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NEOGENE NORMAL FAULTS RELATED TO THE STRUCTURAL ORIGIN
OF THE EASTERN SNAKE RIVER PLAIN, IDAHO

by

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A thesis submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE

IN

GEOLOGY

IDAHO STATE UNIVERSITY

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ACKNOWLEDGEMENTS

Dr. Dave Rodgers has been with me every step of the way, not only with this thesis, but with everything I've done here during the last three years. I couldn't have asked for an advisor more suited to my personality. He has managed to get me enthused about structural geology, and as a result, I feel good about my learning and teaching abilities. He has also taught me how to think. Without Dave's valuable input, I'd still be sitting in the back of the room pretending to be in the discussion.

Dr. Bill Hackett and Dr. Falma Moye have also been very helpful with this study. Bill has given advice ranging from the petrology of the ESRP to the aperture of the camera. Falma has been loyal enough to visit my field area numerous times, and her insight out there was always fresh. Dr. Paul Link was not involved directly with the thesis, but his contributions to my stay here have been numerous.

This thesis has also been supported by people outside of our geology department. Dr. Glen Embree of Ricks College introduced me to the stratigraphy of the Hesse volcanics and got me started out in the field. The State of Idaho, the Geological Society of America, and the I.S.U. Graduate Student Research Council all contributed to the funding of this study.

Thanks to the people and organizations mentioned here. I will always remember these past three years as the turning point of my life.

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NEOGENE NORMAL FAULTS RELATED TO THE STRUCTURAL ORIGIN OF THE EASTERN SNAKE RIVER PLAIN, IDAHO

Nicolaus C. Zentner

Thesis Abstract - Idaho State University (1989)

A northeast-striking normal fault set is present along the margins of the eastern Snake River Plain (ESRP) in eastern Idaho. In the southern Beaverhead Mountains, detailed field mapping has identified northeast-striking normal faults with steep dips (65° to 75°) both to the southeast towards the plain and to the northwest away from the plain. Dip-slip offset on these faults is minor (less than 100 meters), resulting in minor northwest-southeast extension of the crust. Faulting occurred between 4.3 Ma and about 2.0 Ma, and was coeval with movement on northwest-striking Basin and Range normal faults. Compilation of published studies along the northern and southern margins of the ESRP illustrates that northeast-striking normal faults are ubiquitous along the flanks of the ESRP within 30 kilometers of the plain's margins. The faults everywhere offset strata younger than 10 Ma and show no evidence for substantial strike-slip movement.

The development of northeast-striking normal faults, in an area dominated by northwest-striking normal faults of the Basin and Range Province, is inferred to be related to the apparent passage of the Yellowstone 'hot spot' and the subsequent structural development of the eastern Snake River Plain. It is proposed that these faults have formed in response to buckling and lateral thermal contraction of the uppermost crust during downwarping of the ESRP. Downwarped ESRP uppermost crust, which is offset along a major normal fault beneath the plain's northern margin, may be due to thickening of the high-density lower crust, silicic caldera collapse, vertical thermal contraction, surface loading by Quaternary basalt, and/or half graben-style faulting due to NW-SE extension. A ESRP subsidence model is proposed which incorporates the different processes.

INTRODUCTION

The eastern Snake River Plain (ESRP), which extends from Twin Falls, Idaho northeastward to Yellowstone National Park, is a volcanic province that has been active during the last 10 million years [Armstrong and others, 1975] (Fig. 1). On the plain, Quaternary basalts overlie voluminous rhyolitic ash-flow tuffs and lava flows, but along the plain's margins ash-flow sheets are exposed. These rhyolites generally become younger from southwest to northeast, indicating a unique age progression of the ESRP's volcanism [Armstrong and others, 1975]. Volcanism of the ESRP is attributed to a thermal plume, or 'hot spot', such that the North American continent migrates to the southwest over the plume as the locus of volcanism shifts northeastward (Morgan, 1972; Suppe and others, 1975).

The ESRP is a structural depression with respect to the surrounding Basin and Range Province, and in comparison to the Yellowstone Plateau where the plume is presently located. Depression of the ESRP is inferred to be the result of subsidence after passage of the 'hot spot'. This thesis will focus on the subsidence of the ESRP. Specifically, the objectives of this project are (1) to document the surficial expression of subsidence of the ESRP, (2) to identify the processes responsible for the subsidence, (3) to determine the relative timing of these processes, (4) to determine the relation of ESRP subsidence to Basin and Range tectonism, and (5) to illustrate the spatial and temporal relation of normal faults to the passage of a 'hot spot'.

The data presented in this paper were collected both from field mapping along the eastern Snake River Plain's northern margin and by compilation of published geologic maps that have been completed along the plain's northern and southern margins. Field mapping and structural analysis of the Lidy Hot Springs area (Fig. 1) was completed to document the styles and geometries of normal faults related to the subsidence of the ESRP. To understand the more regional problem of the structural history of the ESRP, structures along both margins of the ESRP were located using existing maps, and interpreted using the new results from the

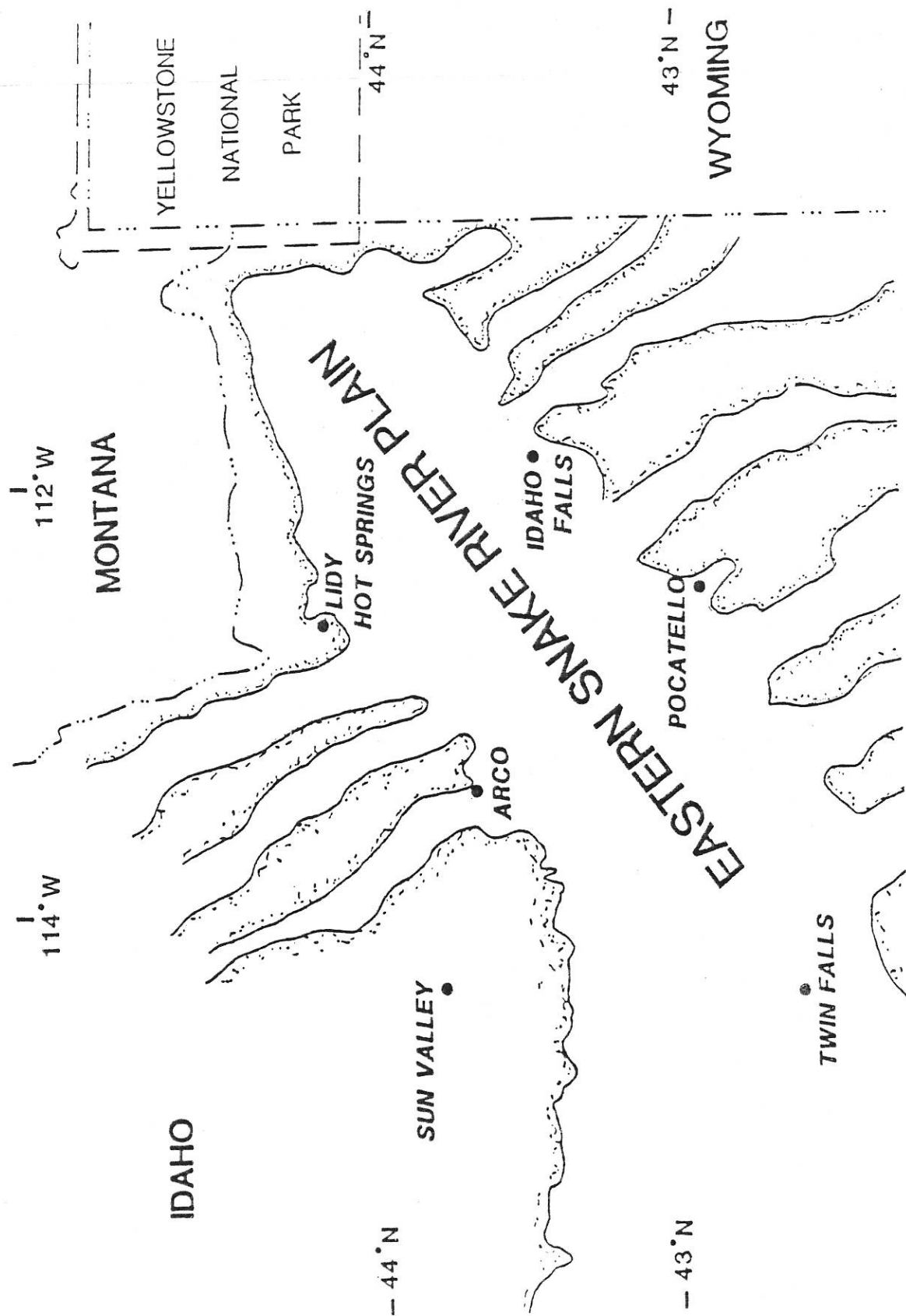


Figure 1: Location map of the eastern Snake River Plain, showing major cities and the Lidy Hot Springs study site.

Lidy Hot Springs area.

The resulting patterns and timing of ESRP-related normal faults have been used to interpret the timing and spatial relations of extension and subsidence in the wake of the Yellowstone 'hot spot'. The data have been used to model various mechanisms of ESRP subsidence. Previous workers have proposed models of ESRP origin based on the plain's petrologic and geophysical characteristics [Sparlin and others, 1982; Braile and others, 1982; Smith and others, 1982], but few investigate the effects that these processes might have on the plain's structural subsidence. This paper will investigate the relative roles of crustal thermal contraction, crustal loading by basalts, magma chamber evacuation, and lower crustal thickening as contributors to the subsidence of the ESRP.

REGIONAL GEOLOGIC SETTING

The eastern Snake River Plain of Idaho is one of the most conspicuous topographic, geologic, and geophysical features of western North America. Trending northeast, the eastern Snake River Plain cuts orthogonally across northwest-trending mountains and valleys of the northern Basin and Range Province. In the following section, the geology of the more extensive Basin and Range Province is described, followed by a description of the ESRP.

BASIN AND RANGE PROVINCE

The Basin and Range Province is characterized by north to northwest-trending mountain ranges and sedimentary basins which have formed during east-west, late Cenozoic extension [Stewart, 1978; Eaton, 1982]. The province extends from southern Oregon and Idaho through most of Nevada and parts of California, Utah, Arizona, New Mexico, and northern Mexico (Fig. 2).

Basin and Range structure within the province has generally been related to block faulting, with ranges formed by uplift along extensive, high-angle normal faults on one or both sides of the mountain blocks [Stewart, 1978]. However, faulting is not only confined to the sides of mountains but is distributed throughout the mountain areas and presumably in the subsurface rocks of the valleys. In addition, detailed field mapping since the mid-1970's has shown that normal faults may progressively rotate from high (60°) to low (10°) angles [Proffett, 1977; Gans and Miller, 1983] as blocks are tilted, or they may form at initially low angles [Wernicke, 1981].

As a result, three general models of basin-range structure in the Great Basin have been proposed [Stewart, 1978]. The first model, the horst-and-graben model, relates the structure to a system of downthrown blocks (grabens) that form valleys, and upthrown blocks (horsts) that form mountains (Fig. 3, model A). The second model relates the structure to a system of structural blocks rotated along curving, downward-flattening listric normal faults. The

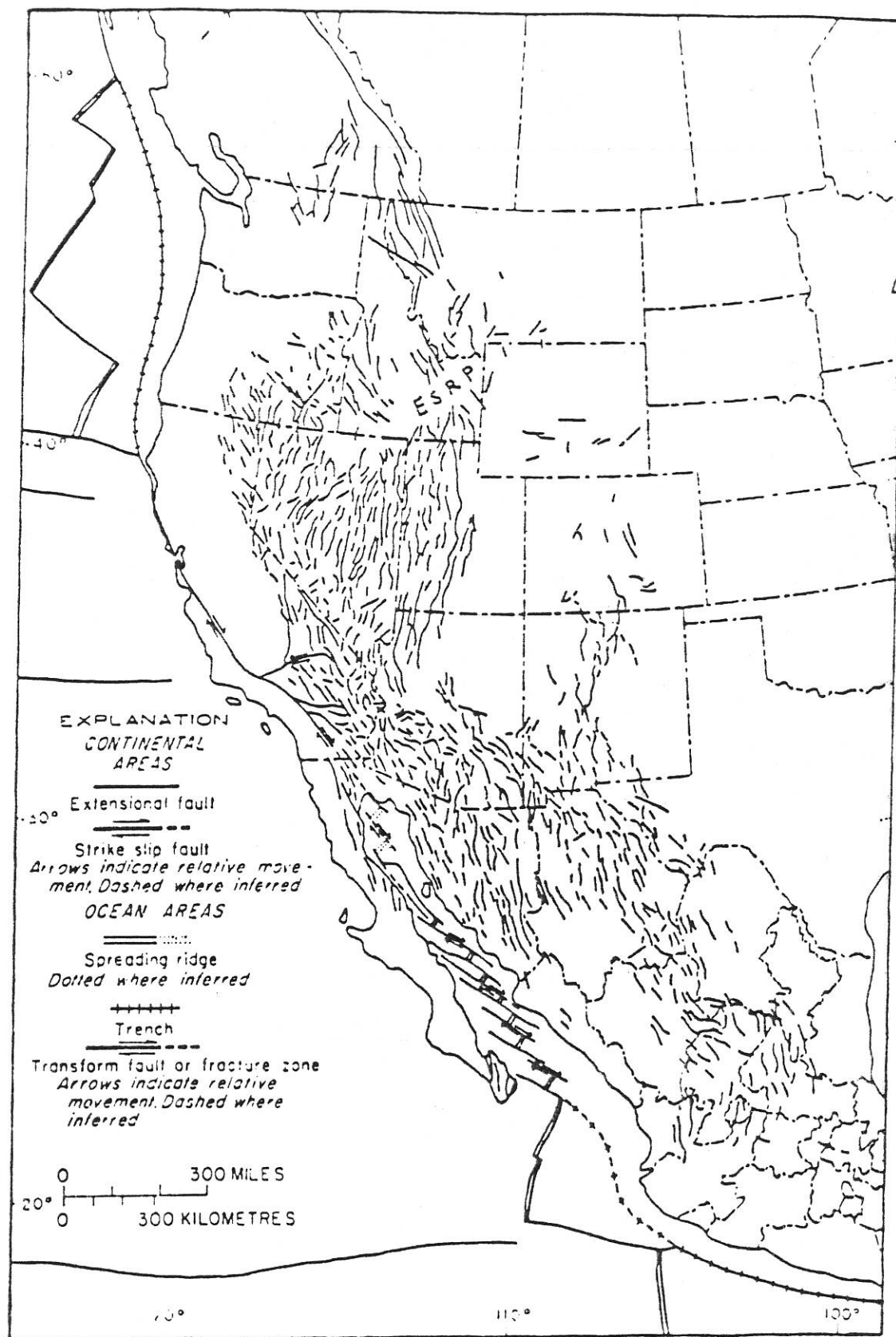
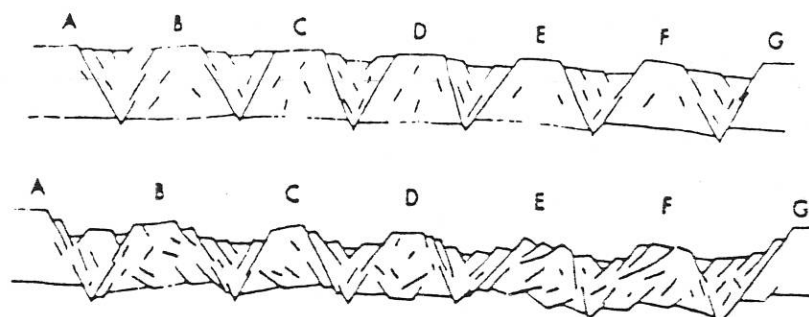
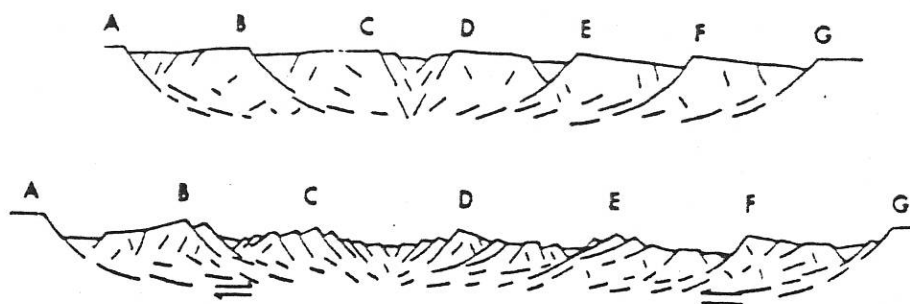


Figure 2: Distribution of late Cenozoic normal faults in western North America. Faults are generalized and, in part, inferred.

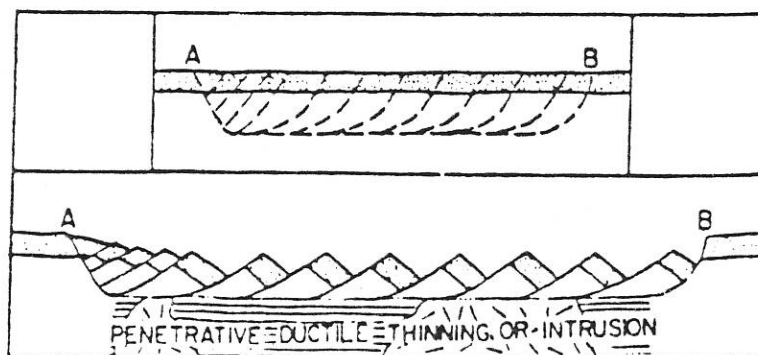
(from Stewart, 1978)



MODEL A. HORSTS AND GRABENS FORMED BY
FRAGMENTATION AND SEGMENTATION
INTO BUOYANT BLOCKS
(from Stewart, 1978)



MODEL B. TILTED BLOCKS RELATED TO
DOWNWARD-FLATTENING (LISTRIC) FAULTS
(from Stewart, 1978)



MODEL C. LOW-ANGLE FAULT MOSAIC SOLES
INTO AN UNDERLYING BASAL FAULT
(from Wernicke, 1981)

Figure 3: Three general models of basin-range structure in the Basin and Range Province. Models show early and late stages of development.

uplifted part of an individual block forms a mountain, and the downdropped part a valley (Fig. 3, model B). A third model relates the structure to a system of high- and low-angle normal faults which 'bottom out' into a single, subhorizontal fault zone below which plastic deformation occurs (Fig. 3, model C) [Wernicke, 1981].

The entire Basin and Range Province is characterized by thin, extended crust, and high heat flow. The crust throughout the province is about 32 km thick [Klemperer and others, 1986], based on P-wave velocity values of 6.7 km/s for the lower crust and 7.9 km/s for the upper mantle. Basin-and-range structures have been produced by east-west extension of the Great Basin region, which has extended the crust of the Basin and Range Province by a factor of about 2 to 3 [Wernicke and others, 1988]. Heat flow values throughout the Basin and Range Province, which are high in comparison to the North American craton, average around 60 mW m⁻² [Blackwell, 1978].

EASTERN SNAKE RIVER PLAIN

The eastern Snake River Plain (ESRP), an aseismic region, is a unique volcanic province. Until the 1970's, the ESRP was thought to be the site of mainly basaltic volcanism, but subsequent evidence from subsurface drilling and geophysical studies indicate that rhyolite is the more voluminous component [Doherty and others, 1979; Pankratz and Ackermann, 1982; Morgan and others, 1984]. Basaltic lava flows appear to form only a relatively thin veneer (typically less than 1 km) over rhyolitic ash-flow tuffs and lava flows with intercalated sediments [Doherty and others, 1979; Embree and others, 1979; Morgan and others, 1984].

Rhyolitic ash-flow tuffs and lava flows are the most voluminous and widespread volcanic deposits of the ESRP, but their exposures are limited to the mountains and adjacent valleys along the margins of the plain [Hackett and Morgan, 1988]. Using these limited ash-flow tuff exposures at isolated locations along both margins, workers have correlated major ash-flow sheets on both sides of the plain and have used lateral facies changes within

the sheets to pinpoint their vents [McBroome, 1981; Morgan and others, 1984]. In all cases, the vents are inferred to be calderas, up to 100 km in diameter, which are now buried beneath basalt flows on the plain [Morgan and others, 1984].

An important feature of the ESRP is that the rhyolitic volcanism generally becomes younger from southwest (10 Ma rocks west of Twin Falls) to northeast (0.6 Ma rocks at Yellowstone) [Armstrong and others, 1975]. Likewise, the inferred buried calderas associated with the extensive silicic activity become younger to the northeast, although the precise location and dimensions of the calderas are still debated. Six calderas, three of the Heise volcanic group and three of the Yellowstone volcanic group, are known or inferred to be part of this northeastward age progression (Fig. 4) [Hackett and Morgan, 1988]. Calderas beneath the ESRP southwest of the Heise volcanic group are suspected to exist based on older ash-flow tuffs exposed along the plain's margins, but their location and dimensions have not yet been documented.

Geophysical characteristics of the ESRP distinguish it from the surrounding Basin and Range Province. The crustal thickness of the ESRP averages around 42 km [Sparlin and others, 1982; Braile and others, 1982], which is about 10 km thicker than the crust of the adjacent Basin and Range (Fig. 5). Heat-flow values of the ESRP average around 190 mW m⁻² [Brott and others, 1981], which is about 130 mW m⁻² greater than the heat flow value of the adjacent Basin and Range province. Finally, a broad regional Bouger gravity high exists over the axis of the ESRP [Mabey, 1982].

In 1978, a large-scale seismic refraction profiling experiment was carried out in the Yellowstone-ESRP region by investigators from several American universities, U.S. government agencies, and two European geophysical institutes [Sparlin and others, 1982; Braile and others, 1982; Smith and others, 1982; Schilly and others, 1982]. The experiment produced seismic velocity data (Fig. 6) collected from the ESRP's subsurface, and were interpreted to represent distinct subsurface layers (Fig. 7). With these data, the geophysicists

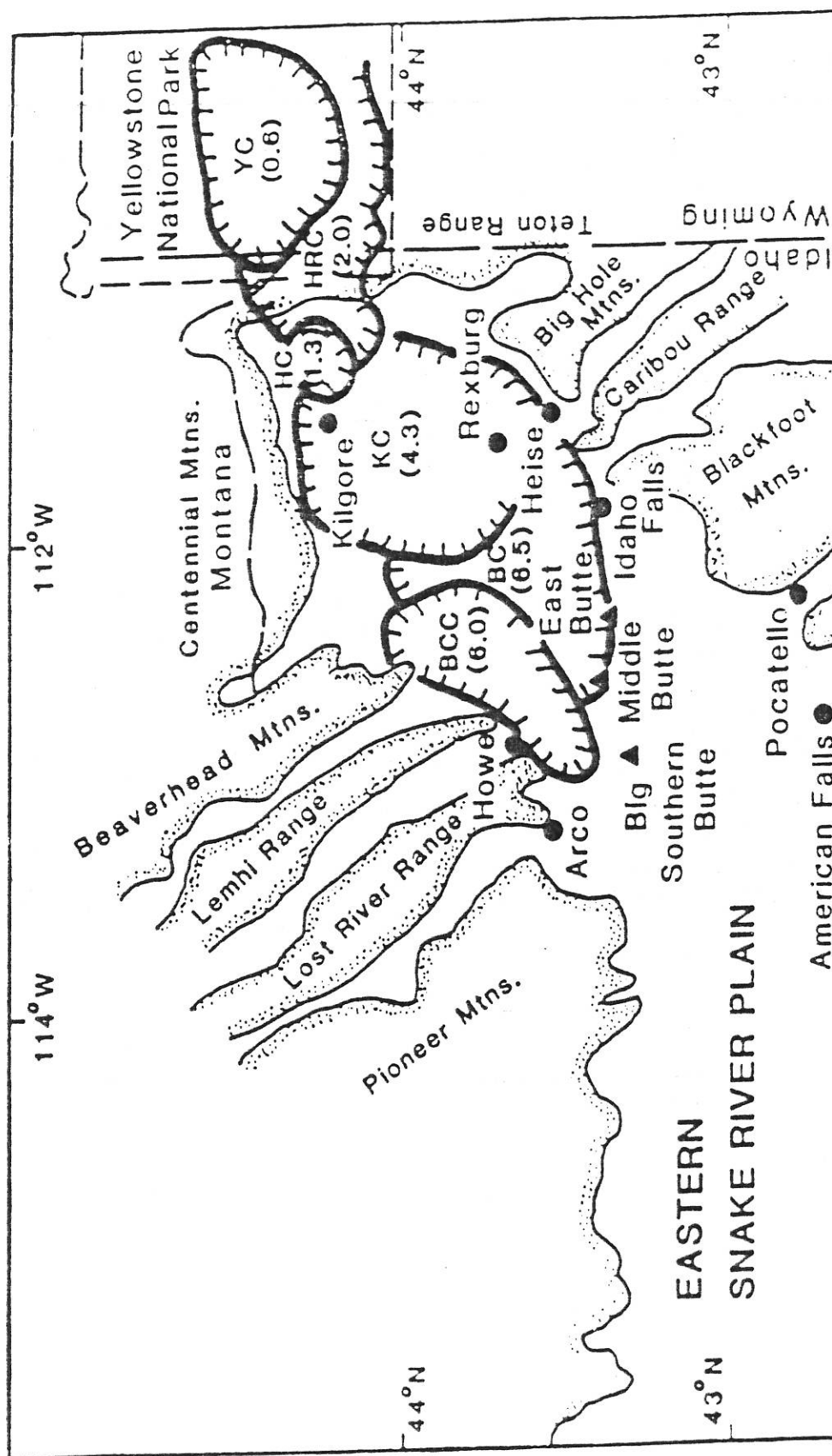


Figure 4: Inferred calderas of the Heise volcanic field and Yellowstone Plateau volcanic field. Ages of calderas (Ma; shown in parentheses) are based on age dates of major ash-flow tuffs. Heise calderas are as follows: BC, Blacktail caldera; BCC, Blue Creek caldera; KC, Kilgore caldera. Calderas of Yellowstone-Island Park region are: HRC, Huckleberry Ridge caldera; HC, Henry's Fork caldera; YC, Yellowstone caldera. (from Hesse, 1981 and McCoy, 1988)

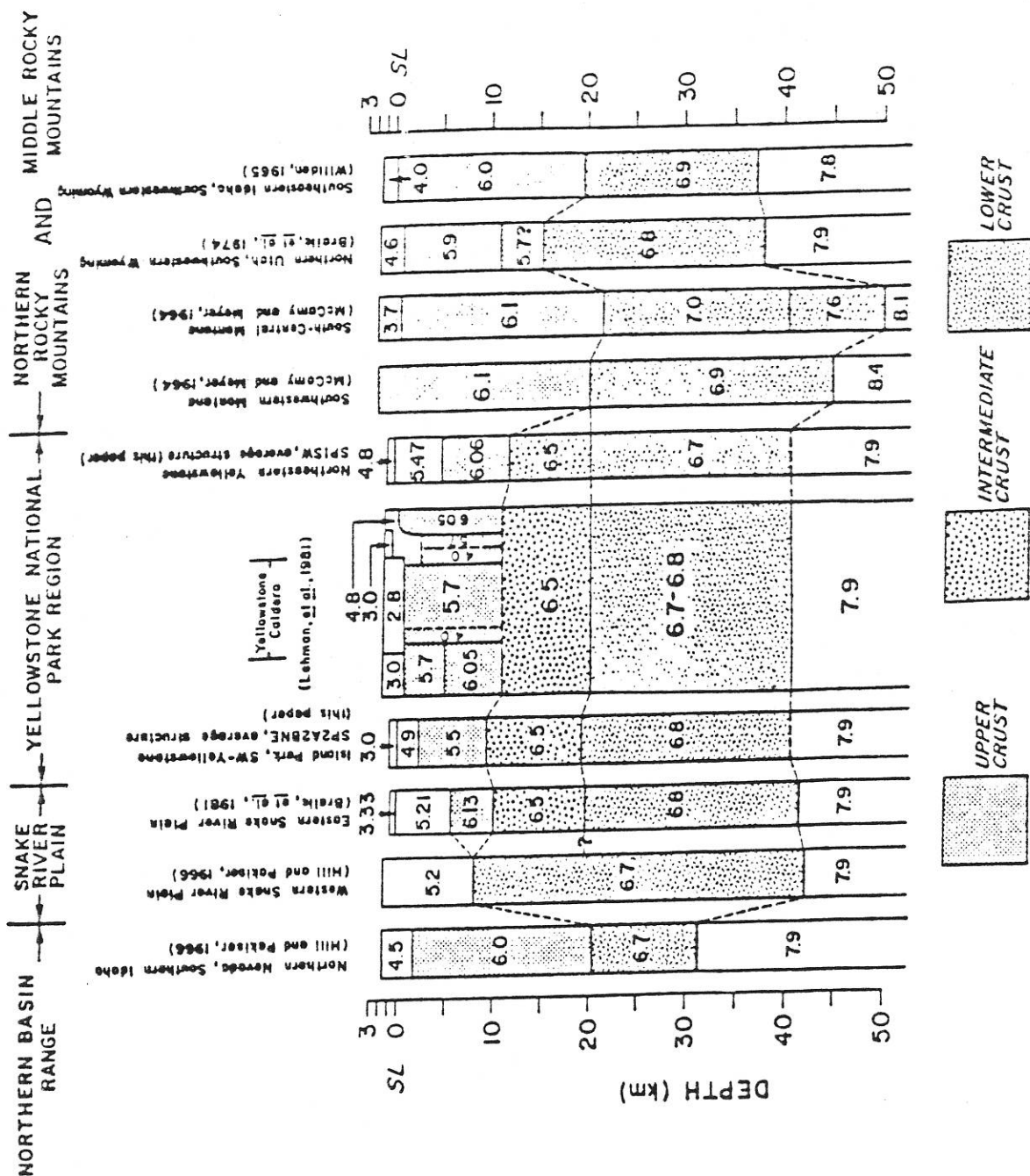


Figure 5: Generalized P wave velocity model for the Yellowstone region for comparison with velocity models for the eastern Snake River Plain, the northern Basin and Range, and the middle and northern Rockies. (from Smith and others, 1982)

SEISMIC VELOCITY DATA FOR E.S.R.P. AND SURROUNDING AREA

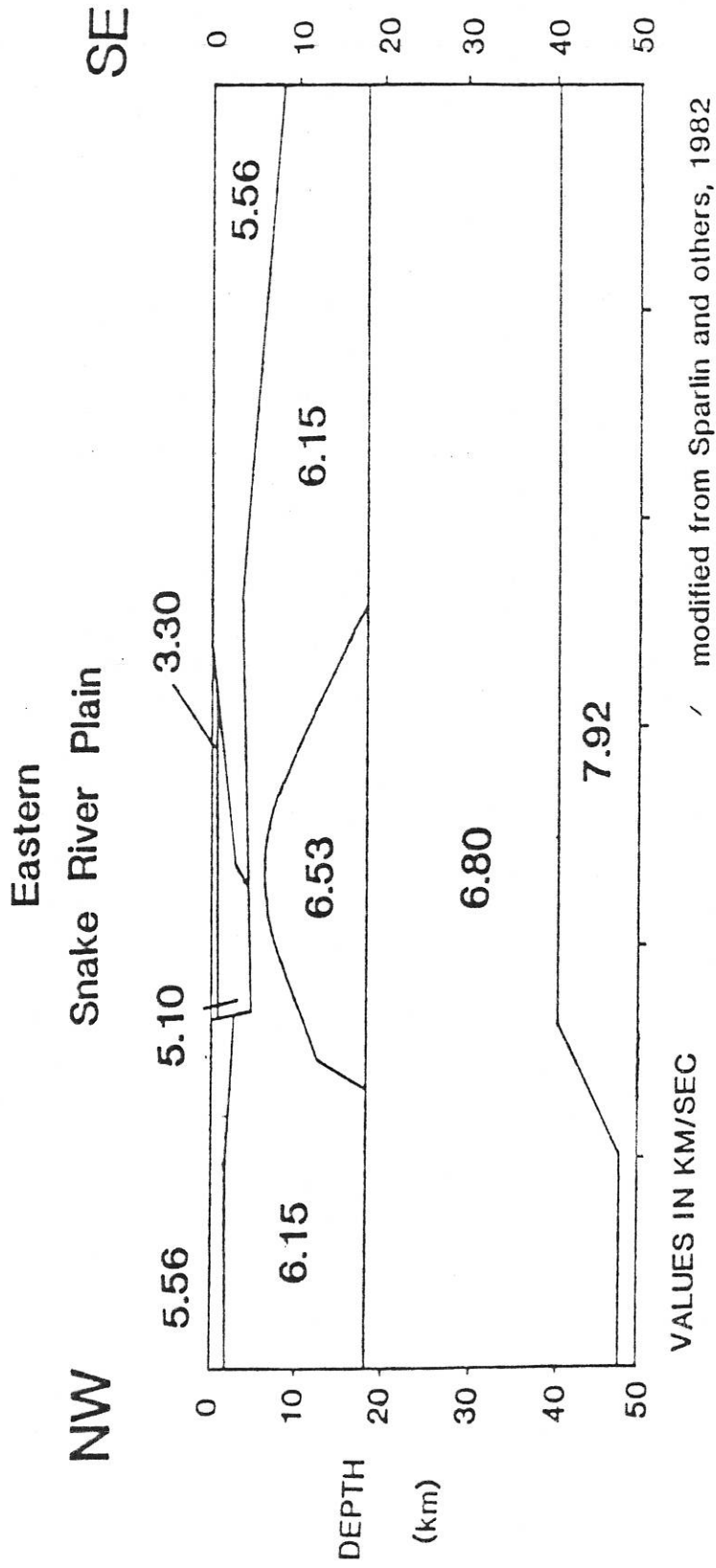


Figure 6: Seismic velocity data for the eastern Snake River Plain and its surrounding area, based on geophysical data collected along a cross section from near Soda Springs, Idaho, to near Mackay, Idaho.

INFERRED GEOLOGICAL MODEL FOR E.S.R.P. AND SURROUNDING AREA

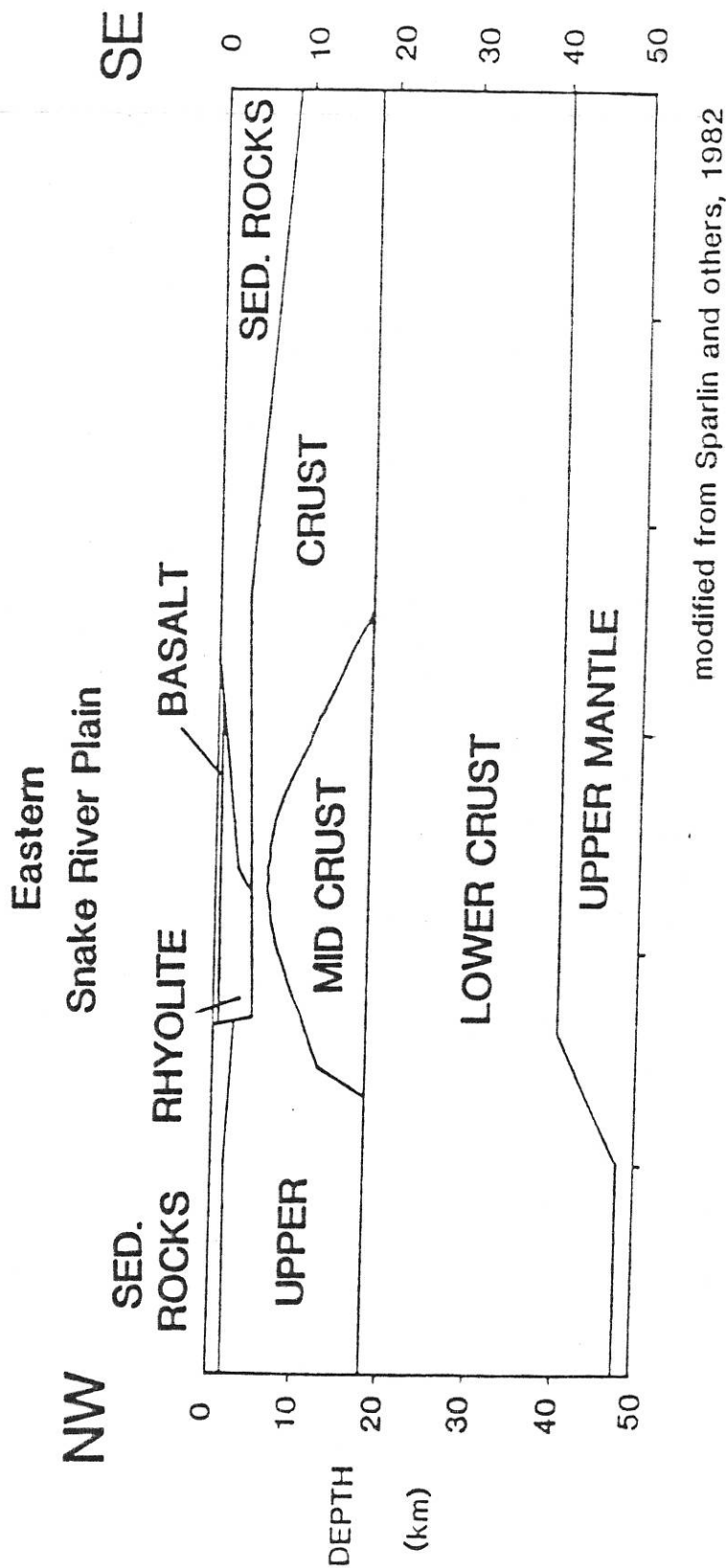


Figure 7: Inferred geological model for the eastern Snake River Plain and its surrounding area, based on geophysical data collected along a cross section from near Soda Springs, Idaho, to near Mackay, Idaho.

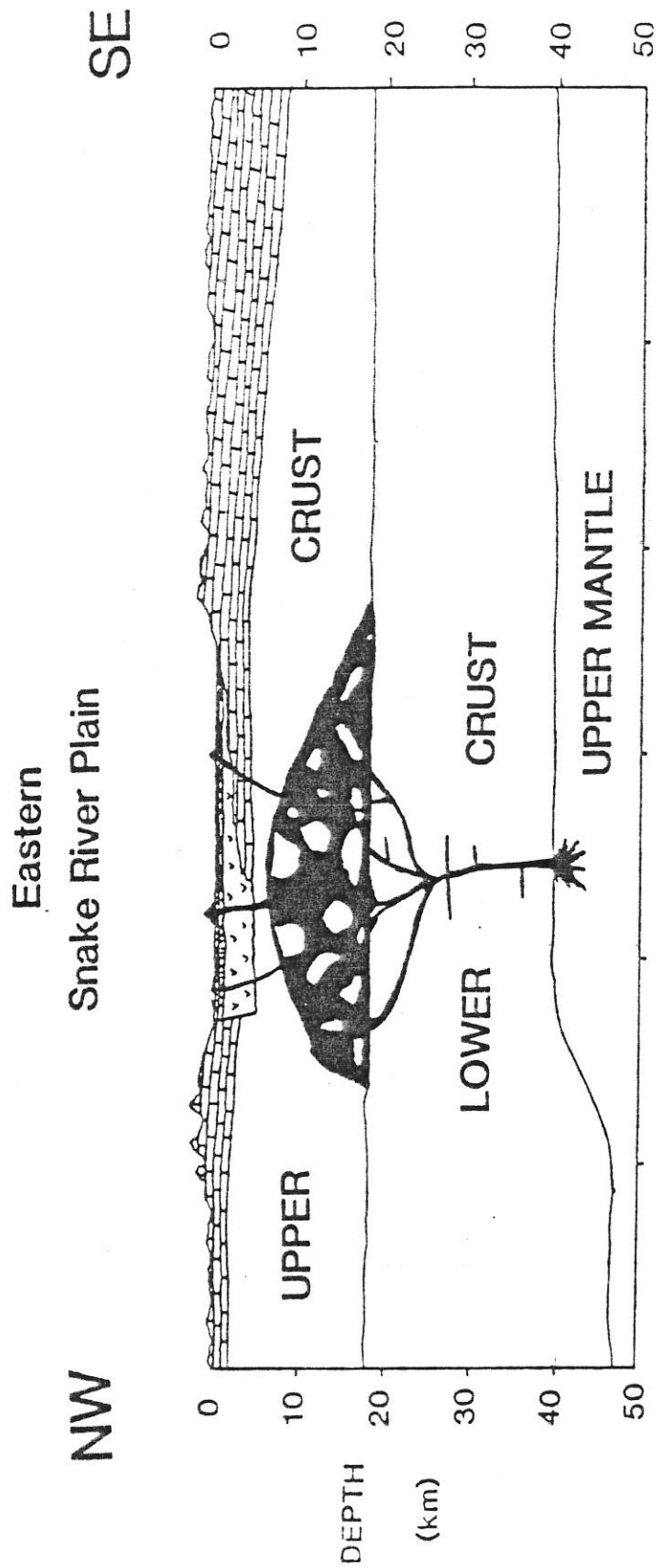
proposed a model for the origin of the ESRP's surface basalt and near surface rhyolite.

The model involves upper crustal underplating of basalt to initiate rhyolitic and basaltic volcanism (Fig. 8) [Sparlin and others, 1982; Braile and others, 1982; Smith and others, 1982]. According to the model, when a section of continental crust is moved over a 'hot spot', basaltic magma from the upper mantle rises rapidly through the lower crust to the base of the upper crust, which causes partial melting of the overlying upper crust, initiating silicic volcanism. As the crust moves past the stationary 'hot spot', cooling of the emplaced basalt generates a high-density (high Bouguer gravity values over ESRP axis), high-velocity (6.5 km/s) intermediate layer in the ESRP, which is unique to the region beneath the plain (Fig. 6). Finally, some of the emplaced basalt, which has not yet cooled, reaches the ESRP surface and floods the previously extruded rhyolite flows and tuffs.

The model proposed by the geophysicists is widely accepted, but the subsurface level at which the emplacement of upper mantle material occurs is unclear. Based on detailed petrologic study of ESRP volcanic rocks, Leeman [1982] agrees that the emplacement of upper mantle mafic material is necessary to initiate silicic and basaltic volcanism, but suggests that the emplacement occurs at the base of the lower crust, instead of at the base of the upper crust. He concludes that (a) the density difference between crust and mantle encourages the mafic material to 'pool' at the base of the crust, (b) the added mafic material from the upper mantle explains the thicker crust beneath the ESRP with respect to the adjacent Basin and Range Province, and (c) the underplating of the lower crust allows both the upper and lower crust to be the source for the voluminous silicic volcanism.

Possibly accompanying the northeastward movement of the locus of active volcanism is a northeast-shifting region of active Basin and Range normal faulting, which is part of a larger zone of seismicity termed a 'seismic parabola', due to its parabolic shape (Fig. 9) [Anders and Piety, 1988]. The parabola is inferred to migrate to the northeast with its vertex centered on the migrating locus of active volcanism, while leaving an aseismic region (today, the ESRP)

SCHEMATIC DIAGRAM ILLUSTRATING CRUSTAL MODEL FOR E.S.R.P. AND SURROUNDING AREA



modified from Sparlin and others, 1982

Figure 8: Schematic diagram illustrating a crustal model for the eastern Snake River Plain and its surrounding area, based on geophysical data collected along a cross section from near Soda Springs, Idaho, to near Mackay, Idaho.

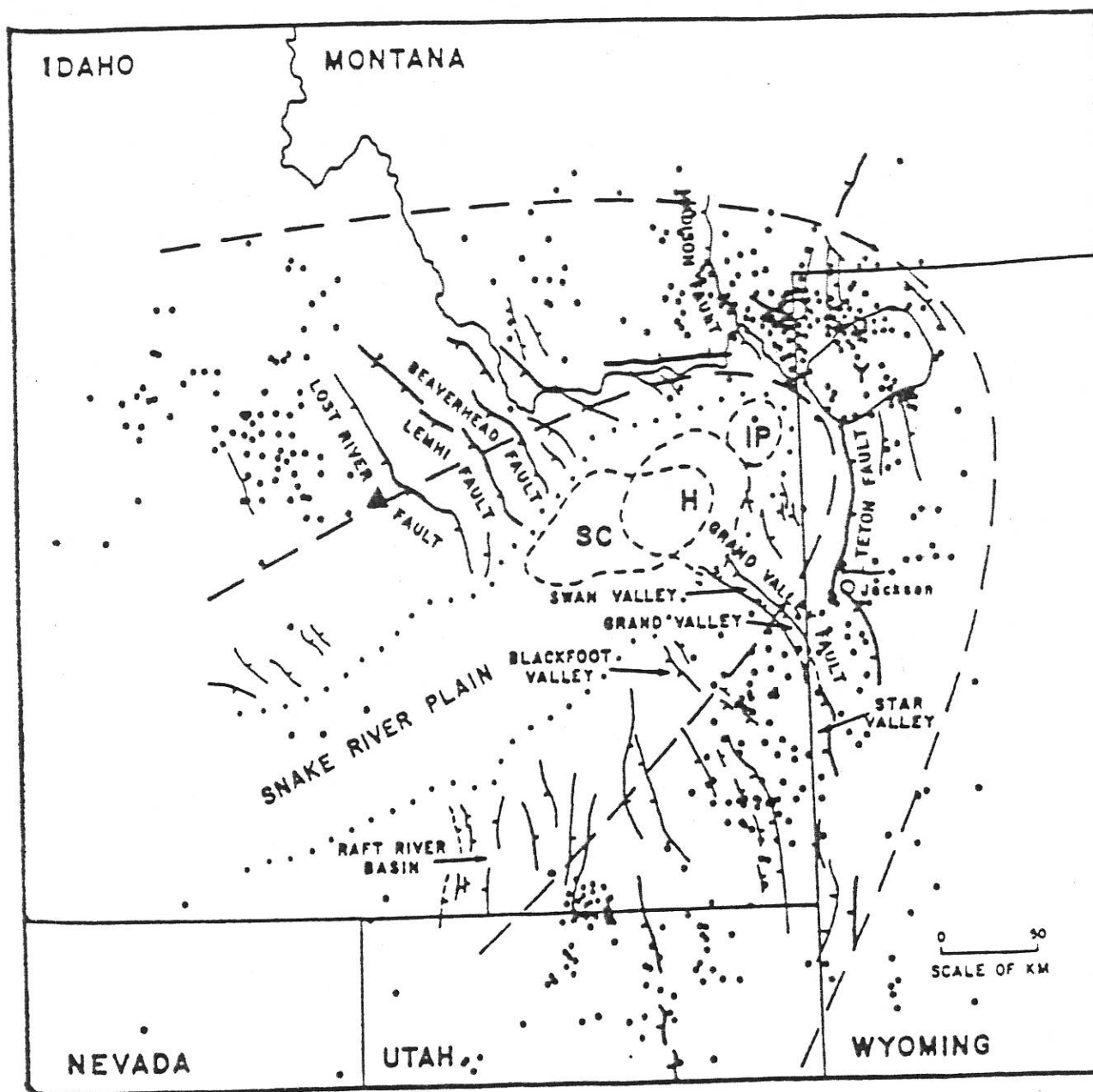


Figure 9: Distribution of earthquakes greater than $M = 3$ (large dots) since 1961 and of latest Quaternary (dark lines) and Cenozoic (light lines) normal faults. Dotted line is the limit of the Snake River Plain and dashed lines represent the inner and outer limits of seismicity and active faulting (from Anders and others, 1989)

in its wake.

The age progression of silicic volcanic rocks, the ESRP's unique geophysical characteristics, and the general increase in elevation toward Yellowstone all suggest that the eastern Snake River Plain is the trace of a mantle plume (or 'hot spot') beneath North America [Morgan, 1972; Suppe and others, 1975] or the tip of an eastward-propagating lithospheric fracture [Christiansen and McKee, 1978]. The 'hot spot' model assumes forceful upwelling of mantle material (and derivative partial melts), while the lithospheric fracture model assumes that crustal extension is accompanied by more passive upwelling of mantle as the lithosphere is thinned [Leeman, 1982]. Since both models incorporate the northeastward migration of volcanism and subsequent subsidence of the plain in its wake, the conclusions of this thesis apply equally to each.

GEOLOGY OF THE LIDY HOT SPRINGS QUADRANGLE

To determine the processes responsible for the subsidence of the ESRP, the nature of subsidence must first be documented by mapping surface structures and interpreting subsurface petrologic and geophysical relations. Other studies [Sparlin and others, 1982; Braile and others, 1982; Pankratz and Ackermann, 1982; Doherty and others, 1982] have addressed the subsurface geology and geophysics, and have proposed several models of ESRP subsidence. As a result, this study aims to support or revise previously proposed models by incorporating previously unrecognized near-surface structural data of the ESRP.

The flanks of structural depressions are usually represented by exposed normal faults, but the Holocene basalts of the ESRP's surface cover valuable normal fault information related to the subsidence of the plain. However, along the plain's margins, isolated exposures of late Tertiary ash-flow sheets are useful for locating normal faults, due to their relatively distinct lithologies, their almost instantaneous deposition (inferred to be days or weeks), and their widespread lateral extent. The Lidy Hot Springs area, at the southern tip of the Beaverhead Mountains (Fig. 1), was chosen for study because of its location on the northern margin of the ESRP and because several ash-flow sheets crop out throughout the area.

Detailed field mapping of 24 square-miles of the Lidy Hot Springs 7.5' quadrangle during the summers of 1987 and 1988, shown in Plate I, shows the distribution of rock units and normal faults. A preliminary stratigraphic framework for many of the extensive rhyolite ash flow sheets of the ESRP was devised by Prostka [1977], which laid the groundwork for further study. McBroome [1981] mapped the units in the southern Lemhi Range, refined Prostka's [1977] stratigraphy, and recognized normal faults which offset the ash flow sheets. In the southern Beaverhead Mountains, G. Embree [unpublished data; personal communication, 1988] has mapped fifteen quadrangles containing tuffs using an updated stratigraphy [Embree and others, 1982] based on Prostka's [1977] work.

STRATIGRAPHY OF THE LIDY HOT SPRINGS AREA

Seven distinct lithologies are present in the Lidy Hot Springs area (Fig. 10). From oldest to youngest, they are: Pennsylvanian Snaky Canyon Formation, Miocene Medicine Lodge Beds, 6.5 Ma Tuff of Blacktail, 5.6 Ma Tuff of Blue Creek, 5.2 Ma Basalt of Indian Creek, 4.3 Ma Tuff of Kilgore, and Quaternary gravel [Embree and others, 1982; Embree, personal communication, 1989]. A sharp contact exists between each of the units.

Snaky Canyon Formation

Pennsylvanian Gallagher Peak Sandstone, a member of the Snaky Canyon Formation, is exposed at only one location in the study area. The sandstone has been described as medium-gray to grayish-orange, very fine-grained to fine-grained, and thin- to medium-bedded [Sipp and others, 1979a] at locations north of the study area, but the sandstone has been severely altered at Lidy Hot Springs. In the study area, the sandstone is tan, very fine-grained, medium-bedded, well-cemented, and highly-fractured. It is assumed that the widespread hydrothermal activity of the area has altered the rock. Sipp and others [1979a] have determined the thickness of the Gallagher Peak sandstone member to be 59 m, but at Lidy Hot Springs, only 30 m of the sandstone are exposed.

Medicine Lodge Formation

Above the sandstone is a Miocene limestone, which represents part of the Medicine Lodge Beds defined by Sipp and others [1979b]. The Medicine Lodge Beds include tuffaceous lacustrine mudstone, tuff, travertine, and gravel where the entire unit is well-exposed north of the study area. Massive, light-gray, fresh-water, ledge-forming travertine [Sipp and others, 1979b] is the only portion of the Medicine Lodge Beds present in the Lidy Hot Springs area. The total thickness of the Medicine Lodge Beds is 300 meters [Sipp and others, 1979b], but only 150 meters of section are present in the field area, and its basal contact with the underlying quartzite is not exposed. Sipp and others [1979b] have determined the age of the Medicine Lodge Beds to be lower Pliocene or upper Miocene based

GENERALIZED STRATIGRAPHIC SECTION OF THE LIDY HOT SPRINGS AREA

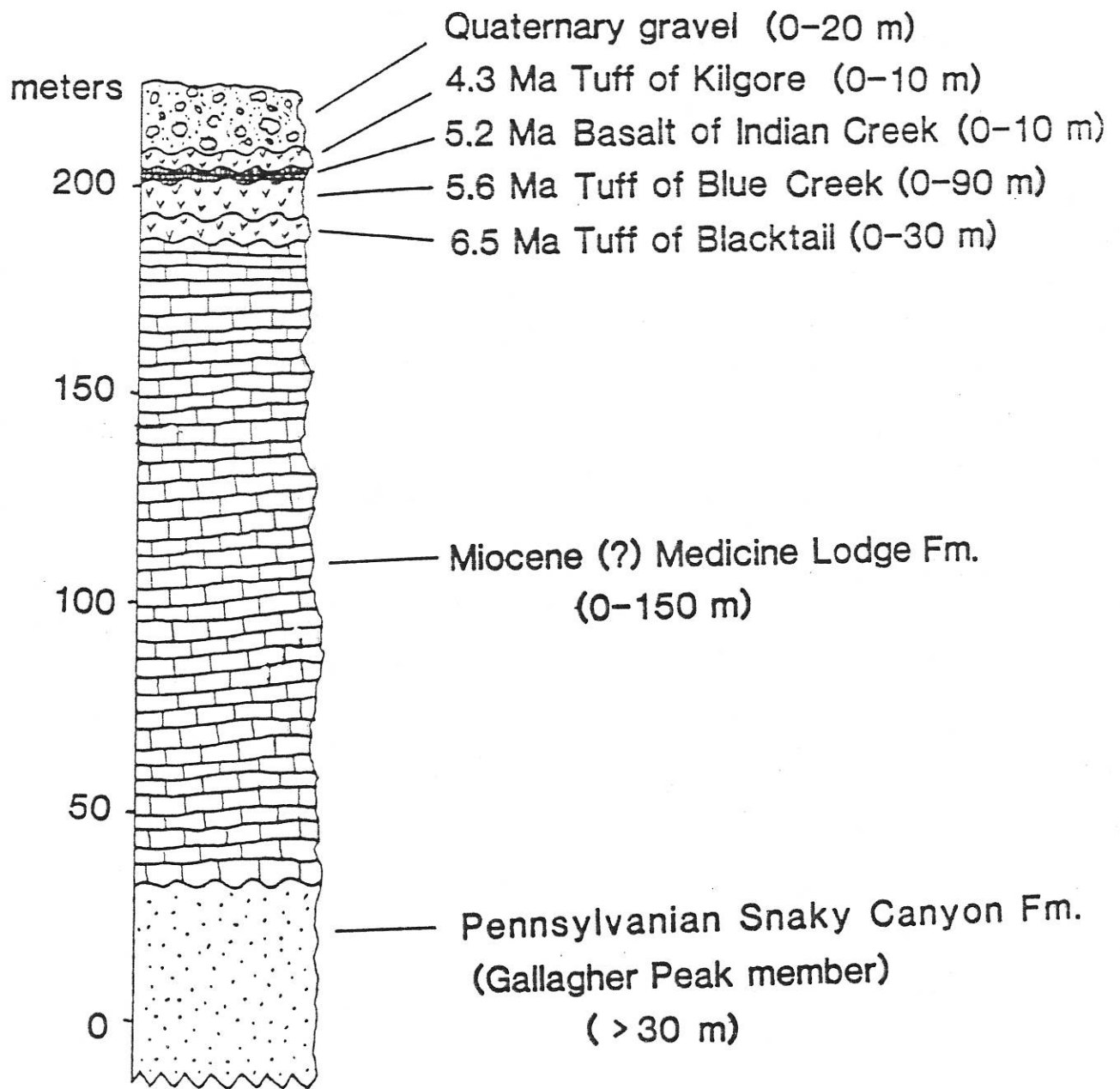


Figure 10: Generalized stratigraphic section of the Lidy Hot Springs study site. [ages from Morgan and others, 1984; Skipp and others, 1979a and 1979b]

on its stratigraphic position in the region north of the study area. However, at Lidy Hot Springs, the limestone is overlain by lower Pliocene and uppermost Miocene ash flow sheets, which means that the limestone is older than 6.5 Ma (the age of the Tuff of Blacktail, the oldest tuff overlying the limestone).

Tuff of Blacktail

The 6.5 Ma Tuff of Blacktail, which overlies the travertine limestone, is a mostly tan, light-gray, purple, and brown, crystal-rich, reversely-graded, and well-sorted ash-flow tuff [Morgan and others, 1984]. The unit is non-welded at the base and grades upward into welded tuff with pumice embedded in a matrix of welded glass shards. The zone near the base is bluish-black to dark brown, moderately-to-densely welded vitrophyre. The upper part of the unit is densely welded and devitrified, grading downward into a spherulitic and lithophysal zone. Phenocryst content ranges from 15-20 percent at the base to about 5 percent at the top, and the phenocrysts are plagioclase, sanidine, quartz, augite, and zircon [Morgan and others, 1984]. The unit is about 75 to 100 m thick [Morgan and others, 1984], but a maximum thickness of 30 m is found in the study area. A widely used age of 6.65 ± 0.68 Ma has been assigned to this unit, based on fission-track dating of zircons obtained from pumice fragments in the non-welded bomb unit [McBroome, 1981], although four additional dates have since been determined (Table 1).

Tuff of Blue Creek

The 5.6 Ma Tuff of Blue Creek, found above the Tuff of Blacktail, is a light-gray, black, purple, and pink, crystal-poor, densely-welded, glassy to devitrified, spherulitic to lithophysal, ash-flow tuff [Morgan and others, 1984]. The base of the unit consists of a tan, locally laminated and crossbedded, non-welded, pyroclastic-surge deposit 1 m thick with local, non-welded, airfall ash deposits about 0.5 thick. The zone near the base of the unit is eutaxitic, densely-welded tuff with abundant, orange pumice lumps in a matrix of black shards. The densely-welded tuff is overlain by a thin, black vitrophyre which grades upward

TABLE 1: Radiometric Ages of Minerals and Whole Rock Samples From the Heise Volcanic Field (modified from Morgan and others, 1984)

UNIT	METHOD	AGE, M.Y.	REF.	LOCATION
Tuff of Kilgore	K-Ar (WR)	4.1 ± 0.1	5	Ammon
Tuff of Kilgore	FT	4.2 ± 0.3	3	INEL - 1
Tuff of Kilgore	FT	4.4 ± 0.4	2	Heise
Tuff of Kilgore	FT	4.1 ± 0.6	3	Howe Point
Tuff of Kilgore	K-Ar (F)	4.3 ± 0.3	2	Kilgore
Tuff of Kilgore	FT	4.4 ± 0.6	2	Heise
Tuff of Kilgore	K-Ar (F)	4.8 ± 0.3	1	Kilgor
Basalt of Indian	K-Ar (WR)	5.2 ± 0.2	4	Indian Creek
Tuff of Blue Creek	FT	5.6 ± 0.6	3	Howe Point
Tuff of Blue Creek	K-Ar (WR)	6.4 ± 0.2	6	Buckskin Basin
Tuff of Blacktail	FT	6.5 ± 0.3	2	Heise
Tuff of Blacktail	FT	6.6 ± 0.7	3	Arco Hills
Tuff of Blacktail	K-Ar (K)	6.6 ± 0.3	6	Buckskin Basin
Tuff of Blacktail	K-Ar (K)	6.7 ± 0.2	6	Buckskin Basin
Tuff of Blacktail	K-Ar (K)	6.7 ± 0.3	6	Buckskin Basin

K-Ar (F) = K-Ar determinations of feldspar phenocrysts

K-Ar (WR) = K-Ar determinations of whole rock samples

FT = fission-track determinations of zircon microphenocrysts

references

- 1 = Samples submitted by Doherty while at the Geothermal Division, Chevron Resources Company, San Francisco, and analyzed at Geochron Laboratories.
 2 = D.J. Doherty (unpublished data, 1981)
 3 = McBroome [1981]
 4 = B. Dalrymple (written communication, 1979; to Morgan and others, 1984)
 5 = Armstrong and others [1975]
 6 = Kellogg and Marvin [1988]

into a perlitic to spherulitic zone. The upper part of the unit is platy, devitrified tuff which is lithophysal at the top. The phenocryst content averages 1 percent; chiefly plagioclase, with minor amounts of pyroxene, magnetite, and zircon [Morgan and others, 1984]. The unit is typically 75 m thick, but locally, deposits are as much as 180 m thick. In the study area, the thickness of the unit ranges from 0 m to 90 m. An age of 5.6 ± 0.6 Ma has been assigned to this unit from samples collected at Howe Point [McBroome, 1981], but a another date, given to a unit thought to be the Tuff of Blue Creek [Kellogg and Marvin, 1988], differs from Morgan's date by 0.8 Ma (Table 1). The age of the Tuff of Blue Creek is not as well-defined as the Tuff of Blacktail and more geochronology on this unit is needed.

Basalt of Indian Creek

The 5.2 Ma Basalt of Indian Creek lies above the Tuff of Blue Creek in a few isolated locations in the study area. The basalt is medium- to dark-gray, generally containing up to 2 percent olivine and a few plagioclase phenocrysts, greater than 2 mm in diameter, in a dense groundmass. The thickness of this unit ranges from 0 to 80 m elsewhere [Morgan and others, 1984], but in the field area, thicknesses never exceed 10 m. An age of 5.17 ± 0.16 Ma has been assigned to the basalt using the K-Ar method (Table 1) [Dalrymple, 1979; from Embree, personal communication, 1989].

Tuff of Kilgore

The 4.3 Ma Tuff of Kilgore, overlying the Tuff of Blue Creek, is a welded, rhyolite, ash flow tuff with multiple lithophysal and devitrified zones and maroon pumice lumps throughout the unit [Morgan and others, 1984]. The basal vitrophyre is black to red and contains black shards and sparse, black to gray, pumice lumps up to 2 cm long, and red to black obsidian grains. The central part of the unit is a gray, pink, or maroon, devitrified, slightly eutaxitic tuff with pronounced slabby partings and strong lineations. The uppermost vitric zone is pink to red, moderately welded, and contains black shards, light-gray silky pumice lumps, and black to red obsidian grains. The phenocryst content ranges from 7

percent at the base to 1 percent at the top of the unit, and the phenocrysts are plagioclase with minor amounts of sanidine, quartz, and pyroxene [Morgan and others, 1984]. Regionally, the unit is approximately 30 m thick [Morgan and others, 1984], but in the study area, the thickness of the unit never exceeds 5 m. A variety of ages have been assigned to the Tuff of Kilgore. Seven age determinations have been made using K-Ar, fission-track, and whole rock methods (Table 1), and the ages average around 4.3 Ma.

Alluvium

Quaternary alluvium (undifferentiated) is a lithologic unit that has been mapped, but has not been studied. Based on detailed geologic mapping of late Cenozoic lava flows and sediments on the plain, Kuntz and others [1984] have assigned a Quaternary age to deposits similar to this unit. The precise age is unknown; it may range from 2.0 Ma to as young as 15,000 yrs.

STRUCTURE OF THE LIDY HOT SPRINGS AREA

Using the uncomplicated stratigraphy of the Lidy Hot Springs area, two distinct normal fault sets are apparent in the study area (see Plate 1). Both a northwest-striking set and a northeast-striking set cut all rock units of the area except the Quaternary gravel. In addition, the fault sets truncate each other at various locations throughout the field area.

Northwest-striking normal fault set

The northwest-striking normal fault set is composed of a series of faults which consistently strike N25°W, are spaced 0.1 to 0.7 km apart, and are confined to the western portion of the study area. Many faults extend throughout the field area, but others are truncated by northeast-striking faults (described below). No fault surfaces are exposed, but fault traces are located where formations are juxtaposed to show map patterns unlike those of

their initial deposition. Therefore, the width of fault zones is not precisely determined, but the fault traces are mapped within a 20-meter zone of confidence. These faults possess a normal sense of offset and dip-slip displacement, as shown in the northern half of section 27 of the geologic map (see Plate 1).

Strikes of faults in this set average around N25°W, but the strikes range from N45°W to N10°W. Dips on these faults range from 55° to 65°, are assumed to be constant with depth, and dip both to the northeast and southwest (see Plate 1: map and cross sections A-A' and B-B'). Individual faults offset the ash-flow sheets up to 250 m. Based on calculations of the area's initial width before extension and final width after extension, the area was extended 7% in a northeast direction. The western portion of the field area has been relatively uplifted along these normal faults (see Plate 1).

Northwest-striking faults cut all lithologic units in the area except for the Quaternary gravel. The age of these faults thus lies between the age of the youngest unit offset by faults (4.3 Ma Tuff of Kilgore) and the age of the oldest unit (Quaternary alluvium) not offset.

These normal faults, which strike to the northwest and dip 60° to the northeast or southwest, are structurally parallel to major range-bounding normal faults of the region. Major faults of this magnitude are typical of the Basin and Range province, and therefore, the minor faults of the study area are inferred to be related to Basin and Range extension.

Northeast-striking normal fault set

The northeast-striking normal fault set is composed of a series of faults which have consistent strikes (N60°E), are spaced 0.3 to 0.7 km apart, and are distributed throughout the study area. Most of the faults extend across the field area (3 km in length) and beyond. As with the northwest-striking faults, no fault surfaces are exposed, the width of the fault traces are mapped within a 20-meter zone of confidence and normal dip-slip displacement on these faults is best documented in the northern half of section 27 of the geologic map (see Plate 1).

Strikes of the faults in this set average around N60°E, with a range from N85°E to N40°E. Dips on these faults are 70° to 80° (steeper than the northwest-striking set) both to the northwest and the southeast (see Plate 1: cross section C-C'). Individual faults offset the ash-flow tuffs up to 100 m. Based on calculations of the area's initial width before extension and final width after extension, the area was extended 2 % in a northwest direction. There is a slight decrease in elevation from the north to the south of the field area, but there is minimal structural relief accompanying the elevation decrease (see Plate 1).

Similar to the northwest-striking fault set, northeast-striking faults cut all lithologic units in the area except for the Quaternary alluvium. Both fault sets truncate one another at various locations within the study area, evidence that the faults were more or less active at the same time.

There is no evidence at Lidy Hot Springs which suggests substantial strike-slip movement along these northeast-striking faults. This conclusion is important, since some believe that the ESRP represents the strike of a major strike-slip zone which bounds regions of differential extension [Pratt, 1982].

The northeast-striking normal faults paralleling the axis of the ESRP suggest that they are related to its development. Prior to this study, it was assumed that since the faults are parallel to the axis of the ESRP, and since the plain is a structural basin, the northeast-striking normal faults must have accommodated downdropping of the plain. However, this study shows that the net vertical displacement along these faults is minimal, and many of the faults dip away from the ESRP's axis (see Plates 1 and 2). Thus, it seems apparent that the northeast-striking, ESRP-related minor normal faults of the Lidy Hot Springs area do not contribute to a structural or topographic downdropping towards the plain. Instead, the faults must be the result of major ESRP subsidence processes which have a more regional extent.

COMPILATION OF E.S.R.P.- RELATED NORMAL FAULTS AND THEIR RELATION TO THE YELLOWSTONE 'HOT SPOT'

To insure that the normal faults found at Lidy Hot Springs are truly related to the development of the eastern Snake River Plain, published geologic maps have been compiled to document the extent and regional pattern of normal faults that strike parallel to the ESRP. Many geologic studies in southern Idaho have identified normal faults which parallel the axis of the ESRP, but a compilation of these maps has never been completed.

PUBLISHED GEOLOGIC MAP COMPILATION

All published geologic maps within 50 kilometers of the ESRP have been combined to form a regional geologic map of southeastern Idaho, northwestern Wyoming, and southwestern Montana (see Plate 2). Northeast-striking normal faults (ESRP-related) are highlighted differently, depending on whether or not a fault cuts rocks that are older or younger than 10 Ma (see Plate 2). Faults which cut rocks older than 10 Ma are symbolized by thin line segments, while faults cutting rocks younger than 10 Ma are symbolized by thick line segments. The age of faults in pre-Miocene rocks is unclear: they may be younger than 10 Ma and thus related to the ESRP, or they may be older than 10 Ma and unrelated to the ESRP.

The map compilation shows that northeast-striking normal faults younger than 10 Ma are restricted to a zone 30 kilometers wide along the north and south boundaries of the ESRP. To insure that these faults were not solely recognized where rocks of appropriate age (2 Ma - 10 Ma) crop out, the regional distribution of Tertiary rocks younger than 10 Ma was compiled (see Plate 2). Tertiary rocks not faulted by ESRP-related normal faults occur greater than 30 kilometers from the ESRP margins (see Plate 2), indicating that the zones of faults are truly restricted to the margins of the ESRP. Because of their proximity to the ESRP, their orientation, and their similar age to the ESRP, these faults are inferred to be related to the ESRP.

NORMAL FAULT RELATIONS TO THE YELLOWSTONE 'HOT SPOT'

To understand the spatial and timing relations of normal faulting to the apparent passage of the Yellowstone 'hot spot', study of northeast-striking normal fault ages is essential not only along the margins of the ESRP, but throughout the Yellowstone Plateau region.

Northeast-striking normal faults with steep dips and minimal offset are not found on the Yellowstone Plateau (see Plate 2). On the plateau, normal faults either strike to the northwest or their strikes form a regionally circular pattern. Northwest-striking normal faults in the region are associated with Basin and Range extension and normal faults that form a regionally circular pattern are related to the formation of silicic calderas. These interpretations seem valid since recent Basin and Range extension activity has been documented south of the plateau (the Grand Tetons) [Love and others, 1972], and recent silicic volcanism has been documented on the plateau [Smith and Christiansen, 1980].

As a result, the temporal pattern of ESRP-related normal faults implies that once the crust passes over the 'hot spot', the northeast-striking minor normal faults result from post-'hot spot' processes. As will be discussed in the next chapter, ESRP-related minor normal faults are thought to result from horizontal thermal contraction and downward flexure of the ESRP crust after the 'hot spot' moves on to the northeast. The further the 'hot spot' moves to the northeast, the more well-developed the northeast-striking normal faults become. Therefore, the location of the youngest ESRP-related normal faults shifts progressively northeastward as the trailing edge of the uplifted plateau moves further to the northeast.

Documentation of an expected northeast-younging of these northeast-striking normal faults has not been accomplished. To date, this study and Allmendinger's [1982] study of similar northeast-striking normal faults across the plain in the northern Caribou Range (Fig. 7) have both defined the age of faulting to be between 4.3 Ma and about 2.0 Ma. However, other northeast-striking normal faults along the plain's margins have not been studied in enough detail to produce precise ages of active faulting. Therefore, it remains to be proven

that there is a southwest to northeast younging of northeast-striking normal faults along both margins of the ESRP.

PROCESSES AND MECHANISMS RESPONSIBLE FOR THE SUBSIDENCE OF THE E.S.R.P.

Geologists have been speculating on the petrologic and structural origin of the eastern Snake River Plain since King [1878], the first geologist in the region, recognized the ESRP as "a depressed area which subsided very gently with minimal faulting" [Kirkham, 1931]. The acceptance of the related theories of plate tectonics and 'hot spots' in the late 1960's led to the interpretation that the ESRP is either the volcanic trace of an underlying 'hot spot' as the North American plate drifts southwestward (Morgan, 1972; Suppe and others, 1975), or a volcanic region which overlies a lithospheric fracture (Christiansen and McKee, 1978). This development, combined with the detailed documentation of the ash-flow tuff stratigraphy of the plain's margins [Embree and others, 1982], has made it possible to relate normal faults that have been identified along the ESRP's margins to ESRP crustal subsidence, uplift, and extension.

Proposed models of subsidence of the ESRP should be capable of explaining the following characteristics of the plain:

- 1) an abundance of plain-bounding normal faults, with less than 100 m offset, along the ESRP margins in 30 km-wide zones that extend from, and are parallel to, the northern and southern margins of the ESRP (see Plate 2).
- 2) an absence of surficial traces of major plain-bounding normal faults (greater than 1 km offset) along ESRP margins [Rodgers and Zentner, 1988].
- 3) a 0.75 km thick surface basalt layer encountered in the INEL-1 test hole [Doherty and others, 1979].
- 4) a rhyolitic ash-flow tuff layer with intercalated sediments which extends from 0.75 km to at least 3.2 km deep in the INEL-1 test hole [Doherty and others, 1979].
- 5) a high-density, 10 km thick crustal layer between the upper and lower crust of the ESRP (Fig. 5) [Sparlin and others, 1982].
- 6) a total ESRP crustal thickness of about 42 km (Fig. 8) [Sparlin and others, 1982].

- 7) a broad regional gravity high over the axis of the ESRP [Mabey, 1982].
- 8) a lack of seismicity greater than $M = 1$ observed at various locations on the ESRP during a three-week recording period [Pennington and others, 1974].
- 9) an abundance of anomalously high heat flow values for the ESRP (190 mW m^{-2}) [Brott and others, 1981].
- 10) an abundance of Mesozoic fold axes (to the north and south of the plain) which gently plunge toward the plain [Garmezy, 1981].
- 11) a gradual decrease in elevation of Basin and Range ranges toward the ESRP.

NEAR-SURFACE E.S.R.P. SUBSIDENCE MECHANISMS

The ESRP's uppermost crust has been faulted and downwarped as the ESRP has subsided. Seismic refraction profiling of the ESRP's subsurface indicates a discontinuity of seismic velocities beneath the plain's northern margin (Fig. 11) [Sparlin and others, 1982; Pankratz and Ackermann, 1982] which has been interpreted to be a normal fault with an offset of 1 to 4 km to the southeast. Downwarping of the ESRP's uppermost crust (Fig. 12) has also occurred since (1) there is an absence of surface evidence indicating the existence of major plain-bounding normal faults [Rodgers and Zentner, 1988], (2) Mesozoic fold axes north and south of the plain gently plunge toward the plain [Garmezy, 1981], and (3) seismic velocities indicate the presence of sedimentary rocks at depth beneath the southern half of the plain [Sparlin and others, 1982].

In addition, the two previously discussed 30 km-wide normal fault zones which parallel the plain's margins represent tensional stresses at the hinges of the downwarped uppermost crust. The faults, dipping both into and away from the plain, were formed as the rigid ESRP crust was flexed downward, and they are evidence of the extended near-surface hinges of a downwarped crust. Overall, the ESRP's uppermost crust has been downwarped, but beneath the plain's northern margin, the crust has been offset along a major normal fault.

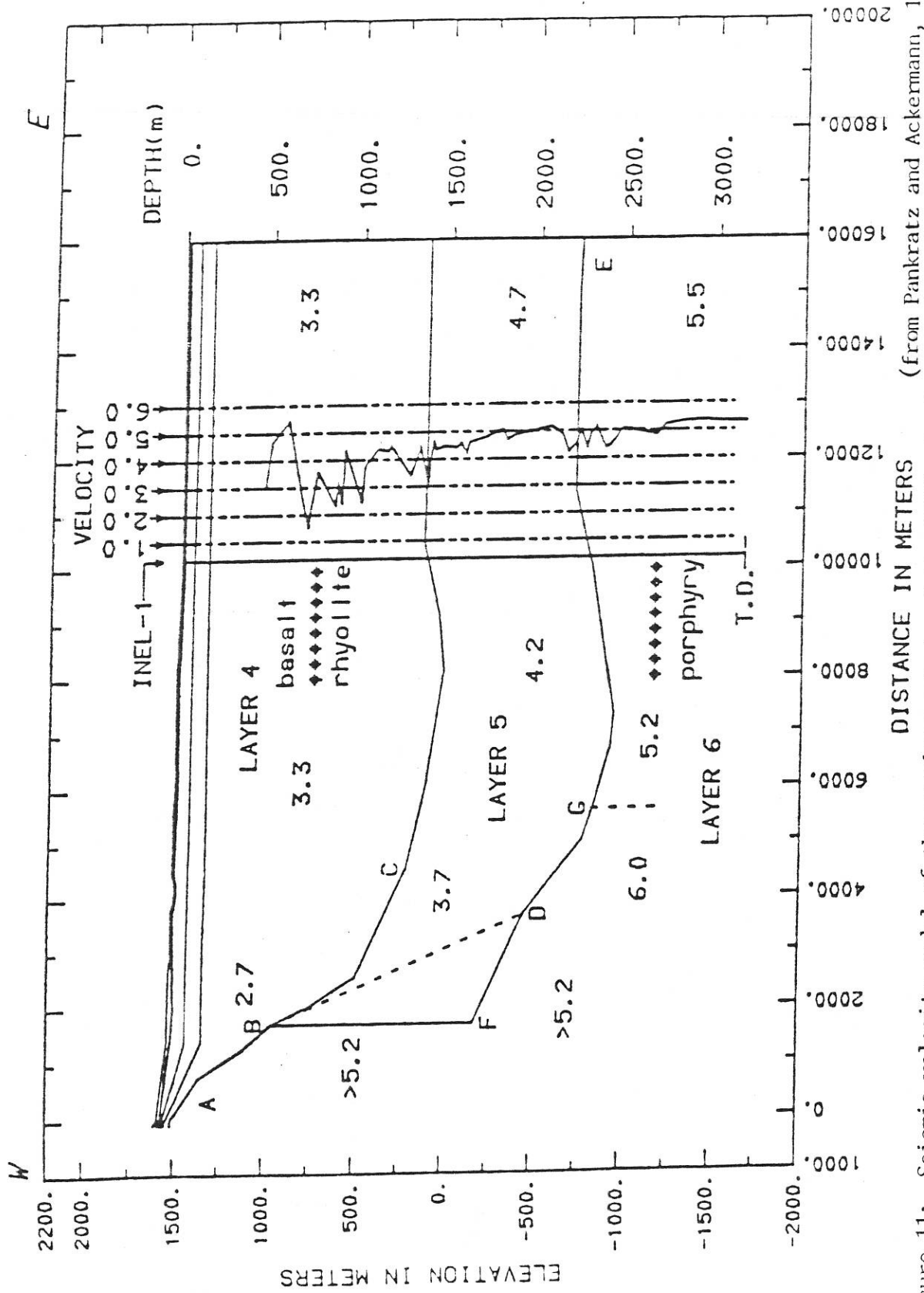


Figure 11: Seismic velocity model of the northern margin of the ESRR, showing the location of the exploratory well INEL-1 and the generalized velocity function obtained from the log. Velocities greater than 5.2 km/s represent sedimentary rocks; less than 5.2 represent volcanic rocks. (from Pankratz and Ackermann, 1982)

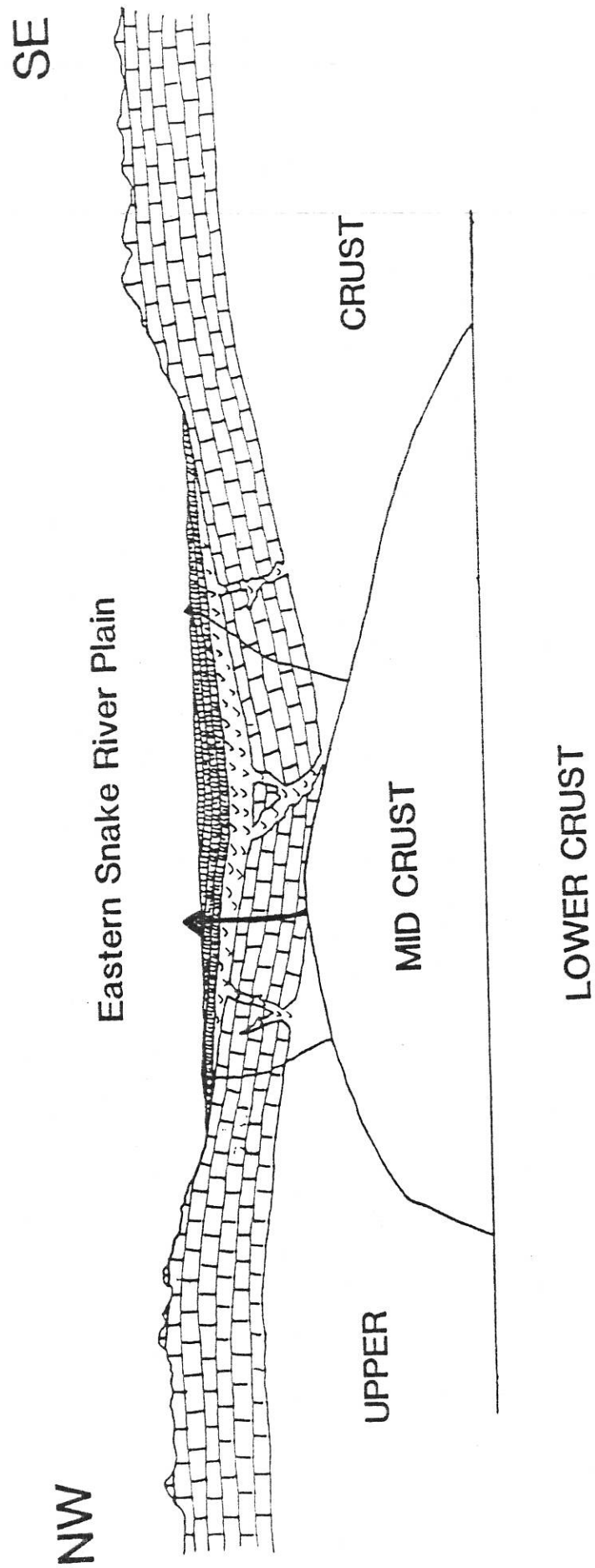


Figure 12: Generalized model showing the downwarping of the uppermost crust beneath the ESRP.

E.S.R.P. SUBSIDENCE PROCESSES

Five different subsidence processes have been proposed as the cause of the ESRP subsidence mechanisms described above. In the following section these processes are discussed, and a model is proposed which incorporates the different processes.

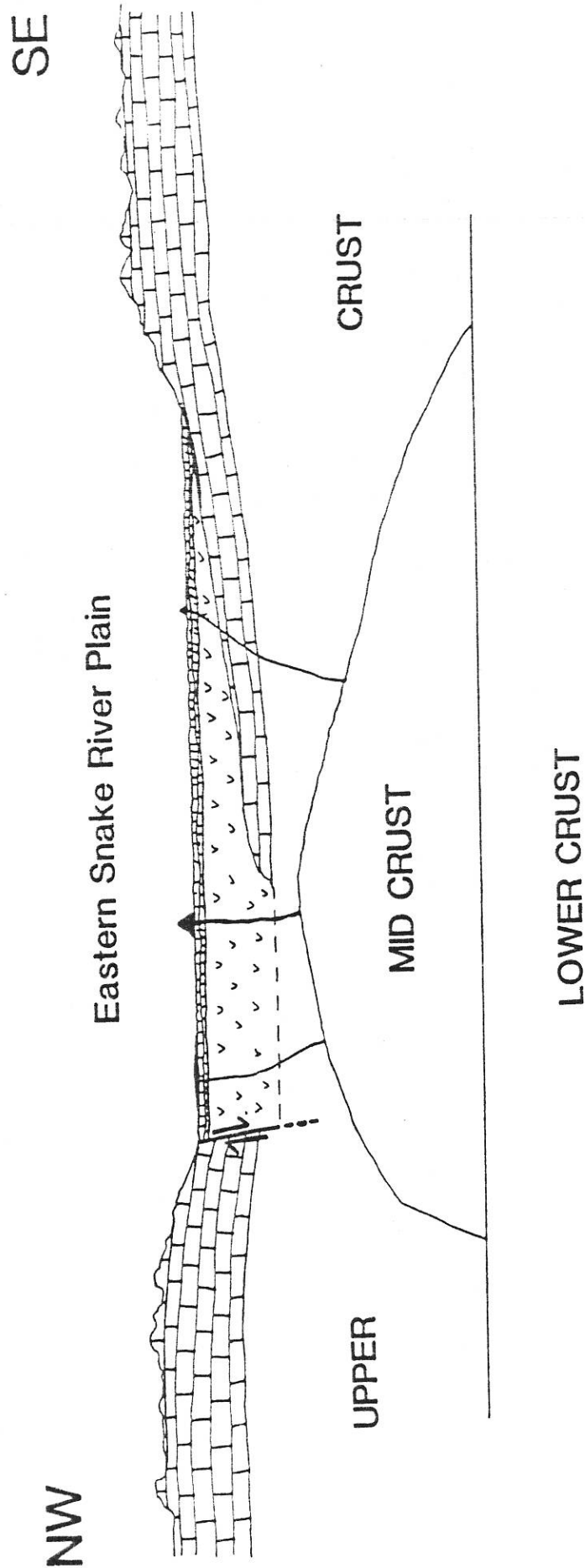
PROCESS #1: ESRP subsidence due to half graben-style faulting, resulting from NW-SE tensile stress

Based on seismic velocity data from the 1978 Yellowstone-ESRP seismic experiment, Sparlin and others [1982], Braile and others [1982], and Smith and others [1982] suggest that the ESRP has subsided due to downdropping, half graben-style, along a normal fault at its northern margin (Fig. 13). If the fault exists, it is concealed beneath the Pleistocene basalts of the ESRP.

Offset along this fault results in northwest-southeast extension. Possibly, this fault reflects regional northwest-southeast extension across the ESRP. However, evidence against such a regional stress regime includes (1) coeval northeast-southwest extension of the Basin and Range Province [this study], (2) modern measured northeast-southwest stress on the ESRP [Zoback and Zoback, 1980], and (3) ESRP volcanic rift zones oriented to accommodate northeast-southwest extension [Kuntz and others, 1982]. Thus, little evidence supports regional northwest-southeast tension as a fundamental cause of northeast-striking normal faults.

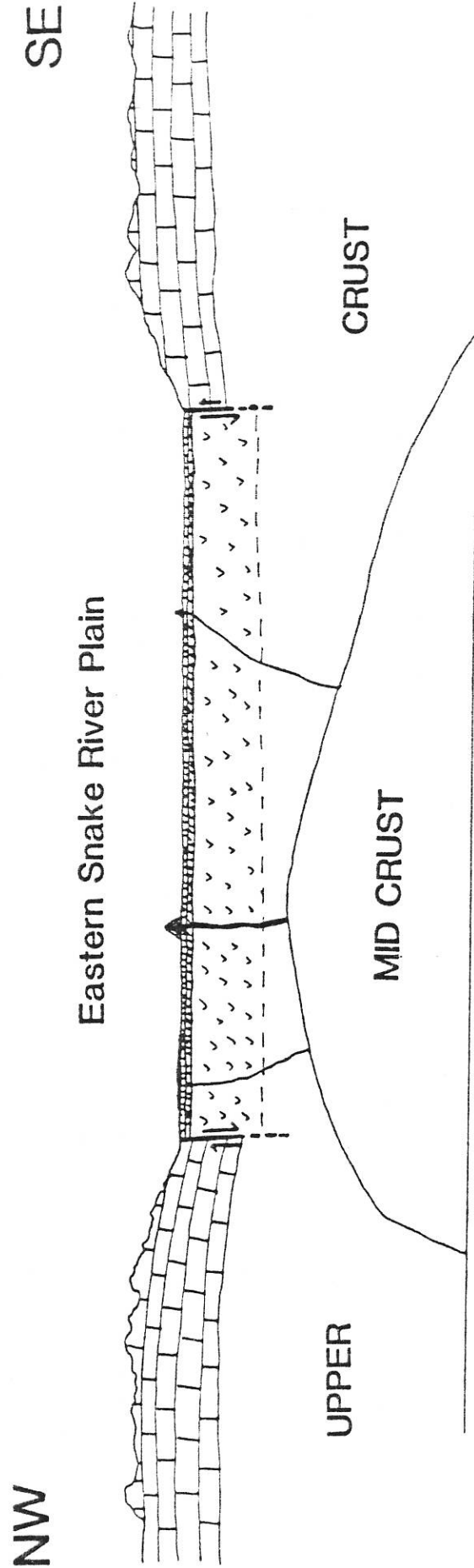
PROCESS #2: ESRP subsidence due to caldera-related faulting

Based on ash-flow tuff petrologic work by L. Morgan [Hackett and Morgan, 1988] and on the seismic velocity data from the northern half of the ESRP [Sparlin and others, 1982; etc.], the margins of the ESRP are inferred to correspond to buried caldera rims (Fig. 14) [Morgan, personal comm. 1988]. In this model, subsidence of the ESRP is due to



modified from Sparlin and others, 1982

Figure 13: Illustration of Process #1, which proposes that the eastern Snake River Plain has subsided due to downdropping, half graben-style, along a normal fault beneath its northern margin. The faulting occurs as the region's near-surface is extended in the northwest-southeast direction.



LOWER CRUST

Figure 14: Illustration of Process #2, which proposes that the eastern Snake River Plain has subsided due to intra-caldera collapse from underlying magma chamber evacuation.
(modified from Morgan, 1988 pers. comm.)

intra-caldera collapse from underlying magma chamber evacuation.

Morgan and others [1984] studied ash-flow tuff exposures along both ESRP margins and concluded that the tuffs possess proximal volcanic facies both north and south of the plain. They inferred that the margins of the ESRP correspond with the edges of huge, 80-km wide silicic calderas. This model implies that the sharp lateral break in seismic velocity observed beneath the plain's northern margin must also exist beneath its southern margin, because the calderas are circular and must bound the ESRP on both sides.

Process #2 agrees with the observed seismic discontinuity beneath the northern margin of the ESRP and the subsurface seismic data of the northern half of the plain, but the model does not agree with seismic data from beneath the southern margin, which indicates a gently downwarped layer of sedimentary rocks (Figs. 6 and 7). To account for the geophysical evidence from beneath the southern margin, it is possible that the rims of the calderas do not correspond exactly with the margins of the ESRP. Instead, the southeastern rims of the calderas could be located 10 to 50 km in from the plain's southern margin. This adjustment would account for the geophysically-inferred subsurface sedimentary rocks that extend 50 km in from the southern margin.

PROCESS #3: ESRP subsidence due to thermal contraction

Based on the study of ESRP heat flow, Brott and others [1981] suggested that the ESRP has subsided due to vertical thermal contraction of the crust after it passed southwest of the 'hot spot'. In addition, they propose that there is a horizontal component of the thermal contraction.

Vertical thermal contraction of the ESRP's crust occurs after the 'hot spot' apparently moves on to the northeast. As the ESRP crust drifts away from the 'hot spot', the thermally inflated crust begins to subside to maintain isostatic equilibrium as it cools and densifies. The further the crust drifts from the 'hot spot', the greater the amount of thermal contraction, and

the greater the amount of subsidence.

Horizontal thermal contraction of the ESRP crust may account for the ESRP-related minor normal faults documented in this study. As the crust drifts from the 'hot spot', the crust will contract horizontally, leading to the formation of the minor normal faults by extending the plain's crust. The farther the crust drifts from the 'hot spot', the greater the offset along the faults. Thus, to the northeast, normal faults should show minor amounts of offset, while to the southwest, normal faults should show greater amounts of offset [Brott and others, 1981].

PROCESS #4: ESRP subsidence due to surface loading by basalt

Brott and others [1981] and Cluer and Cluer [1986], suggested that extrusion of the basalts onto the surface of the ESRP has contributed to the subsidence of the plain (Fig. 12). After silicic volcanism occurred, widespread extrusion of basalt produced a capping basalt layer typically one kilometer thick [Whitehead, 1986]. The additional mass of the basalt would affect the crust's isostatic equilibrium, resulting in subsidence of the underlying rhyolite and sedimentary rocks.

PROCESS #5: ESRP subsidence due to thickening of the crust

The ESRP subsurface seismic velocity profile discussed in Chapter 2 indicates that the ESRP's crust is thicker than the crust of the Basin and Range Province. Leeman [1982] suggested that the ESRP has subsided due to injection of dense, upper mantle material into the ESRP's lower crust. Geophysical data from Sparlin and others [1982] indicates that (1) the crustal thickness of the ESRP averages around 42 km, which is about 10 km thicker than the crust of the Basin and Range Province, and (2) a 10 km-thick mid-crustal layer with a P-wave velocity of 6.5 km/s extends from 10 km to 20 km beneath the plain. Leeman [1982] proposed that the anomalous mid-crustal layer represents dense, mafic upper mantle material

that was injected into the crust, and that thickening of the crust by this dense material contributed to the ESRP's isostatic subsidence.

NEW E.S.R.P. ORIGIN MODEL

The previously discussed ESRP subsidence processes address the ESRP's origin from various viewpoints. The first process seems unsupported, but the others seem well documented. Therefore, a new model for the ESRP's origin is proposed using four of the five previously suggested ESRP subsidence processes.

This model (Fig. 15) proposes that the ESRP has subsided due to a combination of major faulting due to caldera collapse, vertical and horizontal thermal contraction of the crust, surface loading by basalt, and thickening of the lower crust by the injection of dense, upper mantle material. The geophysical evidence from the ESRP's subsurface, which recognizes (1) a downwarped uppermost crust beneath the southern half of the plain, (2) an absence of sedimentary rocks beneath the northern half of the plain, and (3) a major fault beneath the northern margin of the plain, is explained by a combination of a downwarping of the uppermost crust and collapse of silicic calderas centered beneath the northern half of the ESRP along major caldera-related faults. As a result, the major normal fault beneath the northern margin is interpreted to be a caldera-related fault and the seismic discontinuity beneath the center of the plain, where the sedimentary rocks are in contact with rhyolite, is interpreted to be a caldera-related fault along the southeastern rim of the caldera. In addition, the more recent extrusion of basalts onto the surface of the plain, which also significantly contributes to the ESRP's subsidence, explains the lack of surface evidence for both of the proposed major normal faults.

The minor northeast-striking normal faults of both margins of the ESRP are the result of downward buckling of the uppermost crust and horizontal thermal contraction of the crust. The northwest-southeast extension of the near-surface needed to form these northeast-striking

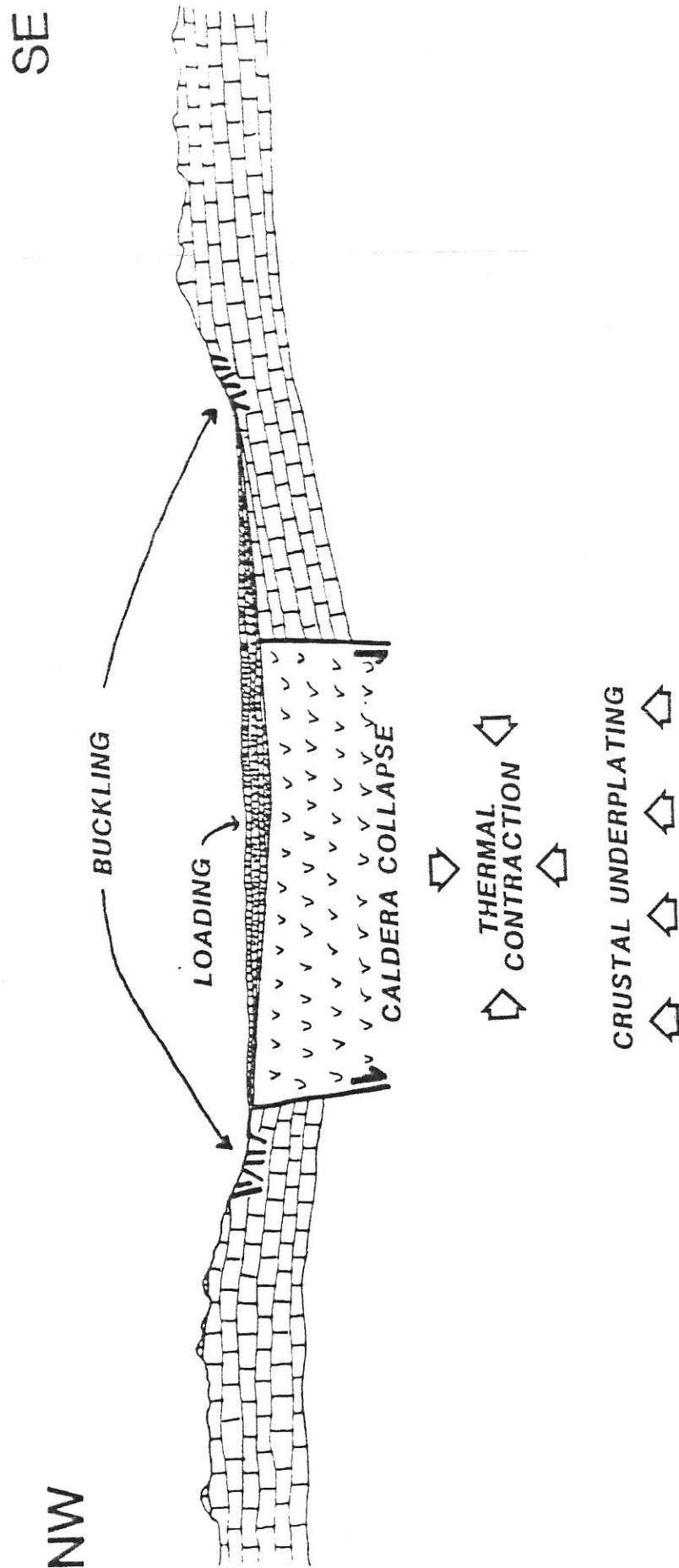


Figure 15: An original ESRP subsidence model, which incorporates the previously discussed subsidence processes.

normal faults is produced by (1) buckling of the near-surface at both margins as the rigid uppermost crust is flexed downward and (2) the lateral component of the crust's thermal contraction. However, these minor normal faults do not contribute to the plain's subsidence, but instead are a result of these subsidence processes.

The downward buckling of the ESRP crust has been caused by (1) thickening of the lower crust by injection of upper mantle material, (2) surface loading by basalt, and (3) vertical thermal contraction of the crust. The relative importance of these processes is not clear, but it is suspected loading and contraction of the crust has not been as significant as thickening of the crust by injection of upper mantle material. The relative timing of these processes is more clear. Thickening of the ESRP crust by injection of dense, upper mantle material occurred prior to and during silicic and basaltic volcanism, resulting in isostatic subsidence. Thermal contraction of the ESRP's crust occurred after movement of the underlying thermal source to the northeast [Brott and others, 1981]. Also after movement of the thermal source to the northeast, loading of the ESRP's surface by Quaternary basalts (averaging 1 km thick) occurred.

CONCLUSIONS

The geometry of the ESRP-related, northeast-striking normal faults, the amount of offset along them, and their regional extent, provides evidence to document ESRP subsidence processes and their relation to the Yellowstone 'hot spot'. The major points of this thesis are best summarized by using the data and interpretations from various chapters of this thesis to address the objectives stated in the introduction.

OBJECTIVE #1: DOCUMENT THE SURFICIAL EXPRESSION OF E.S.R.P. SUBSIDENCE

Downwarping and northeast-striking normal faults along both margins of the plain are the only surficial expressions of ESRP subsidence. The faults, which dip towards and away from the plain, produce minimal net vertical displacement of the margin's ash-flow sheets. They are interpreted to result from horizontal thermal contraction of the crust as it cools in the wake of the 'hot spot', and from tension due to buckling of the uppermost crust during downwarping. Downwarping of the ESRP's crust is documented at the surface by (1) an abundance of Mesozoic fold axes to the north and south of the plain, which gently plunge toward the plain [Garnezy, 1981], and (2) a gradual decrease in elevation of the Basin and Range ranges toward the plain.

OBJECTIVE #2: IDENTIFY ALL POSSIBLE E.S.R.P. SUBSIDENCE PROCESSES

It seems likely that four processes act in concert to cause subsidence of the plain. They are: silicic caldera collapse, vertical thermal contraction, surface loading by basalt, and thickening of the ESRP crust by the injection of upper mantle material. Downwarping and normal faulting of the crust has been the response to these four subsidence processes.

OBJECTIVE #3: DETERMINE THE RELATIVE TIMING OF THESE PROCESSES

Based on the spatial distribution of ESRP-related normal faults, subsurface ESRP geophysical data, and the surface outcrop pattern of ESRP volcanics, the relative timing of processes responsible for the ESRP's subsidence is evident. As the 'hot spot' begins to thermally inflate the overlying crust, upper mantle material is injected into the ESRP crust, which thickens and densifies the crust. At the point of maximum inflation, silicic volcanism is followed by caldera collapse. Following the voluminous rhyolitic volcanism, basaltic volcanism begins as the 'hot spot' begins to migrate to the northeast. Finally, thermal contraction of the crust becomes dominant as the 'hot spot' moves on to the northeast.

OBJECTIVE #4: DETERMINE THE RELATION OF E.S.R.P. SUBSIDENCE TO BASIN AND RANGE TECTONISM

Detailed mapping of faults at Lidy Hot Springs indicate that, in some places, northeast-striking faults cut northwest-striking faults, while in other places they do not, implying that the two fault sets were active at the same time. Both fault sets cut rocks older than 4.3 Ma, but do not cut rocks younger than about 2.0 Ma. The northeast-striking faults are related to ESRP subsidence and the northwest-striking faults are related to Basin and Range tectonism. Therefore, ESRP subsidence and Basin and Range tectonism were both active between 4.3 Ma and about 2.0 Ma in the Lidy Hot Springs area.

OBJECTIVE #5: ILLUSTRATE THE SPATIAL AND TEMPORAL RELATION OF NORMAL FAULTS TO A PASSING 'HOT SPOT'

ESRP-related minor normal faults strictly appear along both margins of the ESRP (in two 30 km-wide zone), southwest of the Yellowstone Plateau, the modern location of the 'hot spot'. The faults have appeared as a result of the ESRP's subsidence in the wake of the passing 'hot spot'. It is suspected that minor normal faults will appear along the borders of any volcanic province that has been created by an underlying 'hot spot' after passing of that

thermal source. However, as demonstrated in southeastern Idaho, the minor faults which border the volcanic province do not contribute to the subsidence of the province, but instead are the resulting surface expression of the subsidence processes at work. Documentation of an expected northeast-younging of these northeast-striking normal faults has not been accomplished, but it is suspected that the age progression will become evident with the completion of additional detailed mapping along the margins of the ESRP.

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