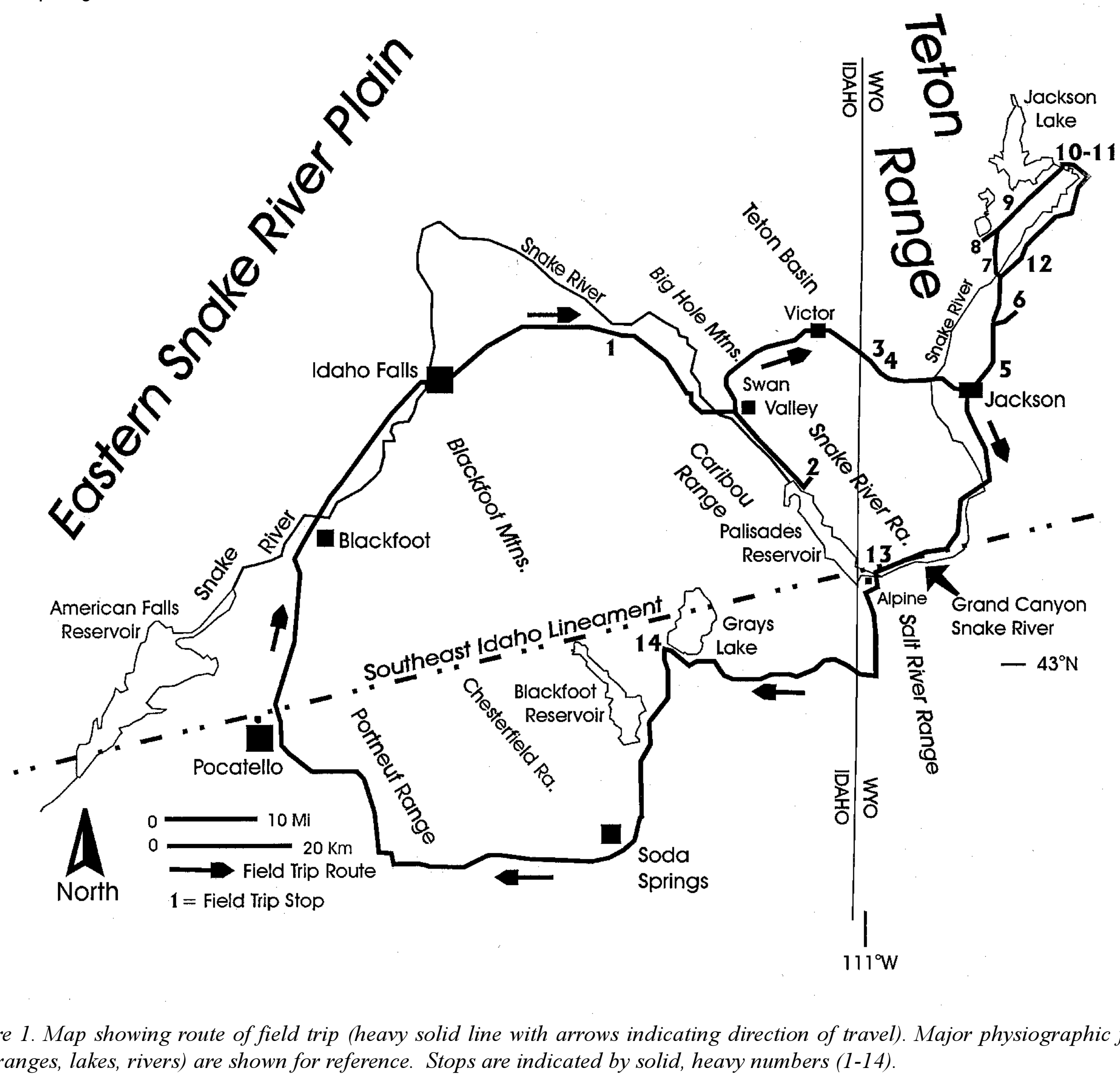

Figure 1. Map showing route of field trip (heavy solid line with arrows indicating direction of travel). Major physiographic features (ranges, lakes, rivers) are shown for reference. Stops are indicated by solid, heavy numbers (1-14).

of the Yellowstone hotspot, following waxing, culminating, and waning phases of development (Pierce and Morgan, 1992). Therefore, the culminating phase of range-front faulting in this region was during the late Neogene or possibly the early Quaternary.

Smith and Braile (1993) subdivided the ìtectonic parabolaî of late Cenozoic faulting adjacent to the path of the Yellowstone hotspot into three zones or ìseismotectonic domainsî extending outward from the eastern Snake River Plain (ESRP): zone I is the ESRP, zone II lies directly adjacent to the ESRP on the north and south, and zone III is defined by the parabolic distribution of Holocene-contemporary seismicity that wraps around Yellowstone National Park. On the south side of the ESRP, zone II is an aseismic zone of waning Quaternary faulting which extends ~80 km from the boundaries of the ESRP and is characterized by faults whose most recent displacements are generally older than post-glacial, ~14,000 years to late Cenozoic in age. Zone II was interpreted by Smith et al. (1985) to be related to a thermal mechanism that reduced stresses by heating or by plate bending, reducing its seismic capability and therefore fault potential.

The progressive relative northeastward migration of range-front faulting, coeval with the migration of silicic volcanism along the path of the Yellowstone hotspot (Armstrong et al., 1975), has been recognized by many workers. Smith et al. (1985) made the observation of declining seismic activity adjacent to the ESRP (in the wake of the Yellowstone hotspot) as part of the regional study of ESRP flanking seismicity and faulting, including the occurrence of the 1983 M 7.3 Borah Peak earthquake. Other workers have also documented the relative northeastward decrease (or southwestward increase) in the age of range-front faulting adjacent to the ESRP, namely Allmendinger (1982), Pierce and Scott (1986), Anders et al. (1989), Rodgers et al. (1990) and Pierce and Morgan (1992), although anomalies in the time-space distribution of silicic volcanism complicate the model (Leeman, 1989).

The Pocatello and Portneuf Ranges both involve thrust sheets that place Late Proterozoic quartzites and related metasedimentary rocks over Paleozoic strata. Kellogg (1992) and Kellogg and Rodgers (this volume) have documented the structural geology of the northern Portneuf Range, subtended by the Putnam thrust fault. The hanging wall of the Putnam thrust contains three major imbricate thrust faults that merge laterally into the Putnam thrust, in addition to numerous smaller horse blocks, duplexes, recumbent folds with axial-planar cleavage fans, and small-displacement high-angle normal faults. Both the Pocatello and Portneuf Ranges are bound along their western flanks by probable listric normal faults that locally have rotated Neogene deposits up to 35∞ E adjacent to the fault, and are interpreted to sole at depth into reactivated decollement horizons (Kellogg, 1992). Kellogg and Marvin (1988) report that significant range-front normal faulting occurred along the west side of the Portneuf Range between 7.0 ñ 6.5 Ma based on bracketing ages on a boulder conglomerate at the north end of the range. Only minor normal offset (50 m) has occurred of a 2.2-Ma basalt, suggesting that range-front faulting was more active in the Neogene than the Quaternary (Pierce and Morgan, 1992).

Several excellent field guides and review papers provide a regional overview of the Neogene-Quaternary silicic and basaltic volcanism that characterizes the eastern Snake River Plain, most notably Kuntz (1989), Hackett and Morgan (1988), Leeman (1982), and Greeley and King (1977). I-15 skirts along the inferred margins of two major Neogene silicic volcanic centers interpreted to lie between Pocatello and Idaho Falls, namely the eastern margin of the Picabo volcanic field (about 10.2 Ma) north of Pocatello and the southern margin of the Heise volcanic field (7.5-4.0 Ma) near Idaho Falls (Pierce and Morgan, 1992). The tuff of Arbon Valley erupted from the Blackfoot caldera in the Picabo volcanic field at 10.21±0.07 Ma (Kellogg et al., 1989; Morgan and McIntosh, in press). The tuff of Arbon Valley is distinct from many of the other Snake River Plain ignimbrites in that it is characterized by phenocrysts of biotite and bipyramidal quartz (Pierce and Morgan, 1992). To the northeast, the Heise volcanic field is interpreted to have erupted four major welded ignimbrites from four overlapping caldera complexes, the Blacktail Creek Tuff (6.62 Ma), the Walcott Tuff (6.28 Ma), the Conant Creek Tuff (5.51 Ma), and the Kilgore Tuff (4.45 Ma) (Morgan, 1992; Morgan and McIntosh, in press). Pierce and Morgan (1992, p. 6) summarize the criteria used to delimit the spatial extent of extinct caldera complexes along the Snake River Plain that are now largely covered by a veneer (~1.0 km) of tholeiitic basalt.

Hellís Half Acre lava field is the most recent basaltic lava flow on the easternmost side of the Snake River Plain (Kuntz et al., 1989), although younger flows occur at Craters of the Moon. Excellent views of the lava fieldís rough, fresh appearing surface are visible adjacent to I-15, particularly at designated rest stops. Aa texture and fractured pressure ridges are especially common. Charcoal beneath the edge of the lava field has been dated at 5,200±150 a (Kuntz and Dalrymple, 1979; Kuntz et al., 1989). The vent system is located along the western margin and near the north end of the field where a total of eight eruptive events have been documented. The first two events produced ~4.6 km^3 of basalt which delimited the areal extent of the field, while the remaining six events produced smaller flows and spatter cones superjacent to the first two flows (Hotchkiss, 1976; Kuntz et al., 1989).

The northern Blackfoot Mountains form the skyline southeast of Idaho Falls. The range is subtended by the Meade thrust fault which locally places thick-bedded upper Paleozoic strata in the hanging wall over less competent Mesozoic strata in the footwall (Allmendinger, 1981). Folds in the hanging wall are typically kink folds with sharp hinges and planar limbs and curved axial surfaces that steepen westward; in contrast, folds in the footwall Mesozoic section are more open and concentric (Allmendinger, 1981). Based on detailed mapping, this was one of the first places in the Sevier orogenic belt of Idaho-Wyoming where out-of-sequence thrusting was clearly documented, whereby late-forming imbricate thrusts were strongly influenced by the geometry of early fault-bend folds. The anisotropy of the sedimentary section became ineffective in controlling stratigraphic levels of thrusting after the strata were rotated >35∞ W, thus forcing late faults to cut down-section in the direction of tectonic transport (Allmendinger, 1981). The Gateway normal fault bounds the west flank of the northern Blackfoot Mountains. Allmendinger (1982) concluded that major motion on the Gateway fault occurred between the emplacement of ignimbrites dated using K-Ar techniques at ~5.8 Ma (G.B.Dalrymple, pers. comm., 1979, *in* Allmendinger, 1986) and ~4.7 Ma (Armstrong et al., 1975), largely coeval with silicic eruptions from the Heise volcanic field immediately to the north (Pierce and Morgan, 1992).

Idaho Falls to Swan Valley, Idaho via Highway 26

From Idaho Falls to Swan Valley, Highway 26 wraps around the northwest end of the Caribou Mountains and follows the Snake River upstream (to the southeast) through the Swan Valley. The Caribou Mountains are composed of Triassic through upper Cretaceous strata that are parallel-folded and locally thrusted (at the surface) in the hanging wall of the Absaroka thrust sheet. Many folds at depth are cored by blind thrusts and thus are interpreted as fault-propagation folds (Dixon, 1982), although unpublished industry reflection seismic data suggest very complicated detachment folding and local duplexing within the Absaroka thrust sheet. Several large folds southwest of Palisades Reservoir are mentioned near the end of this road log in the context of the ìsoutheast Idaho lineament.î

The Snake River has deposited a broad fan-shaped floodplain where it flows from the northwest end of the Swan Valley onto the Snake River Plain northeast of Idaho Falls. U.S. Highway 26 traverses this floodplain between Idaho Falls and the Snake River. It is mapped as outwash, fanglomerate, and flood and terrace gravel, with adjacent higher terrain composed of Pliocene-Pleistocene welded ignimbrites and Pleistocene basalt (Geologic Map of Idaho, 1978). Scott (1982) mapped the surficial deposits northeast of Idaho Falls as ìdeposits of major fills of Pinedale age along mainstreams,î or upper Pleistocene deposits. These gravel-dominated deposits consist of pebbles and cobbles of quartzite, limestone, basalt, obsidian, and welded ignimbrite, typically subrounded and poorly sorted.

As Highway 26 approaches the Snake River near Heise and Poplar, higher terrain north and south of the river is covered by thick deposits of loess and colluvium, with locally developed boulder-sized colluvium in areas of steep topography (Scott, 1982). The loess ranges in age from upper to lower Pleistocene and consists of well-sorted, non-bedded silt, sandy silt, locally developed clayey silt, and sparse gravel that averages 7-15 m thick, but can be in excess of 60-m thick in lowland areas (Scott, 1982). Loess forms elongated drifts parallel to the prevailing wind direction, but more commonly is found as a thick blanket on rolling uplands that are extensively cultivated. In addition, sandy colluvium is well developed (1-3 m thick on slopes) in areas underlain by welded ignimbrites (Scott, 1982).

Stop 1 - Snake River viewpoint (view to north of Kelly Mountain across river)

L.A. Morgan: Excellent views can be seen along U.S. 26 in the Heise cliffs where a thick section of volcanic rocks from the 4.0-7.5-Ma Heise volcanic field is exposed in the uplifted block of the Grand Valley fault. The Heise volcanic field is the next-to-youngest of seven volcanic fields identified in the Snake River Plain-Yellowstone Plateau (SRP-YP) volcanic province (Pierce and Morgan, 1992). The Heise cliffs are one of the main areas along the margins of the eastern Snake River Plain in which the stratigraphy of the Heise volcanic field has been established.

The Heise cliffs are capped by a thick section of 4.45±0.05-Ma Kilgore Tuff (Morgan and McIntosh, in press). The next prominent cliff-forming unit is the 5.51±0.13-Ma Conant Creek Tuff (Morgan and McIntosh, in press), formerly referred to as the tuff of Elkhorn Spring (Morgan, 1992). Below the Conant Creek Tuff is the tuff of Wolverine Creek which in turn overlies the 6.62±0.03-Ma Blacktail Creek Tuff (Morgan and McIntosh, in press). The 7.50±0.05-Ma rhyolite of Hawley Spring forms the prominent steep cliffs below the Blacktail Creek Tuff and has an undulating surface typical of many rhyolitic lava flows. The rhyolite of Hawley Spring caps a sequence of white, tuffaceous deposits which in turn overlie a thin basalt. This volcanic section is separated by a segment of the Grand Valley fault from Permian units which form small hills adjacent to the road next to Heise Hot Springs. Other volcanic units exposed along the Heise cliffs are mainly rhyolitic in composition and are of local extent (Morgan and Bonnichsen, 1988).

The Kilgore Tuff, the Conant Creek Tuff, and the Blacktail Creek Tuff are densely welded ignimbrites of regional extent and comprise three of the four major ignimbrite units that form the stratigraphic framework of the Heise volcanic field. The Kilgore and Blacktail Creek Tuffs are exposed along the northern and southern margins of the eastern Snake River Plain while distribution of the Conant Creek Tuff is more limited. The Conant Creek Tuff is exposed discontinuously from the Heise cliffs north to the west side of the northern Teton Range. The fourth ignimbrite of regional extent in the Heise field is the 6.28±0.07-Ma Walcott Tuff (Morgan and McIntosh, in press). While not present in the Heise cliffs, the Walcott Tuff is exposed along both margins of the plain and is exposed in the Conant Valley to the east (Morgan, 1992).

Resume field trip.

Piety et al. (1986), Anders et al. (1989), Anders (1990), McCalpin et al. (1990), and Pierce and Morgan (1992) have reported on the neotectonic development of the Swan Valley-Grand Valley-Star Valley fault system. Their work has shown conclusively that active (Holocene) extensional faulting is restricted to the southern end of the valley system, the Star Valley, and that the age of normal faulting becomes progressively older towards the Snake River Plain to the northwest. Using thermoremanent magnetism to discriminate between tectonic dip and primary dip of volcanic units, Anders et al. (1989) documented ~4 km of displacement on the Grand Valley fault between 4.3 and 2.0 Ma, at an average rate of 1.8 mm/yr. This rate is comparable to current rates on the Teton fault (1.7-2.2 mm/yr, Gilbert et al., 1983; and 0.9 mm/yr from post-glacial offset to 2 mm/yr from trenching of up to 7,900-year-old alluvium and moraine, Byrd, 1995; Smith et al., 1993), and the Star Valley fault (1.2 mm/year, Anders et al., 1989). Older volcanic units, such as the 6.62-Ma Blacktail Creek Tuff and the 4.45-Ma Kilgore Tuff (Morgan and McIntosh, in press), dip as much as 25-30∫ into the fault, whereas the ~2.1-Ma Huckleberry Ridge Tuff (Christiansen, 1984) shows negligible tectonic dip after accounting for primary dip. Furthermore, the 1.5-Ma basalt of Pine Creek is displaced only 28 m at the mouth of Pine Creek by the Grand Valley normal fault (Piety et al., 1986), providing further evidence that rates of range-front displacement have substantially decreased over the past 2 m.y. along the northwest portions of the Swan Valley-Grand Valley-Star Valley fault system. Anders and Geissman (1983), Smith et al. (1985), Pierce and Morgan (1992), and Smith and Braile (1993) have related this pattern of seismicity, which has a mirror image on the north side of the eastern Snake River Plain, to the passage of the Yellowstone hotspot. Pierce and Morgan (1992) placed the Swan Valley fault within neotectonic belt IV (latest offset = Neogene or early Quaternary), most of Grand Valley fault within neotectonic belt III (latest offset = late Pleistocene), and the Star Valley fault within neotectonic belt II (major Holocene offset on range-bounding faults).

Between the Snake River viewpoint stop and the town of Swan Valley, U.S. Highway 26 traverses Antelope Flat. Antelope Flat is covered by thick deposits of loess underlain by the 2.1-Ma Huckleberry Ridge Tuff. At Conant Valley, a 30-m-high cliff west of the highway exposes a section of Conant Valley volcanics (Hackett and Morgan, 1988), consisting of tuff breccia, yellow-brown palagonite, lapilli tuffs, and basalt flows with pahoehoe and pillow structures. The basalt may correlate with the 1.5-Ma basalt of Pine Creek (Anders, 1990), possibly flowing into water of the ancestral Snake River.

Fall Creek, draining into the Snake River south of Conant Valley (west of the town of Swan Valley), exposes a thick section of Neogene basin-fill sediments within the northern Swan Valley-Grand Valley-Star Valley system. The ~10-Ma tuff of Cosgrove Ranch (?) is exposed near the base of the section. Due to time constraints, we will not visit this locality on this field trip, but the interested reader is referred to Anders (1990). Just before entering the town of Swan Valley, columnar-jointed basalt is exposed north of the highway. This unit dips 14∫ NE and is correlated with the 4.0-Ma basalt of Irwin (Anders, 1990).

At the town of Swan Valley, continue south on Highway 26 to Big Elk Creek. The Palisades Bench forms the prominent intra-valley table east of the highway between Irwin and Palisades Creek. The Huckleberry Ridge Tuff is exposed near the top, overlain by loess and underlain by unconsolidated sand and gravel. Anders (1990) contends that the bench is not fault-bounded and that the 15∫ NE dip of the Huckleberry Ridge Tuff is non-tectonic. The Huckleberry Ridge Tuff also is exposed to the southwest, forming smooth, planar, NE-dipping slopes (Anders, 1990). On the north side of Palisades Creek, approximately 100 m east of the highway, is a well exposed slide block of Cambrian Gros Ventre Formation resting on Neogene conglomerate (ìSalt Lake Formationî). Albee et al. (1977) incorrectly identified this as a ìback-thrust klippeî (presumably thinking it was related to contractional deformation), but there is little doubt that this Cambrian block is a continuation of the larger slide mass to the east (Anders, 1990). Continuing south to Big Elk Creek, we climb the east buttress of Palisades Dam which is composed of late Miocene high-silica andesite (Adams, 1997). Dated by Armstrong et al. (1980) at 6.3±0.2 Ma, this columnar jointed flow is ~60 m thick and quite massive.

Stop 2 *- Big Elk Creek Slide Blocks*

L.A. Morgan and D.R. Lageson: Spectacular exposures of slide blocks derived from Paleozoic outcrops in the Snake River Range immediately east of Grand Valley are seen along Big Elk Creek. These slide blocks are a characteristic feature of the east side of Grand Valley between the Swan Valley townsite and Alpine. Boyer and Hossack (1992) interpreted these slide blocks to have been emplaced by slow, down-slope creeping motion based on limited field data and certain assumptions about the origin of mesoscopic structural features. Alternatively, Anders (1990) suggested a debris flow origin or ìfluidized flowî model and McCalpin et al. (1990) made a case for fluidized rock slides. We (Morgan and Lageson) suggest a new model for the origin of these slide blocks that places a greater emphasis on the ash deposits that bound many slide blocks and the concomitant explosive volcanism that was occurring in the Heise volcanic field immediately to the north (Morgan and McIntosh, in press). Based on characteristics of bracketing ash layers, we suggest that at least some slide blocks were emplaced catastrophically during major ignimbrite eruptions from the Heise volcanic field. Large caldera-forming pyroclastic eruptions of the magnitude recorded adjacent to the Snake River Plain would have been accompanied by swarms of precursory and syn-eruption seismicity, with a high probability that some seismic events may have been quite large. Seismicity associated with the climax phase of an eruption could have triggered catastrophic slides from the western flanks of the Snake River Range onto late Miocene tuffaceous lacustrine deposits, which in turn were covered by plinian ash- and pumice-fall deposits. The occurrence of breccia deposits and liquefaction features at some localities also supports the model of seismically-induced rapid emplacement.

Resume field trip. Return to Swan Valley townsite and turn east on Highway 31 to Victor, Idaho.

Swan Valley to Victor, Idaho via Pine Creek Pass and Highway 31

Albee et al. (1977) provide an excellent, detailed road log over the northern Snake River Range at Pine Creek Pass. Immediately east of the Swan Valley townsite, Highway 31 climbs onto the Pine Creek Bench. This intra-valley bench is essentially a continuation of the Palisades Bench to the southeast and includes, in ascending order, Pliocene conglomerate, a ~2-m cliff of Huckleberry Ridge Tuff near the top and a cap of loess (Albee et al., 1977). The highway traverses loess for the next ~5 km to the mouth of Pine Creek Canyon and the Pine Creek bridge, where the approximate trace of the Grand Valley normal fault is crossed. Cliffs in the gorge of Pine Creek are the 1.5-Ma basalt of Pine Creek, displaced 28 m by the Grand Valley normal fault (Piety et al., 1986). From here to the summit of Pine Creek Pass, the highway traverses numerous imbricate thrust faults and tight folds in Paleozoic strata in the hanging wall of the Absaroka thrust fault, crosses the trace of the Absaroka thrust near the North Fork of Pine Creek, and traverses Cretaceous strata (Aspen-Frontier interval) in the footwall of the Absaroka thrust to the summit (Albee et al., 1977). On the west side of the Pass, slabby road cuts of Huckleberry Ridge Tuff are once again encountered as the highway descends into the Teton Basin, or ìPierreís Holeî.

Victor, Idaho to Jackson, Wyoming via Teton Pass and Highway 33/22

Junction of State Highways 31 and 33 at Victor, Idaho. Turn right on Highway 33 to Jackson, Wyoming. Albee et al. (1977) provide a detailed road log over the summit of Teton Pass and into Jackson, Wyoming, focusing on the interaction of the SW-dipping Jackson thrust sheet to the right (south) and the NE-dipping Cache Creek thrust sheet to the left (north) of the highway. Also, Schroeder (1969, 1972) provides geologic maps of Teton Pass at 1:24,000. On the west side of Teton Pass, Trail Creek Valley follows coal-bearing sandstones and shales of the Upper Cretaceous Frontier Formation in the common footwall that separates the two thrust sheets. The Cache Creek hanging wall consists of lower Cretaceous through Mississippian strata, whereas the Jackson hanging wall consists of Triassic (distant hilltops to right) through Cambrian strata at road level. Red shales of the Triassic Woodside Formation are intermittently exposed in road cuts on the left side of the highway, hanging wall to the Cache Creek thrust. The trace of the Jackson thrust is crossed just after Wyoming Highway 22 curves to the right (south) and begins to climb the steeper, upper portions of the west side of Teton Pass. Numerous imbricate thrust faults at the eroded, leading edge of the Jackson thrust sheet have thoroughly sliced and duplicated the Paleozoic section. Some of these imbricate thrust faults have been overturned by convergence with the Cache Creek thrust, and thus appear to have normal offset. Triassic, Permian, Pennsylvanian and Mississippian strata are encountered near the top of Teton Pass, with stratigraphic relations complicated by the northwest-striking Teton Pass normal fault system (not to be confused with the Teton normal fault at the eastern base of the Teton Range).

Stop 3 *- Teton Pass Summit (weather permitting)*

The summit of Teton Pass offers a tremendous visual overview of the common footwall valley between the NE-dipping Cache Creek thrust (subjacent to East and West Gros Ventre Buttes and the southern Teton Range) and the SW-dipping Jackson thrust (subjacent to Snow King Mountain at the north end of the Hoback Range). The town of Jackson lies within this common footwall valley in the distance, with the Gros Ventre Range framing the eastern skyline. To the south (right), South Park comprises the hanging wall of the Hoback normal fault.

K.L. Pierce: During the next-to-last glaciation, Jackson Hole was filled with a thick glacier that flowed south (Pierce and Good, 1992; Good and Pierce, 1996). The 8,000-ft. contour on the reconstructed glacier surface went from Phillips Ridge eastward across Jackson Hole to the top of the Snow King Ski area above Jackson. The local term for this glaciation is the Munger Glaciation for Munger Mountain at the south end of Jackson Hole, where moraines extended up to 7,420 ft. in altitude. We correlate the Munger glaciation with the Bull Lake Glaciation and conclude that both are about 140,000 years old, and use the term Bull Lake for convenience in this report.

D.C. Adams: From this vantage point, several outcrop localities of the Jackson Hole volcanic field are visible, namely Phillips Ridge, low on the east side of Teton Pass, and East and West Gros Ventre Buttes in the distance. The Jackson Hole volcanic field, or JHVF, is distinct from the volcanic fields associated with the Snake River Plain-Yellowstone volcanic province. The JHVF comprises late Miocene (~8 Ma) lava flows that are distinctly intermediate, calc-alkaline in composition, in sharp contrast to the bimodal basalt-rhyolite assemblages that characterize most Neogene volcanic rocks in the greater Yellowstone region. Adams (1997) has studied the geochemistry and petrology of JHVF rocks, as summarized below. The JHVF suite consists of basaltic andesites and andesites (54-58% SiO_2, with olivine and augite), dacites (60-62% SiO_2, aphyric or hornblende-rich), rhyodacites (66-69% SiO_2, with hypersthene and rounded andesine), and rhyolites and obsidian (73-75% SiO_2). Despite limited stratigraphic continuity between flows, silica variation diagrams suggest a co-genetic, if not co-magmatic, origin. As a whole, JHVF rocks are significantly lower in K and Fe and higher in Ca and 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. Varying degrees of crustal contamination and/or magma mixing are indicated by geochemical and petrologic data, especially in the more silicic rocks of the suite. Low $^{143}Nd/^{144}Nd$ ratios clearly distinguish the JHVF suite from Snake River Plain-Yellowstone volcanic rocks and, coupled with high Ba/Nb values, suggest that the JHVF was derived principally from the lithospheric mantle with possible involvement of a hydrous flux from a subducted slab as a trigger for melt generation (Adams, 1997). The tectono-magmatic implications of this conclusion are difficult to rationalize for the late Miocene of western Wyoming, but Adams (1997) has proposed a model involving the disruption and eastward transport, by the Yellowstone hotspot, of a fragment of subducted oceanic lithosphere from the Cascadian subduction zone. Another possible model may be extensional decompression melting, but Adams (1997) argues against this on the grounds of needing hydrous influx (from a slab) to depress the solidus and generate olivine-rich, high-Mg andesites.

Resume field trip.

On the east side of Teton Pass, Highway 22 traverses down-section to a thick section of Cambrian Flathead Sandstone at Glory Slide (avalanche gully), then makes a 180∫ turn back to the south near the trace of the Phillips Canyon normal fault (on the west side of Phillips Ridge). Lageson (1992) proposed that the Phillips Canyon normal fault is one of several ìhorsetailingî normal faults at the south end of the Teton range-front normal fault system, and that the southern end of the Teton normal fault system may be geometrically detached on the older Laramide Cache Creek thrust fault at depth.

Pierce (field notes, 1988) measured 3-6 m offsets of Pinedale moraines on the east side of the Mount Glory mountain mass at sites that extend from 1.4 km north of the Glory Slide to 1.3 km further north (across the Ski Lake trail). On their 1992 field trip, Pierce and Good suggested that Phillips Ridge was a slide block that is moving across the Teton fault, and that offsets on the Teton structure now surface at the Phillips Canyon fault. The upper limit of Munger glacial deposits is anomalously low (~100 m) at the south end of Phillips Ridge, suggesting it may have subsided relative to sites at the northern end of Phillips Ridge and sites 4 km to the south. In view of this slide block interpretation for Phillips Ridge, it also seems possible that the Gros Ventre Buttes might be similar (but older) slide blocks that have slid to the valley floor.

***Stop 4** - Roadcut of basaltic andesite, west side of Phillips Ridge (hanging wall of Phillips Canyon normal fault)*

D.C. Adams: This flow may correlate with basaltic andesite on the west side of Teton Pass in the hanging wall of the Open Canyon normal fault, north of Highway 22 in the southern Teton Range. Both flows are clearly offset by adjacent normal faults and thus pre-date displacement. Maximum thickness of the two flows is ~20-m and both tend to be massive with only minimal flow foliation (Adams, 1997). Subjacent rocks range in age from Triassic to Pennsylvanian (Schroeder, 1972). Basaltic andesite of almost identical chemical composition forms a cap ~5-m thick on the extreme south end of East Gros Ventre Butte overlooking Jackson (Adams, 1997), suggesting a series of closely related flows that have been offset from west to east by several synthetic, domino-style normal faults, including the Teton normal fault. The East Gros Ventre Butte flow is highly foliated (~subvertical) and it grades downward into low-silica andesite, and thus is not entirely identical to basaltic andesite flows on Teton Pass.

Resume field trip.

Further down the east side of Teton Pass, Highway 22 curves around the south end of Phillips Ridge, which exposes the Paleozoic section on its east face, then descends to the top of a recessional kame ìinwashî bench (Bull Lake) and down a steep terrace face to the town of Wilson. Although the scarp at the east margin of this Bull Lake kame terrace has been considered by some to be a southward continuation of the Teton fault scarp, field studies by Pierce and Good (et al.) suggest this is not a fault scarp, but a fluvial scarp eroded back into the kame terrace. The southern limit of Holocene surface rupture along the Teton normal fault occurs ~5 km north of Wilson on the north side of Phillips Creek (Smith et al., 1993) where the Teton fault system is interpreted to bifurcate into several splays (Lageson, 1992).

Eastern Base of Teton Pass.

R.B. Smith: Welcome to Jackson Hole, the great ìgapî in the intermountain seismic belt. A study of the space-pattern of historic earthquakes of the central Intermountain region (Smith, Byrd and Susong, 1993; Smith and Arabasz,1991) revealed that the Teton fault has been notably aseismic for magnitudes $M_L \geq 1$ for the period 1959-1989. A very low regional strain rate and the general seismic quiescence of the Teton fault compared to the rest of the surrounding region suggests a notable ìgapî in the historic seismicity of this region at, at least the $M_L > 3$ level. If this interpretation is valid, the Teton fault may be ìlockedî and the area of seismic quiescence would be expected to reactivate with moderate to large earthquakes in the future. However, alternate interpretations for the aseismic nature of the Teton fault are possible and include: 1) the Teton fault is no longer active and therefore is not storing significant strain energy required for earthquake nucleation. Based on the Holocene history of faulting and the long-term geologic record, however, Smith et al. (1995) suggest there is no reason to believe that the Teton fault is not active. Alternate ideas for the lack of significant seismicity are: 2) the main belt of regional seismicity may have migrated eastward onto unknown structures in the Gros Ventre Range thereby relieving stress accumulation on the fault, or that 3) the period of historic seismological observations may not be sufficiently long to accurately assess the temporal pattern of the long-term seismicity.

Jackson Hole Itinerary

The remainder of the first day, as well as the beginning of the second day, will be spent in Jackson Hole. The focus of this portion of the field trip will be on late Tertiary magmatism, neotectonics, and active tectonics of the Teton ñ Jackson Hole region. Elements of this story inevitably involve the Yellowstone hotspot and the glacial record of greater Yellowstone. There are, of course, numerous field guides, road logs, and maps that address the geology of this region, such as Love and Reed (1971), Love and Love (1983), Love and Love (1988), Love (1989), Pierce and Good (1990), Smith et al. (1990), Love et al. (1992), Good and Pierce (1996), and Smith and Siegel (1999) to mention a few. We will not attempt to synthesize or compile these publications into one road log. Instead, we will have several stops that will highlight various aspects of the Neogene-Quaternary tectonic, volcanic, and glacial history of the greater Teton-Jackson Hole area and feature new information and data not contained in previous road logs.

***Stop 5** - Jackson National Fish Hatchery or south end of East Gros Ventre Butte (depending on weather/road conditions)*

The low undulating terrain of the upper Flat Creek Valley was shaped partly by glacial ice that moved south from Yellowstone through Jackson Hole during at least one of three major periods of glaciation in the region during the past 2 million years, as well as by normal faulting that down-dropped the valley. The East Gros Ventre Butte likely has an east-facing normal fault that runs north-south along its east base, but there is little or no evidence of Holocene activity on these faults.

D.C. Adams: This locality features porphyritic dacite with large rounded plagioclase phenocrysts and hypersthene. It is a remnant of a large dacitic (68% SiO_2) dome that was broken into several fault blocks across southern Jackson Hole. Other remnants of this dome are found at the top north-end of West Gros Ventre Butte and at a quarry at the north end of West Gros Ventre Butte. This dacitic dome may be the remains of a volcanic center within the JHVF.

L.A. Morgan: On the west side of the road leading into the Fish Hatchery, the late Miocene Teewinot Formation is exposed (J. D. Love, unpublished mapping) as two fine-grained units. The lower unit is ash-rich, well-sorted, planar-bedded siltstone overlain by approximately 0.5 m of planar-bedded ash (L.A. Morgan, 1996, field notes). Recent field mapping of the Teewinot Formation by L.A. Morgan has subdivided the Teewinot Formation into several lithofacies (Love et al., 1997). Grain-size and lithofacies distribution indicate that the ancestral Laramide portion of the Teton Range was not high enough to supply any coarse detritus to Lake Teewinot. Likewise, no field evidence (e.g., coarse clastic detritus) has been recognized in the Teewinot Formation to suggest that the 2-km-high escarpment of the Teton Range existed at the time of deposition. The Teewinot Formation likely predates significant structural relief on the Teton fault.

Stop 6 *- Blacktail Butte (observed from south along the Gros Ventre Junction-Kelly Road)*

R.B. Smith: From this point one can see a nominal westward tilt of the valley floor from the west side of Jackson Hole. Precise surveying measurements of elevation on the alluvial fan at the north end of the Butte reveal a shallow dip, a few tenths of a degree on an outwash surface near the Snake River, increasing up the fan to almost a degree. These data, along with other valley-wide elevation profiles, suggest a general westward tilt which is considered evidence of valley-wide hanging wall subsidence into the Teton fault since at least post-glacial time or longer (Byrd et al., 1994).

L.A. Morgan: Looking to the north toward Blacktail Butte, a sequence of westward-dipping (~25∫ W) Miocene sediments, known as the Teewinot Formation, are exposed (Love et al., 1986). The formation can be subdivided into several lithofacies recognized from the base upward as: 1) thick basal conglomerate in ash matrix; 2) thick claystone, marlstone and travertine sequence containing significant amounts of tephra; 3) alternating beds of clastic limestone and tephra; and 4) predominately tephra with fossiliferous claystones containing abundant aquatic fossils and pollen (Love et al., 1997). From east to west, these sediments comprise the basal portion of the unit beginning as a thick (>200 m) section of conglomerate containing coarse, subangular to rounded clasts of locally derived Paleozoic limestones. The matrix of this conglomeratic zone appears to increase in ash content with height. The remaining part of the section up to the top of the eastern hill is composed of alternating beds of tuffaceous limestones, marls, travertines, siltstones, and ashes. A topographic saddle separates the eastern hilltop from a higher western ridge which also is capped by the Teewinot Formation, but appears to be a section from higher in the stratigraphic sequence than that to the east. The Teewinot Formation in this upper, more westerly section is also dipping ~25∫ W, similar to the lower, more easterly section. Separating these two Teewinot sections are blocks of Paleozoic and Mesozoic strata, some of which appear extremely fractured and jointed. A current interpretation, subject to ongoing research and revision, is that the blocks of Paleozoic and Mesozoic strata represent large slide blocks emplaced in the late Miocene during deposition of the Teewinot Formation.

K.L. Pierce: About 1 km south of Blacktail Butte, Love et al. (1992) show a fault offsetting terrace gravels and extend it into the Butte. The terrace is mantled by up to 3 m of loess (but not including a buried soil), and the fault forms a graben (Gilbert et al., 1983; Love and Love, 1988; Pierce and Good, 1992, p. 13-14). The northeastern and western margins of Blacktail Butte are steep slopes near the angle of repose and, rather than fault scarps, are considered by Pierce to be fluvial facets formed by the undercutting by glacial age streams that flowed along the base of these scarps, and whose channel patterns are still clearly visible on aerial photographs.

DAY 2: JACKSON HOLE, WYOMING TO POCATELLO, IDAHO VIA ALPINE, GRAYS LAKE, SODA SPRINGS, I-15

Grand Teton National Park, Moose Entrance

This part of the field trip emphasizes the origin of the spectacular mountain scenery and topographic relief of almost 2,200 m from the top of the range to the valley floor of Jackson Hole, the product of multiple episodes of mountain uplift and valley subsidence along the Teton normal fault ó the essence of Grand Teton National Park. Detailed studies of the evolution of the Teton fault and the Teton Range, its seismotectonic importance and post-glacial history, the evolution of Jackson Lake from seismic profiling and coring, as well as the overall origin of the Teton-Jackson Hole area, have been studied in multifaceted projects by the University of Utah for more than two decades (see summaries by Smith et al., 1990; Byrd et al., 1995), by the U. S. Bureau of Reclamation (Gilbert et al., 1983) for dam safety aspects of Jackson Lake, et al. (e.g., Lageson, 1992; Roberts and Burbank, 1993; etc.). These efforts were built upon the mapping and studies of Teton geology by Dave Love, John R. Reed, John Behrendt, Ken Pierce and many others of the U.S. Geological Survey.

Stop 7 *(rolling) - Teton Glacier Turnout (Glacier Gulch)*

R.B. Smith: West of the Teton glacier turnout, the post-glacial offset of moraine and alluvium has been measured at several locations by detailed scarp profiling (Smith et al., 1993a; Byrd, 1995) that reveals surface offsets from 4 to 52 m on slopes from 12∞ to 35∞. The youngest offsets measured by ^{14}C dating from organic material obtained in a trench at Granite Creek ~14 km south, reveal two post-glacial paleo-earthquakes totaling ~4 m of offset. The oldest is 7,900 radiocarbon years with 2.8 m of offset, and the youngest is bracketed between 7,000 and 4,840 years with 1.3 m of offset. These observations point out the notable hiatus of faulting on the Teton fault during the past ~5,000 years and require a much greater fault slip rate following Pinedale glacier recession, taken to be ~14,000 years, to make up for about 15 m of fault offset. This requires slip rates of 0.9 to 1.1 mm/yr (Byrd, 1995). The post ~5,000 year hiatus is commensurate with the observation of a historic seismic gap, described above.

Also west of this area, the tops of trees along Cottonwood Creek can be seen. The creek, along with String and Jenny Lakes, sits within a topographic depression that is adjacent to the Teton fault and is thought to be a product of hanging-wall subsidence accompanying large earthquakes. The depression is in part accentuated by glacial outwash, but the trough closest to the Teton fault has dropped downward more than the rest of the valley. Here the stream trends notably south from as far north as Leigh Lake along Cottonwood Creek to Windy Point near Moose. This direction, parallel to the mountain front, is not the expected eastward drainage to the Snake River and emphasizes the youthful nature of fault offset in restraining, in part, the flow of streams to ìsagî ponds along the active fault.

***Stop 8** - South end of Jenny Lake (Lupine Meadows)*

K.L. Pierce: This stop offers an excellent view of the compound fault scarp at the base of Mt. Teewinot (ìLupine Meadows scarpî). Jenny Lake was formed by a glacier that flowed down Cascade Canyon from the Teton Range. It is held in by moraines studded with boulders of Precambrian rocks from the Teton Range. Along the eastern margin of Jenny Lake, the outer Jenny Lake moraines are largely buried by quartzite rich gravel of the large outwash fan that heads to the northeast in the Spaulding Bay area.

R.B. Smith: A well-developed exposure of post-glacial offset on the Teton fault is located west of this location ~2 km (~1.3 mi) on the upper horse trail on the south end of Jenny Lake. The upper horse trail turns northwest from the main trail in about 0.8 km (0.5 mi) as it climbs the Pinedale moraine adjacent Jenny Lake. This trail climbs for a few hundred yards up the moraine, then drops a few meters, makes a switchback where it begins to climb the scarp formed in the face of the Teton fault. The small valley between the trail drop and the switchback is a well developed graben produced as a ìwedgeî of the valley floor adjacent to the fault that slumped down along both the east-dipping Teton fault and a smaller west-dipping fault, creating the trough. At this point there is about 10 m of post-glacial offset.

***Stop 9** - Cathedral Group Turnout*

R.B. Smith: One of the most dramatic examples of an active normal fault in the western United States is visible to the west of this location as a steep bank and break in vegetation at the base of Rockchuck Peak. The scarp visible from here was formed by multiple post-glacial earthquakes on the Teton fault. It is located west of String Lake and measures up to 59 m in height. However, this height must be corrected for back-tilt which shows that it was created by vertical movements on the Teton fault of about 38 m. It could represent as many as a half-dozen M 7.5 earthquakes, or perhaps twenty M 7.3 earthquakes since the glaciers receded about 14,000 years ago. The west-tilted hanging wall (Jackson Hole) is also apparent from this stop. As you look west, you see only the tops of trees near the lake that sit in a trough. During major earthquakes, the area closest to the fault dropped downward more than the valley floor farther east (behind you) and, furthermore, the entire valley floor has been tilted westward as far east as 20 km due to multiple large earthquakes. In addition, smaller faults in the valley floor form a few hundred meters east of the Teton fault. These antithetic faults dip westward and intersect the east-dipping Teton fault creating a down-dropped ìwedgeî of ground separate from the rest of the valley floor. The height of the fault scarp and the depth of the trough are amplified at the base of the mountains by this wedge. Along with lake-damming glacial moraines, this trough ó which is about 29 m deeper than the glacial outwash plain to the east ó explains why Leigh, String, Jenny and other lakes formed along the fault, and why streams connecting the lakes drain south, not east away from the Teton Range.

K.L. Pierce: The Teton fault offsets Pinedale slope deposits and a cascade of Pinedale morainal debris about 19 m (Gilbert et al., 1983) or 22.8 m (Byrd et al., 1994). We estimate the minimum age of the glacial moraines and slope stabilization to be about 15 ka. To the left, the fault offsets moraines of Laurel Lake (on the front). Farther left, moraines on the north side of Jenny Lake are broken in three places (apparent offsets, from west to east of 19 m, 12 m, and 19 m for a total of 50 m). Because the structural offset at nearby sites is about 20 m, this 50 m of apparent offset is probably the combined result of structural offset and possible ìshake downî of hanging wall sediments (i.e., sediment compaction coupled with surficial slumping). The Cathedral Group turnout is on outwash of Jackson Lake age, rich in quartzite from northeastern Jackson Hole. Interpretation of cuttings and well logs from a drill hole northeast of Jenny Lake suggest Pinedale outwash rich in quartzite is $\geq$60 m thick. The channel pattern on the outwash surface trends obliquely toward the Teton front, defining a source to the northeast near Spaulding Bay. The direction of stream flow (Pierce and Good, 1992, annotated aerial photo, Stop 2-1) suggest this outwash deposition may have been filling a tectonic depression created by Jackson Hole-tilting into the Teton fault. Post-depositional tilting of this outwash surface probably has occurred, but is of much lesser amount than the original depositional slope. Tilting into the Teton fault appears to have created String Lake from a flat-bottomed outwash channel that flowed east around the northern Jenny Lake moraines (Pierce and Good, 1992). In the trees to the north are Pinedale moraines rich in Precambrian rocks from the Teton range. In contrast, the outwash fan on which we are standing, which fronts the moraines, is dominated by non-Teton Range rocks (quartzite).

***Stop 10** (rolling) - Jackson Lake Dam*

R.B. Smith: A log-crib dam first was built in 1905-1907 to impound the Snake River draining from a preexisting, natural Jackson Lake, raising it 6.7 m above its natural level. The early dam, however, failed in 1910. A concrete dam was built between 1911 and 1916, raising the maximum lake level another 3.5 m, to about 14 m above the lakeís natural elevation. The dam impounds irrigation water for agriculture downstream on the Snake River in Idaho and also provides flood control. In 1976 on the west side of the Teton Range, the Teton Riverís Teton dam ruptured, causing a catastrophic flood that prompted the U.S. Bureau of Reclamation to study other regional dams. Jackson Lake dam was interpreted to be susceptible to failure during nearby large earthquakes, so it was upgraded during 1986-1989. The Bureau of Reclamation now believes it can withstand the ìmaximum credible earthquakeî ó a M 7.5 quake on the Teton fault. Ancestral Jackson Lake formed in a trough at the base of the Teton Range, probably soon after the Teton fault became active [the time of inception of the Teton fault is equivocal and the subject of ongoing research by several individuals]. The trough was created by the downward movement of Jackson Hole along the Teton fault. The lake now includes a deeper western trough, west of here but out of view, and a shallower eastern trough, that begins at the dam site and stretches 3 miles to the southwest. The western trough, initially created by faulting, was deepened by glacial scouring that flowed south from the Yellowstone Plateau during the multiple glacial advances, which ended roughly 14,000 years ago. The lakeís eastern trough, seen from the dam, was carved by earlier glaciers flowing down Pacific Creek and Buffalo Fork. The water is 133 m deep in Jackson Lakeís western trough and 44 m deep in the shallower eastern trough. Both troughs were deeper at one time, but have filled with sediment. Seismic reflection profiling and piston coring (Smith et al., 1993b) have revealed the thickness and layering of these sediments that shows the lakeís western trough may once have been as much as 243 m deep, but nearly half of it has been occupied with 115 m of sediment carried into the lake by the Snake River from the Yellowstone Plateau. Only an estimated 12-to-21 m of those sediments were deposited in the lake since the last glaciers receded. The lakeís eastern trough once was more than 92 m deep, but now is more than half full of sediments that are about 51 m thick. Early researchers hypothesized that the Teton fault reached the surface beneath Jackson Lake. However the seismic reflection profiles show that the mud and deeper sediment beneath the lake have not been broken or folded by faulting. Instead, mapping of the Teton fault (Smith et al., 1993a) reveals that it is west of the west side of the lake and parallels a few hundred meters from the west shore of the lake. It extends northward to about three-fourths the length of the lake, then begins to splay into a series of normal faults, some crossing the lake to the east side, that continue into Yellowstone National Park as a series of major right-stepping normal faults.

K. L. Pierce (1992): The south end of the concrete section [of Jackson Lake dam] is founded on 2-Ma Huckleberry Ridge Tuff, whereas the long dike to the north is built on unconsolidated sediments at least 180 m thick (Gilbert et al., 1983), filling a scour basin excavated by the Pacific Creek glacier lobe in Burned Ridge (older Pinedale) time. The upper 30 m of these sediments contain sand beds found to be subject to liquefaction were an earthquake to occur on the Teton fault. This dike section of the dam was completely rebuilt in the late 1980ís at a cost of $82 million. The liquefiable sediments were strengthened by a combination of dynamic compaction by dropping a 30-ton weight repeatedly from a height of 30 m and by in situ injection and auger mixing of cement to form concrete pilings.

Stop 11 *- Willow Flats overlook*

K.L. Pierce: This bench is a glacial outwash/delta at the margin of a 6,840-ft altitude lake. To the south on Signal Mountain, one can see dips of two resistant units that suggest a general chronology for the structural development of Jackson Hole/Teton Range. The 2-Ma Huckleberry Ridge Tuff dips 11∫ west (into the Teton fault) whereas the underlying 4.45-Ma Kilgore Tuff (L. Morgan, oral communication, 1998) dips 22∫ to the west (Gilbert et al., 1983). The 7.5-Ma Teewinot Formation in this area also dips about 17-27∫ to the west (Love et al., 1992; Love et al., 1997). Although local faulting offsets these units (Gilbert et al., 1983), the nearly equal dip of the 7.5-Ma and 4.45-Ma units suggest that Teton fault tilting is dominantly younger than 4.45 Ma. Furthermore, the distribution of outflow facies of the 4.45-Ma Kilgore Tuff around Jackson Hole following eruption from a caldera on the eastern Snake River Plain indicates that the northern Teton Range was not a significant topographic feature at this time (Morgan and McIntosh, in press). The 2:1 ratio of dips between 4.45-Ma and 2-Ma units suggests that roughly half the late Cenozoic development of the Teton/Jackson Hole structure may be younger than 2 Ma. Changes in Jackson Lake provide an interesting history for the Teton fault. Tilting of Jackson Lake during Teton fault earthquakes would lower the west side of the lake relative to its outlet on the east side, thus submerging shorelines. In the southwest part of the lake near the Teton fault, about 10 submerged shorelines below the natural level of Jackson Lake suggest a similar number of down-faulting events on the Teton fault in post-glacial time. In the Snake River delta area at the north end of the lake, down-faulting events on the Teton fault are recorded by (1) submergence of deltaic river floodplain and building of beaches on these floodplain deposits about 2,000 years ago, and (2) formation of ridge and basin terrain from floodplain sediments created by inferred strong shaking about 4,000 years ago (Pierce et al., 1998, p. 41-47). These suggest significant earthquake events on the northern section of the Teton fault about 4,000 and 2,000 years ago (Pierce et al., 1998, Figure 30).

Stop 12 *- Glacier View Turnout*

K.L. Pierce: End moraines of the Pinedale glaciation from the greater Yellowstone glacial system are 2 to 7 miles up-valley. We are on glacier outwash near the boundary between two large outwash fans. On the west side of the valley is a large outwash fan of older Pinedale age (Burned Ridge), which was deposited by the ice-marginal Spread Creek held in on the north by the Buffalo Fork glacial lobe. We are standing on the easternmost part of a large outwash fan of intermediate Pinedale (Hedrick Pond) age that rises northward towards a glacial source near Spaulding Bay. The post-glacial Snake River roughly follows the low point seam between these two fan forms. To the west (at 9:00) across the valley at the base of the Teton Range are Pinedale moraines enclosing Bradley and Taggart Lakes. The upper strand of the Teton fault offsets the lateral moraine south of Taggart Lake by 9.8±2 m left-lateral slip and 7 m of vertical offset (K.L. Pierce and J.D. Good, field notes, 1986). At 10:00 is Timbered Island, one of the farthest upvalley remnants of loess-mantled till and outwash of Bull Lake age. At 3:00, aspen trees grow on the loess covered, older (Bull Lake) part of the large Ditch Creek alluvial fan. At 4:00 is Sheep Mountain, glaciated to near timberline (9,600-10,000 feet) by the Bull Lake glacier that filled Jackson Hole. Near the mouth of the Gros Ventre valley is the Gros Ventre Slide that released along a dip slope in 1925.

The Pinedale outwash terraces that cover the floor of Jackson Hole decrease in both age and height above the Snake River with distance southward. The age decrease down-valley occurs because the older, up-valley terraces have steeper slopes and are buried down-valley by younger terraces.

West from this viewpoint, the surface of the prominent inset terrace of the Snake River is marked by large-scale flood bars and channels of younger Pinedale (Jackson Lake) age. These flood features were formed by the last of probably many floods about 30-45 feet deep (10-15 m) and 1 mile wide (1.5 km) that rushed from the Deadmans Bar area down this flood flume. The highest and oldest of this flood sequence left longitudinal flood bars locally along the edge of the highest terrace.

Three glacial lobes from the Yellowstone/Absaroka glacial source area fed into Jackson Hole. From here, the locations of these lobes were: 11:00 Snake River lobe, 12:30 Pacific Creek lobe, and 1-2:00- Buffalo Fork lobe. The balance between these lobes changed during the last glaciation from easterly-dominant to westerly-dominant (Pierce and Good, 1992; Good and Pierce, 1996).

Figure 2. Black-and-white Landsat image of the eastern end of the southeast Idaho lineament, crossing the Idaho-Wyoming fold-and-thrust belt (Sevier orogenic belt). Palisades Reservoir is visible just left-of-center. Thin white lines lie parallel to the trend of the lineament.

Resume field trip. Return to Jackson via Highway 191.

Jackson to Alpine, Wyoming via Highway 26

Albee et al. (1977) provide a detailed road log from Jackson to Alpine, Wyoming through the beautiful Snake River Canyon. We will summarize only the major features of this route here. The town of Jackson is located in the common footwall of the thin-skinned (Sevier), southwest-dipping Jackson thrust fault and the thick-skinned (Laramide), northeast-dipping Cache Creek thrust fault, identical to the structural position of Trail Creek Valley on the west side of Teton Pass (Day 1). East and West Gros Ventre Buttes are glacially streamlined, normal fault-bound blocks composed of Paleozoic strata in the hanging wall of the Cache Creek thrust, which passes through the saddle between the main and south summits of East GVB. The Jackson thrust passes through this saddle as well, carrying Paleozoic strata that are exposed on the south summit of East GVB and Snow King Mountain directly south of Jackson. As we leave Jackson and travel south, we cross the trace of the southwest-dipping Jackson thrust near the junction of Highways 22 and 26 (at the saddle) and pass into the Sevier orogenic belt. After crossing Flat Creek, we pick up the trace of the Hoback listric normal fault at the base of the range immediately to the left (west end of Snow King Mountain), which has down-dropped South Park in the hanging wall. Royse et al. (1975) have shown that the Hoback normal fault soles into a thrust ramp within the Jackson thrust sheet, and thus reactivates the Jackson thrust at depth (to the west) with a normal sense of displacement. South Park has been structurally rotated to the east into the Hoback listric normal fault (opposite to the west-tilt of Jackson Hole to the north), causing Flat Creek to hug the east side of South Park instead of flowing west into the Snake River, and forcing the Snake

River to turn almost 90∫ to the southeast towards the Hoback normal fault from its southwest-directed flow along the eastern base of the Teton Range. Where it begins to change direction, southeast of Wilson, the Snake River appears to lose gradient and founder into a braided channel system before reestablishing a meandering channel further downstream to the southeast. These geomorphic changes (valley tilt and fluvial drainage patterns) spatially correspond to the rather abrupt transition from the Cache Creek to Jackson thrust sheets from north to south, and to the change from the west-tilted hanging wall of the Teton normal fault to the east-tilted hanging wall of the Hoback normal fault (Lageson, 1992).

Highway 26 follows the hanging wall of the Hoback listric normal fault between South Park and Hoback Junction. Quaternary sediments and Neogene conglomerates of the Camp Davis Formation overlie the Cretaceous Aspen and Bear River Formations (Albee et al., 1977). The Camp Davis Formation is locally folded on the opposite (east) side of the Snake River. At Hoback Junction, we bear right and continue west on Highway 26 to Alpine. Immediately north of Astoria Hot Springs the Darby thrust fault places Permo-Pennsylvanian strata (Phosphoria and Wells Formations, respectively) over steeply dipping Jurassic and lower Cretaceous strata. Between Astoria Hot Springs and Alpine, Highway 26 winds through the Grand Canyon of the Snake River, traversing the Darby thrust sheet and the eastern portion of the Absaroka thrust sheet. Notable structural features include the Little Greys River anticline in the Darby thrust sheet, the St. Johns imbricate fan (duplicating Cambro-Ordovician strata) in the Absaroka thrust sheet, and the Grand Valley listric normal fault as the canyon opens out into the Grand Valley immediately east of Alpine. Also, the Grand Canyon of the Snake River marks the eastern end of the southeast Idaho lineament (Lageson, 1998).

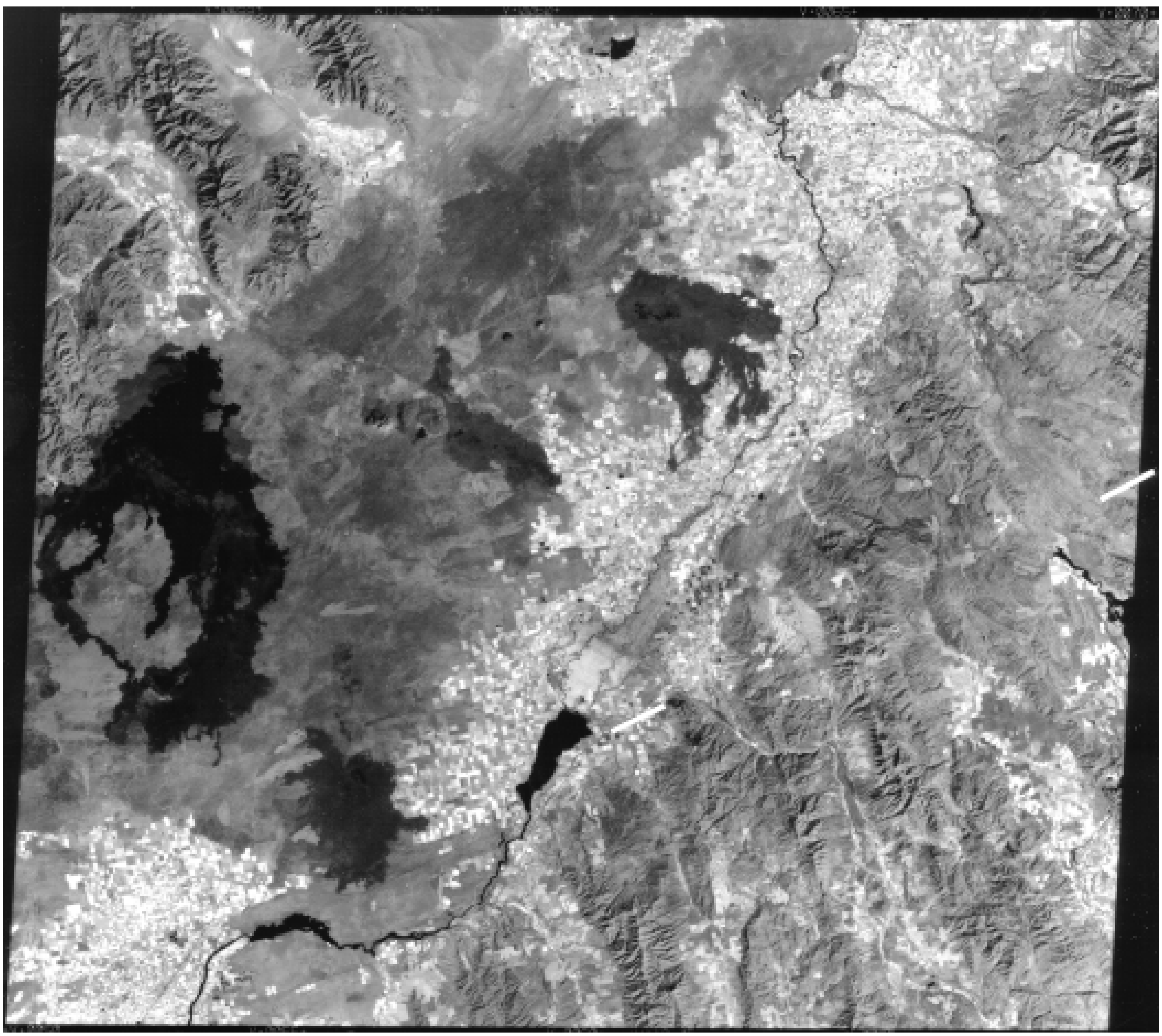

Figure 3. Black-and-white Landsat image of the western end of the southeast Idaho lineament, showing its apparent "truncation" by the eastern Snake River Plain immediately southwest of Pocatello, Idaho. American Falls Reservoir, just west of Pocatello, is clearly visible in the lower-center portion of the image. Thin white lines lie parallel to the trend of the lineament.

Alpine Junction to Pocatello via Grays Lake, Soda Springs and I-15

***Stop 13** – Alpine, Wyoming:*

D.R. Lageson: This locality marks the boundary between neotectonic belts III and IV (Pierce and Morgan, 1992), as well as the boundary between the northern Star Valley segment (ìolder Star Valley faultî of Piety et al., 1986) and Grand Valley segment of the Star Valley-Grand Valley-Swan Valley range-front normal fault system (McCalpin et al., 1990). The Grand Valley normal fault does not offset a ~25-30 ka (Pinedale maximum) outwash terrace (Qt2) at the canyon mouth of the Snake River (Anders, 1990; Piety et al., 1992), testifying to the fact that the northern Star Valley segment has not been active (in the sense of ground-rupturing earthquakes) during the Holocene, quite unlike the southern Star Valley fault near Afton.

The purpose of this leg of the field trip is to highlight some features associated with the ìsoutheast Idaho lineamentî (Lageson, 1998). Trending ~N75E from Pocatello, Idaho on the west to the Grand Canyon of the Snake River on the east (Fig. 2), the lineament is oblique to the ~N45E trending eastern Snake River Plain. The lineament appears to be truncated by the SRP southwest of Pocatello (Fig. 3). Aside from standing out on several generations of satellite imagery (Lageson first identified this lineament on ERTS/Landsat color-IR imagery in the late 1970s), the lineament is defined on the basis of physiographic, geologic, geophysical, and geochemical data.

The most notable physiographic expression of the SE Idaho lineament is the Grand Canyon of the Snake River, which is transversely oriented to the major structural features of western Wyoming and adjacent Idaho (Figs. 2 and 3). The canyon crosses the north-plunge of the Stewart Peak culmination in the Absaroka thrust sheet (Lageson, 1984), it occupies the axis of a major oroclinal bend in the Salt River-Snake River Range, and it corresponds to a segment boundary in the Grand Valley normal fault. Between the Grand Canyon of the Snake River and Pocatello, the lineament roughly corresponds to the northern or southern termination of several northwest-trending linear ranges. From east to west, the lineament lies at the north end of Black Mountain, Bald Mountain, Caribou Mountain, the Little Valley Hills, Wilson Ridge, the Chesterfield Range, and the Portneuf and Pocatello-Bannock Ranges. Again from east to west, the lineament also defines the south end of Poker Peak ridge, Big and Little Elk Mountains, Sheep Mountain, and the Blackfoot Mountains.

The structural expression of the SE Idaho lineament is varied and extensive, but it can be categorized as: a) folds that plunge

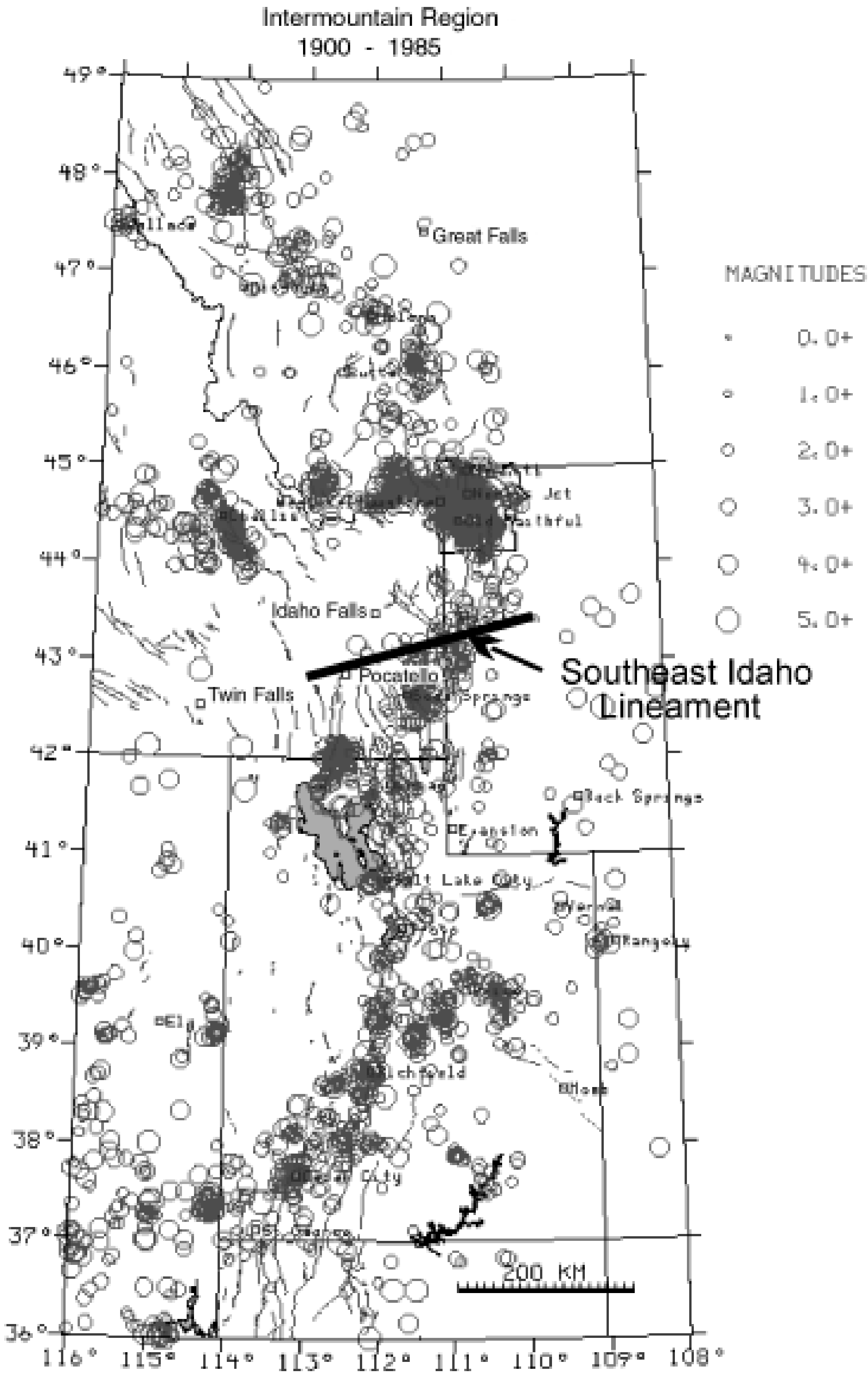

Figure 4. Regional epicenter map of the intermountain seismic belt showing the location of the southeast Idaho lineament and the offset of earthquake epicenters northeast of the lineament. Source: University of Utah Seismograph Station.

north or south into the lineament (e.g., folds in the Caribou Range west of Alpine), b) structures sub-parallel to the lineament (e.g., tear faults in the northern Portneuf Range), c) en echelon folds and faults (e.g., east and west of the north end of Blackfoot Reservoir), and d) small (<3 km) left- and right-lateral offsets across the lineament. Additionally, the lineament is marked by several igneous centers, most notably the Indian Peaks and Caribou Mountain intrusive centers (Neogene hornblende andesites; new $^{40}Ar/^{39}Ar$ dating in-progress as of this writing).

Most significantly, the central intermountain seismic belt is offset to the east on the north side of the lineament, accounting for a major ìkinkî in the spatial pattern of contemporary seismicity throughout this region (Fig. 4). Therefore it appears that the regional bend in the central intermountain seismic belt, from a northeast trend in northern Utah and southeast Idaho to a northwest trend further north, occurs at or near the SE Idaho lineament and not at the Yellowstone hotspot. The lineament may also account for the occurrence of numerous small earthquakes between Soda Springs, Idaho and Jackson, Wyoming that are up to 16 km deep (i.e., within the basement), having no apparent correlation to structure within Phanerozoic rocks (Smith and Arabasz, 1991). Furthermore, the eastern end of the lineament corresponds to the boundary between Quaternary and Neogene range-front faulting (Pierce and Morgan, 1992), and it defines the north end of a gravity/magnetic anomaly under the northern Salt River Range.

Initial interpretations of the SE Idaho lineament are as follows (Lageson, 1998): The SE Idaho lineament is geometrically interpreted to be a regional lateral ramp that spans the Sevier orogenic belt of SE Idaho and western Wyoming. Contractional structures within the Sevier orogen not only plunge into the lineament from the south and north, but they seem to have lateral offset and step up-to-the-south across the lineament (e.g., Stewart Peak culmination). Kinematically, the lineament may have served as a regional tear fault that accommodated differential translation from the hinterland to foreland parts of the Sevier orogen, in effect being parallel to the regional displacement vector. However, some degree of basement-rooted control on the lineament is indicated by igneous centers along its trend and the distribution and depth of seismicity within the central intermountain seismic belt. The SE Idaho lineament appears to have been reactivated during Neogene and Quaternary time as a cross-strike regional feature that has controlled, at least in part, the location of segment boundaries of range-front normal faults, the lateral termination of some ranges, the boundary between neotectonic belts III and IV south of the Snake River Plain (Pierce and Morgan, 1992), and the spatial pattern of contemporary earthquake epicenters. Therefore, the SE Idaho lineament appears to have had a long history of probable basement control over contractional and extensional events across the central intermountain region south of the Snake River Plain. We will discuss many of these features associated with the lineament as we travel across southeast Idaho from Alpine to Pocatello via Grays Lake, Soda Springs, and I-15.

Resume field trip. At Alpine Junction, turn left on Highway 89 (towards Afton) and continue to Freedom, Wayan, Grays Lake, Soda Springs, and Pocatello.

***Stop 14** - Grays Lake area*

Grays Lake is part of a large marsh formed by normal faulting along its west side (K.L. Pierce, field notes). There, the eastern half of basalt vents are down-faulted into the marsh. Pierce took a 20 m core from the central part of the marsh, from which Jane Beiswenger (1991) determined the paleoclimatic history over the last 80,000 years. A lapilli tephra at a depth of 15.5 m correlates with the China Hat rhyolite dome, whose K-Ar age is 61,000±6,000 yrs (G.B. Dalrymple, written communication, 1982).

Continue to Pocatello, Idaho.

END OF ROAD LOG

ACKNOWLEDGMENTS

The authors would like to thank Richard P. Smith and David W. Rodgers for their thorough reviews and helpful suggestions to improve this field guide. We all stand on the shoulders of John David Love of the U.S. Geological Survey when it comes to understanding the geology of Jackson Hole and the Tetons. We also thank the faculty and staff of the Department of Geology at Idaho State University for their hard work and organizational skills in all logistical matters concerning this field trip, and for conducting the last meeting this century of the Rocky Mountain Section of The Geological Society of America.

REFERENCES CITED

Adams, D.C., 1997, Miocene calc-alkaline volcanism in southern Jackson Hole, Wyoming: evidence of subduction-related volcanism [M.S. thesis]: Bozeman, Department of Earth Sciences, Montana State University, 127 p.

Albee, H.F., Lingley, W.S., Jr., and Love, J.D., 1977, Geology of the Snake River Range and adjacent areas, *in* Heisey, E.L., Lawson, D.E., Norwood, E.R., Wach, P.H., and Hale, L.A., eds., Rocky Mountain thrust belt geology and resources: Wyoming Geological Association 29th Annual Field Conference Guidebook (in conjunction with Montana Geological Society and Utah Geological Society), p. 768-783.

Allmendinger, R.W., 1981, Structural geometry of Meade thrust plate in northern Blackfoot Mountains, southeastern Idaho: American Association of Petroleum Geologists Bulletin, vol. 65, no. 3, p. 509-525.

Allmendinger, R.W., 1982, Sequence of late Cenozoic deformation in the Blackfoot Mountains, southeastern Idaho, *in* Bonnichsen, B., and Breckenridge, R.M., eds., Cenozoic geology of Idaho: Idaho Bureau of Mines and Geology Bulletin 26, p. 505-516.

Anders, M.H., 1990, Late Cenozoic evolution of Grand and Swan Valleys, Idaho, *in* Roberts, S., ed., Geologic field tours of western Wyoming and parts of adjacent Idaho, Montana, and Utah: Geological Survey of Wyoming Public Information Circular No. 29, p. 15-25.

Anders, M.H., and Geissman, J.W., 1983, Late Cenozoic structural evolution of Swan Valley, Idaho: EOS, Transactions, American geophysical Union, v. 64, p. 625.

Anders, M.H., Geissman, J.W., Piety, L.A., and Sullivan, J.T., 1989, Parabolic distribution of circum-eastern Snake River Plain seismicity and latest Quaternary faulting: migratory pattern and association with the Yellowstone hot spot: Journal of Geophysical Research, v. 94, p. 1589-1621.

Armstrong, R.L., Leeman, W.P., and Malde, H.E., 1975, K-Ar dating, Quaternary and Neogene volcanic rocks of the Snake River Plain, Idaho: American Journal of Science, v. 275, p. 225-251.

Armstrong, R.L., Harakal, J.E., and Neill, W.M., 1980, K-Ar dating of Snake River Plain (Idaho) volcanic rocks – new results: Isochron/West, no. 27, p. 5-10.

Beiswenger, J.M., 1991, Late Quaternary vegetational history of Grays Lake, Idaho: Ecological Monographs, v. 61, p. 165-182.

Boyer, S.E., and Hossack, J.R., 1992, Structural features and emplacement of surficial gravity-slide sheets, northern Idaho-Wyoming thrust belt, *in* Link, P.K., Kuntz, M.A., and Platt, L.B., eds., Regional geology of eastern Idaho and western Wyoming: Geological Society of America Memoir 179, p. 197-213.

Byrd, J.O.D., 1995, Neotectonics of the Teton fault, Wyoming [Ph.D. thesis]: Salt Lake City, University of Utah, 213 p.

Byrd, J. O. D., Smith, R.B., and Geissman, J.W., 1994, The Teton fault, Wyoming: topographic signature, neotectonics and mechanism of deformation, Journal of Geophysical Research, vol. 99, p. 20,122-20,140.

Christiansen, R.L, 1984, Yellowstone magmatic evolution: Its bearing on understanding large-volume explosive volcanism: *in* Studies in Geophysics: Explosive Volcanism: Inception, Evolution, and Hazards, National Academy Press, 1984, p. 84-95.

Dixon, J.S., 1982, Regional structural synthesis, Wyoming salient of western overthrust belt: American Association of Petroleum Geologists Bulletin, v. 66, p. 1560-1580.

Gilbert, J.D., Ostenna, D., and Wood, C., 1983, Seismotectonic study, Jackson Lake Dam and Reservoir, Minidoka Project, Idaho-Wyoming: U.S. Bureau of Reclamation Seismotectonic Report 83-8, 122 p. and 11 appendices.

Good, J.M., and Pierce, K.L., 1996, Interpreting the landscapes of Grand Teton and Yellowstone National Parks: recent and ongoing geology: Grand Teton Natural History Association, Moose, WY, 58 p.

Greeley, R., and King, J.S., 1977, Volcanism of the eastern Snake River Plain, Idaho: a comparative planetary geology guidebook: NASA, CR-154621, 308 p.

Hackett, W.R., and Morgan, L.A., 1988, Explosive basaltic and rhyolitic volcanism of the eastern Snake River Plain, Idaho, *in* Link, P.K., and Hackett, W.R., eds., Guidebook to the geology of central and southern Idaho: Idaho Geological Survey Bulletin 27, p. 283-301.

Hotchkiss, S.A., 1976, The geology of Hell's Half Acre area, southeast Idaho [M.S. thesis]: Pocatello, Idaho State University, Pocatello.

Kellogg, K.S., 1992, Cretaceous thrusting and Neogene block rotation in the northern Portneuf Range region, southeastern Idaho, *in* Link, P.K., Kuntz, M.A., and Platt, L.B., eds., Regional geology of eastern Idaho and western Wyoming: Geological Society of America Memoir 179, p. 95-113.

Kellogg, K.S., and Marvin, R.F., 1988, New potassium-argon ages, geochemistry, and tectonic setting of upper Cenozoic volcanic rocks near Blackfoot, Idaho: U.S. Geological Survey Bulletin 1086, 19 p.

Kellogg, K.S., and five others, 1989, New ages on biotite-bearing tuffs of the eastern Snake River Plain, Idaho: stratigraphic and mantle-plume implications: Geological Society of America Abstracts with Programs, v. 21, p. 101.

Kuntz, M.A., 1989, Geology of Craters of the Moon lava field, Idaho, *in* Smith, R.P., and Downs, W.F., eds., Snake River Plain-Yellowstone volcanic province: American Geophysical Union, 28th International Geological Congress Field Trip Guidebook T305, p. 51-61.

Kuntz, M.A., Downs, W.F., Smith, R.P., and Ruebelmann, K.L., 1989, Geology of the Snake River Plain from Idaho Falls to Arco, Idaho, *in* Smith, R.P., and Downs, W.F., eds., Snake River Plain-Yellowstone volcanic province: American Geophysical Union, 28th International Geological Congress Field Trip Guidebook T305, p. 48- 49.

Kuntz, M.A., and Dalrymple, G.B., 1979, Geology, geochronology and potential volcanic hazards in the Lava Ridge-Hell's Half Acre area, eastern Snake River Plain, Idaho: U.S. Geological Survey Open-File Report 79-1657, 65 p.

Lageson, D.R., 1984, Structural geology of the Stewart Peak culmination, Idaho-Wyoming thrust belt: American Association of Petroleum Geologists Bulletin, vol. 68, no. 4, p. 401-416.

Lageson, D.R., 1992, Possible Laramide influence on the Teton normal fault, western Wyoming, *in* Link, P.K., Kuntz, M.A., and Platt, L.B., eds., Regional geology of eastern Idaho and western Wyoming; Geological Society of America Memoir 179, p. 183- 196.

Lageson, D.R., 1998, The southeast Idaho lineament: a regional transverse structural discontinuity: EOS, Transactions, American Geophysical Union, in press.

Leeman, W.P., 1982, Development of the Snake River Plain-Yellowstone Plateau province, Idaho and Wyoming: an overview and petrologic model, *in* Bonnichsen, B., and Breckenridge, R.M., eds., Cenozoic geology of Idaho: Idaho Bureau of Mines and Geology Bulletin 26, p. 155-178.

Leeman, W.P., 1989, Origin and development of the Snake River Plain (SRP)—an overview, *in* Ruebelman, K.L., ed., Snake River Plain-Yellowstone Volcanic Province: American Geophysical Union, 28th International Geological Congress Field Trip Guidebook T305, p. 4-13.

Love, J.D., 1989, Yellowstone and Grand Teton National Parks and the Middle Rocky Mountains: 28th International Geological Congress Field Trip Guidebook T328, American Geophysical Union, Washington, D.C., 93 p.

Love, J.D., and Love, J.M., 1983, Road log, Jackson to Dinwoody and return: Geological Survey of Wyoming Public Information Circular No. 20, 34 p.

Love, J.D., and Love, J.M., 1988, Geologic road log of part of the Gros Ventre River Valley including the Lower Gros Ventre slide: Geological Survey of Wyoming Reprint 46, 14 p.

Love, J.D., L.A Morgan, and W.C. McIntosh, 1997, The Teewinot Formation: Evidence for late Miocene basin formation in response to volcanism, faulting, and uplift associated with the Yellowstone hotspot?: Geological Society of America Abstracts with programs, p. A-365.

Love, J.D., and Reed, J.C., 1971, Creation of the Teton landscape: Grand Teton Natural History Association, Moose, WY, 120 p.

Love, J.D., Reed, J.C., Jr., and Christiansen, A.C., 1992, Geologic map of Grand Teton National Park, Teton County, Wyoming: U.S. Geological Survey Map I-2031, 1:62,500.

McCalpin, J.P., Piety, L.A., and Anders, M.H., 1990, Latest Quaternary faulting and structural evolution of Star Valley, Wyoming, *in* Roberts, S., ed., Geologic field tours of western Wyoming and parts of adjacent Idaho: Geological Survey of Wyoming Public Information Circular 29, p. 5-12.

Morgan, L. A., 1992, Stratigraphic relations and paleomagnetic and geochemical correlations of ignimbrites of the Heise volcanic field, eastern Snake River Plain, eastern Idaho and western Wyoming, *in* Link, P.K., Kuntz, M.A., and Platt L.B., eds., Regional Geology of Eastern Idaho and Western Wyoming, Geological Society of America Memoir 179, p. 215-226.

Morgan, L.A., and Bonnichsen, B., 1989, Heise volcanic field: New Mexico Bureau of Mines and Mineral Resources Memoir 47, p. 153-160.

Morgan, L.A., and McIntosh, W.C., in press, $^{40}Ar/^{39}Ar$ ages of silicic volcanic rocks in the Heise volcanic field, eastern Snake River Plain, Idaho: Timing of volcanism and tectonism: submitted to Idaho Geological Survey, volume on "Tectonic and Magmatic Evolution of the Snake River Plain Volcanic Province."

Pierce, K.L., and Good, J.M., 1990, Quaternary geology of Jackson Hole, Wyoming, *in* Roberts, S., ed., Geologic field tours of western Wyoming and parts of adjacent Idaho, Montana, and Utah: Geological Survey of Wyoming Public Information Circular No. 29, p. 79-87.

Pierce, K.L., and Good, J.D., 1992, Field guide to the Quaternary geology of Jackson Hole, Wyoming: U.S. Geological Survey Open File Report 92-504, 54 p.

Pierce, K.L., Lundstrom, S., and Good, J., 1998, Geologic setting of archeological sites in the Jackson Lake area, Wyoming, *in* Connor, M., ed., Final report on the Jackson Lake archeological project, Grand Teton National Park, Wyoming: Midwest Archeological Center [Lincoln, Nebraska], National Park Service Technical Report No. 46, p. 29-48 and 19 figures, p. 222-242.

Pierce, K.L., and Morgan, L.A., 1992, The track of the Yellowstone hot spot: volcanism, faulting and uplift, *in* Link, P.K., Kuntz, M.A., and Platt, L.B., eds., Regional geology of eastern Idaho and western Wyoming: Geological Society of America Memoir 179, p. 1-53.

Pierce, K.L., and Scott, W.E., 1986, Migration of faulting along and outward from the track of thermo-volcanic activity in the eastern Snake River Plain region during the last 15 m.y.: EOS, Transactions, American Geophysical Union, v. 67, p. 1225.

Piety, L.A., Wood, C.K., Gilbert, J.D., Sullivan, J.T., and Anders, M.H., 1986, Seismotectonic study for Palisades Dam and Reservoir, Palisades Project: U.S. Bureau of Reclamation Seismotectonic Report 86-3, 198 p.

Piety, L.A., Sullivan, J.T., and Anders, M.A., 1992, Segmentation and paleoseismicity of the Grand Valley fault, southeastern Idaho and western Wyoming, *in* Link, P.K., Kuntz, M.A., and Platt, L.B., eds., Regional geology of eastern Idaho and western Wyoming: Geological Society of America Memoir 179, p. 15-182.

Roberts, S.V., and Burbank, D.W., 1993, Uplift and thermal history of the Teton Range (northwestern Wyoming) defined by apatite fission-track dating: Earth and Planetary Science Letters, vol. 118, p. 295-309.

Rodgers, D.W., Hackett, W.R., and Ore, H.T., 1990, Extension of the Yellowstone plateau, eastern Snake River Plain, and Owyhee plateau: Geology, v. 18, p. 1138-1141.

Royse, F., Jr., Warner, M.A., and Reese, D.L., 1975, Thrust belt structural geometry and related stratigraphic problems, Wyoming-Idaho-Northern Utah, *in* Bolyard, D.W., ed., Symposium on deep drilling frontiers in the central Rocky Mountains: Rocky Mountain Association of Geologists, Denver, CO, p. 41-54.

Schroeder, M.L., 1969, Geologic map of the Teton Pass quadrangle, Teton County, Wyoming: U.S. Geological Survey Map GQ-793, 1:24,000.

Schroeder, M.L., 1972, Geologic map of the Rendezvous Peak quadrangle, Teton County, Wyoming: U.S. Geological Survey Map GQ-980, 1:24,000.

Scott, W.E., 1982, Surficial geologic map of the eastern Snake River Plain and adjacent areas, 111° to 115° W., Idaho and Wyoming: U.S. Geological Survey Miscellaneous Investigations Map I-1372, 1:250,000.

Smith, R.B., and Arabasz, W.J., 1991, Seismicity of the intermountain seismic belt, *in* Slemmons, D.B., Engdahl E.R., Zoback, M.D., and Blackwell, D.D., eds., Neotectonics of North America: Geological Society of America Decade Map Volume 1, p. 185-228.

Smith, R.B., and Braile, L.W., 1993, Topographic signature, space-time evolution, and physical properties of the Yellowstone-Snake River Plain volcanic system: the Yellowstone hotspot, *in* Snoke, A. W., Steidtmann, J., and Roberts, S.M., eds., Geology of Wyoming: Geological Survey of Wyoming Memoir No. 5, p. 694-754.

Smith, R.B., Byrd, J. O. D., and Susong, D.D., 1990, Neotectonics and structural evolution of the Teton fault, *in* Roberts, S., ed., Geologic field tours of western Wyoming and parts of adjacent Idaho, Montana, and Utah: Geological Survey of Wyoming Public Information Circular No. 29, 126-138.

Smith, R.B., Byrd, J.O.D., and Susong, D.D., 1993a, The Teton fault, Wyoming: seismotectonics, Quaternary history, and earthquake hazards, *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., eds., Geology of Wyoming: Geological Survey of Wyoming Memoir No. 5, p. 628-667.

Smith, R.B., Pierce, K.L., and Wold, R.J., 1993b, Quaternary history and structure of Jackson Lake, Wyoming, from seismic reflection surveys, *in* Snoke, A.W., Steidtmann, J., and Roberts, S.M., eds., Geology of Wyoming: Geological Survey of Wyoming Memoir No. 5, p. 668-693.

Smith, R.B., Richins, W.D., and Doser, D.I., 1985, The Borah Peak earthquake: Seismicity, faulting kinematics and tectonic mechanism: Workshop XXVIII on “The Borah Peak Earthquake,” U. S. Geological Survey Open-File Report, 85-290, 236-263.

Smith, R.B., and Siegel, L., 1999, A Window On Earth: The Geologic Story Of Yellowstone and Grand Teton National Parks: Oxford University Press (in press).

Smith, R.P., and Downs, W.F., 1989, Snake River Plain-Yellowstone volcanic province: American Geophysical Union, 28th International Geological Congress Field Trip Guidebook T305, 103 p.