Stratigraphy, Age, and Tectonic Setting of the Miocene-Pliocene Lacustrine Sediments of the Western Snake River Plain, Oregon and Idaho

by

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ABSTRACT

Correlations of lacustrine sediments based on comparisons of fossil fish faunas, volcanic ash chemistries, and lithologies show that sediments of the late Miocene Chalk Hills and Pliocene Glenns Ferry Formations in the western Snake River Plain were deposited by two successive, large lakes. Fission track dates of volcanic ashes show that several million years elapsed between episodes of lacustrine deposition. The extent of Miocene and Pliocene fish localities from the Oregon-Idaho border eastward to Glenns Ferry, Idaho, along the southwest edge of the plain suggests that these lakes occupied approximately the same basin.

The Grassy Mountain and Blackjack basalts, deposited in eastern Oregon just before late Miocene and early Pliocene lacustrine deposition, may have blocked drainage outlets from the western Snake River Plain. Other basalts at about the same stratigraphic levels, deposited as far east as Hagerman, Idaho, suggest widespread volcanism at these two times. The two separate episodes of widespread volcanism and subsequent lacustrine deposition suggest the formation of the western Snake River Plain by episodic rifting.

Subsidence at the drainage outlet of the plain may have ended lacustrine deposition in the Miocene. Nearshore sediments of the Chalk Hills Formation closest to the outlet are over 60 meters lower than time-equivalent lacustrine sediments to the southeast. Nearshore sediments of the Glenns Ferry Formation in the same area are not lower than lacustrine sediments to the southeast, suggesting that subsidence ended before deposition of the Glenns Ferry Formation. Lacustrine deposition of the Glenns Ferry Formation probably ended with the erosion of a new, lower outlet to the Columbia River drainage system.

INTRODUCTION

An understanding of the nature and timing of sedimentation in the western Snake River Plain is essential in interpreting the tectonic history of the basin. This paper will outline the history of lacustrine deposition on the western plain during the Miocene and Pliocene (as defined by Van Couvering, 1978) and will discuss the implications for tectonic activity along the plain.

Lacustrine sediments were recognized in the western Snake River Plain by the first geological surveys in the area. King (1878) hypothesized that the sediments were deposited in an enormous lake covering parts of southern Idaho, Utah, and eastern Oregon. Later, other geologists suggested that the lakes were more restricted and that some sediments were deposited by streams and rivers. More recently, Malde (1972, p. D13) interpreted Pliocene sediments near Glenns Ferry, Idaho, and eastward (Figure I) as deposits of a river flowing in "a wide valley marked by temporary lakes and by broad stretches that were seasonally flooded." Fossils and sediments in the western plain have also been interpreted as evidence for a large, permanent lake occupying most of the basin (Smith, 1975; Kimmel, 1975; Smith and others, 1982 this volume) during the late Miocene and most of the Pliocene. The lacustrine sediments discussed in this paper are characterized by light tan siltstones, abundant and pure volcanic ash beds, and occasional fossiliferous sandstones and conglomerates.

Part of the problem in determining the nature of sedimentation in this basin stems from difficulties in correlating and dating the lacustrine sediments. The scarcity of mammal fossils, abrupt facies changes, and faulting often prevent correlations among lacustrine sediments. Lacustrine sediments of different ages usually have similar lithologic properties. Basalt flows within the sediments are not common, are often altered, and have yielded contradictory potassium-argon dates (Armstrong and others, 1975). Several...
additional methods of correlating and dating lacustrine sediments have recently been applied successfully to this basin. The correlations used in this paper are based on fossil fish faunas (see Smith and others, 1982 this volume), volcanic ash chemistry (see Swirydzuk and others, 1982 this volume), and depositional sequences of volcanic ashes. Fission track dates of volcanic ashes provide absolute ages for some of the important ash horizons. These methods provide data for a reevaluation of depositional models and their relation to the tectonic history of the western Snake River Plain during the late Miocene and Pliocene.

**STRATIGRAPHY**

**STRATIGRAPHIC SETTING**

Most lacustrine sediments in the western Snake River Plain can be placed in the late Miocene Chalk Hills Formation and the Pliocene Glenns Ferry Formation (Figure 2). Before 1962 these sediments were included in the Idaho Formation of Cope (1883). Malde and Powers (1962) revised the upper Cenozoic stratigraphy of the western Snake River Plain and elevated the Idaho Formation to group status by dividing it into seven separate formations ranging in age from middle Miocene to middle Pleistocene (Figure 2). The sediments of the Idaho Group are confined to the western Snake River Plain and are underlain by the Idavada Volcanics, thought to have been deposited before or during the formation of the western plain (Malde and Powers, 1962). Formations older than the Idavada Volcanics such as the Deer Butte Formation, the Owyhee Basalt, and the Sucker Creek Formation are not exposed within the Snake River Plain and do not show evidence that the plain existed during their deposition. These older formations were deposited in north-trending basins and are now exposed mainly to the south and west of the plain in Oregon (Kittleman and others, 1965; Corcoran and others, 1962).

The Chalk Hills and Glenns Ferry Formations are bounded by unconformities. The Chalk Hills Formation unconformably overlies the Idavada Volcanics as well as unnamed basalts within the Idaho Group (Armstrong and others, 1975). The Glenns Ferry Formation unconformably overlies the Banbury Basalt near Hagerman and the Chalk Hills Formation along most of the rest of the southwestern edge of the plain. Malde and Powers (1962) report a moderate angular unconformity at the base of the Glenns Ferry Formation. From Grand View to Murphy, Idaho, the basal sediments are oolitic limestones. Swirydzuk and others (1979, 1980) show that this oolite was a transgressive lacustrine deposit. Although Malde and Powers (1962) correlated these oolitic limestones with an algal limestone south of Bruneau, Idaho, additional work (Swirydzuk and others, 1982 this volume) shows that the algal limestone is actually in the Chalk Hills Formation and that the basal Glenns Ferry Formation in this area is represented by a quartzite conglomerate. The Glenns Ferry Formation is unconformably overlain by the early Pleistocene Tuana Gravel, the middle Pleistocene Bruneau Formation, and other younger formations.

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Figure 2. Stratigraphy of the western Snake River Plain. Idaho formations are modified from Malde and Powers (1962) and Armstrong and others (1975). Oregon formations are modified from Corcoran and others (1962) and Bryan (1929).
Extent of the Chalk Hills Formation

As originally described, the Chalk Hills Formation included sediments from the Bruneau area to the Oreana area, Idaho, along the southwestern edge of the western Snake River Plain (Figure 1). More recent correlations suggest that sediments in the Adrian area, Oregon, should also be included in this formation. When first mapped these sediments were placed in the Chalk Butte Formation, a partial equivalent of the Chalk Hills Formation (Corcoran and others, 1962). Later they were assigned to the middle-Miocene Deer Butte Formation on the basis of supposed lithologic similarities (Kittleman and others, 1965). Recent correlations based on fish fossils (Smith and others, 1982 this volume), volcanic ash chemistry (Swirydczuk and others, 1982 this volume), and fission track dates confirm the presence of late Miocene lacustrine sediments in this part of Oregon. The name Chalk Hills Formation is preferred instead of Chalk Butte Formation for these sediments because the Chalk Butte Formation includes sediments of widely differing ages (Shotwell, 1970), including some now correlated with the Pliocene Glenns Ferry Formation (Smith and others, 1982 this volume; Kimmel, 1979). The sediments also appear to have been deposited in the same basin as those of the Chalk Hills Formation.

Extent of the Glenns Ferry Formation

Malde and Powers (1962) recognized intermittent exposures of the Glenns Ferry Formation along the southwestern edge of the western Snake River Plain from Hagerman to Homedale, Idaho, on the basis of geologic mapping and fossil collections. Fossil evidence suggests that equivalent sediments are also present from Boise, Idaho, to Ontario, Oregon, along the northeastern edge of the plain (Taylor, in Malde and Powers, 1962). Fossil fish evidence (Kimmel, 1975) shows that Glenns Ferry sediments are also present in Oregon along the southwestern edge of the plain near Adrian, Oregon.

STRATIGRAPHIC METHODS

Fossil fish faunas are useful in distinguishing between sediments of the Chalk Hills Formation and those of the Glenns Ferry Formation. Chalk Hills faunas are characterized by the presence of a minnow, *Mylocheilus robustus*, and a salmon, *Paleolox larsoni*, both of which are absent from all but the lowest Glenns Ferry sediments. Many fossils in the basal Glenns Ferry Formation are worn and may be reworked from older sediments. *Mylocheilus robustus*, a minnow, and *Prosopium prolixus*, a whitefish, are common in the Glenns Ferry Formation. *Mylocheilus robustus* is also increasingly abundant in stratigraphically higher faunas of the Chalk Hills Formation. A third minnow, *Mylopharodon hagermanensis*, is found primarily in nonlacustrine sediments of the Glenns Ferry Formation. *Mylocheilus robustus* fossils are rare in these sediments. Fossils of at least one of these minnows are found in almost every sizable fish collection. Additional differences between the fish faunas of these two formations are discussed in a later paper (Smith and others, 1982 this volume). A fossil fish collection can almost always be used to assign lacustrine sediments to the Chalk Hills or Glenns Ferry Formation.

Volcanic ash beds are useful in correlating among outcrops of lacustrine sediments. Ash chemistry can be used to "fingerprint" individual ashes for correlations over long distances. Correlations among measured sections in the Horse Hill, Poison Creek, Oreana, and Adrian areas used in this paper were proposed by Swirydczuk and others (1982 this volume) based on comparisons of ash chemistry.

Over shorter distances ash beds may not change appreciably in color, relative thickness, or relative spacing, and these properties may be used to correlate outcrops. Figure 3 illustrates the variations in color, thickness, and spacing of several ash beds traced over three quarters of a mile along a single outcrop. In Figure 4, a comparison of longer measured sections containing more ashes suggests that correlations can be made over a distance of 20 miles. Correlations can be made only between areas which had similar rates of deposition over long periods of time and which show excellent preservation and exposure of ash beds. Nearshore lacustrine environments appear to fit these criteria.

The reliability of correlations which use lithologic properties of several ashes in sequence can be tested by comparing such correlations with those established using ash chemistry. Because not all correlations based on the lithology of ashes in sequence include ashes that have been chemically analyzed (Swirydczuk and others, 1982 this volume), only six correlations between measured sections of the Glenns Ferry Formation can be compared. Five of these correlations match with those based on ash chemistry (Figure 4). The exception, where two different ashes are correlated with a third using the different methods, is also consistent with ash chemistry data since all three of the ashes involved have nearly identical chemistries. Swirydczuk and others (1982 this volume) speculate that these ash layers represent multiple eruptions from the same source or redeposition of one ashfall from separate drainage systems. Thus correlations of localities using only the chemistry of
single ash layers may be ambiguous.

An additional correlation by ash chemistry illustrates the limits of correlation using lithologies of several ashes in sequence. Two ashes from the Glenns Ferry Formation near Horse Hill were chemically correlated with ashes in other sections using ash chemistry (Swirydczuk and others, 1982 this volume). One of the ashes (H3 at Horse Hill) is 10 feet thick, but it correlates with an ash at Crayfish Hill only 1 foot thick. The Horse Hill area appears to have had much higher rates of deposition than other areas studied (Swirydczuk and others, 1982 this volume). Only three of the ten ashes in this measured section resembled those in other sections using ash lithology. Thus correlations between areas with different depositional characteristics are not possible using this method.

Simple lithologic correlations are also possible among sediments of the Chalk Hills and Glenns Ferry Formations, based on the transition from nonlacustrine to lacustrine sedimentation. Measured sections are shown in Figures 5 through 10. Fossiliferous beach sands and conglomerates, oolitic limestones, and algal limestones all indicate the beginning of lacustrine deposition. The angular unconformity between Chalk Hills and Glenns Ferry sediments and the transgressive nature demonstrated for most of these layers shows that the layers are not necessarily time-equivalent and were probably deposited while the basin was filling with water.

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**Figure 3.** Lateral variations in ashes of the Chalk Hills Formation over a distance of ¼ mile in the Poison Creek area (Figure 1, location 5). Only ashes 6 inches or more in thickness are shown. Locations of measured sections: 5A—NW¼SW¼ sec. 5, T. 7 S., R. 3 E., Owyhee County, Idaho; 5B and 5C—SW¼ sec. 5, T. 7 S., R. 3 E., Owyhee County, Idaho; 5D—NE¼SE¼ sec. 5, T. 7 S., R. 3 E. Elevations given are for the top of each measured section.

**Figure 4.** Ash correlations within lacustrine siltstones of the Glenns Ferry Formation. Correlations based on ash chemistry are shown by dashed lines (dotted where an ash within a section was not analyzed). Correlations based on ash thickness, color, and spacing are shown by solid lines. Modified from Swirydczuk and others (1982 this volume).
STRATIGRAPHIC RESULTS

Lithostratigraphic and biostratigraphic correlations and the fossil fish faunas suggest that lacustrine sediments of the Chalk Hills and Glenns Ferry Formations were deposited in a large, permanent lake. Such a depositional model would not require substantial local subsidence during deposition, but would imply a large and relatively stable basin. This depositional model fits well with regional tectonic models for the formation of the western Snake River Plain.

A second model for deposition of the Glenns Ferry Formation has been proposed by Malde (1972) based on sediments studied between Hammett and Hagerman, Idaho. Malde recognized three major facies: fluvial sands, lacustrine silts, and floodplain silts and clays. Malde interprets the pattern of sedimentary facies in this area as a wide valley with a river, temporary lakes, and broad stretches that were seasonally flooded. This model conflicts with the hypothesis that the lacustrine sediments were deposited in a large lake in a relatively stable basin.

There are two ways of reconciling Malde’s data with a large lake model. Either Malde’s fluvial sands can be reinterpreted as near shoreface sands (Smith and others, 1982 this volume), or the time-equivalence of lacustrine and fluvial sediments can be questioned.

The facies relationships between floodplain and lacustrine facies is consistent with a large lake in the basin. Malde (1972) shows that eastern floodplain sediments near Hagerman pass westward into lacustrine sediments, whereas floodplain sediments to the west rest on lacustrine silts. This pattern of facies suggests that floodplain environments coexisted with a lacustrine environment near the margins of the basin, replacing lacustrine environments near Glenns Ferry as the lake drained or was filled with sediments.

The time-equivalence of lacustrine and fluvial sediments near the axis of the basin does not fit the large lake model for deposition of lacustrine sediments. Malde’s correlation of lacustrine and fluvial facies is not direct but depends on correlations with sections in the floodplain facies. One important correlation depends on the chemical and physical similarities of two ash samples. Since chemically
Figure 6. Measured section at location PK3A. Located in the SW¼SW¼ sec. 22, T. 22 S. R. 46 E., Malheur County, Oregon. Base elevation is 2,560 feet.
indistinguishable ashes can occur at different horizons within the same measured section (Swirydczuk and others, 1982 this volume), this correlation and the time-equivalence of fluvial and lacustrine sediments need to be reevaluated.

If the lacustrine and the fluvial facies are not time-equivalent, the distribution of these facies can be explained as a result of the draining of the Glenns Ferry lake. Lacustrine deposition over the whole basin is followed by fluvial deposition along the axis of the plain, precisely where Malde maps the fluvial facies. Malde also reports that in some measured sections lacustrine sediments are overlain by floodplain sediments. This could have occurred as the lake drained or as it filled in some areas with sediments. Lacustrine deposition may have ceased when drainage capture by a tributary of the Columbia River created a new, lower outlet from the western Snake River Plain (Wheeler and Cook, 1954).

Smith (1975) argued on the basis of the diversity of the fossil fish and mollusk fauna, the size of individual fossil specimens, and the nature of specializations in the fossil fish that some sediments of the Glenns Ferry Formation must have been deposited in a large lake. Kimmel (1975) reported on a similar fauna from the Chalk Hills Formation (which he incorrectly referred to as the Deer Butte Formation) and reached a similar conclusion. The known distribution of fossil fish localities in the Chalk Hills and Glenns Ferry Formations supports the large-lake depositional model. Figure 11 shows collecting localities for fossil fish recorded by University of Michigan field parties. All of the localities west of Glenns Ferry, Idaho, contain lacustrine species and are found in lacustrine sediments. In addition to the University of Michigan localities shown on Figure 11, Cope (1883) reported fish species known elsewhere only from Glenns Ferry lacustrine sediments in a locality along “Willow Creek, Oregon,” north of Vale, Oregon. This distribution of fossil fish faunas suggests that the Chalk Hills lake covered at least 80 miles and the Glenns Ferry lake at least 110 miles of the southwestern edge of the western Snake River Plain. Other areas of the plain have not been examined by the author for fish localities.

The extent of some volcanic ash beds also supports the presence of large lakes during the late Miocene and Pliocene. Correlations using ash chemistry (Swirydczuk and others, 1982 this volume) and the lithology of ash beds show that the lower Horse Hill ash layer of Swirydczuk and others (1982 this volume) in the Chalk Hills Formation is present in all the study areas. Similar comparisons of ashes from the Glenns Ferry Formation show that ash beds can be correlated from localities near Bruneau, Idaho, to Oreana, Idaho. Comparisons of ash thickness, spacing, and color show that these ashes were deposited in nearly identical environments (Figure 4). This similarity of environments of deposition over wide stretches (up to 40 miles in length) suggests that deposition occurred in a large lake rather than in several small lakes.

Lithologic correlations, strengthened by fossil fish correlations, support the large-lake model. Oolitic limestones are found in the Poison Creek, Oreana, and Adrian areas (Figure 1), just above the base of the Glenns Ferry Formation. These widely separated oolites suggest either synchronous changes in lake chemistry for several lakes, or one change in lake chemistry in a large lake.

Lithologic correlations also suggest that lake levels were affected simultaneously in widely separated areas. In the upper part of the Glenns Ferry Formation measured sections at Poison Creek and Crayfish Hill show a coarse-grained fossiliferous layer at about the same stratigraphic position (Figure 4). Overlying sediments do not show evidence of lacustrine deposition such as fish fossils or interbedded volcanic ash beds and siltstones. Similar fossiliferous sandstones containing wood, fish, bird, and mammal fossils are found near the top of the Chalk Hills Formation in the Horse Hill and Adrian areas (Figures 6 and 10). These sands are immediately overlain by the lower Horse Hill ash layer, but no other lacustrine deposition is present above the sands. These fossiliferous sands may represent beach deposits laid down as lake
levels dropped. The presence of regressive beach sands laid down simultaneously in widely separated areas supports the large-lake depositional model. Intermediate measured sections (Figures 8 and 9) do not show beach deposits at the same level, and lacustrine siltstones and volcanic ash beds are found above the lower Horse Hill ash layer of Swirydczuk and others (1982 this volume). These intermediate sections suggest that lacustrine deposition continued at lower elevations and that lake levels dropped slowly and may have fluctuated.

GEOCHRONOLOGY

SETTING

Early workers in the Snake River Plain based age determinations of sediments on fossil faunas. Cope (1883) on the basis of fish fossils suggested a Pliocene age for the sediments now placed in the Glenns Ferry Formation. Malde and Powers (1962) relied on fossil faunas in dating the Chalk Hills as late Hemphillian and the Glenns Ferry Formation as Blancan. Early potassium-argon dates (Evernden and others, 1965) provided absolute ages for these mammal faunas and a date of 3.5 million years for the Glenns Ferry Formation. Later potassium-argon dates revealed a more complicated situation. Armstrong and others' (1972) potassium-argon dates of 8.5 million years for a basalt below the Chalk Hills Formation agree with accepted biostratigraphy. However Armstrong and others' dates for basalts within the Glenns Ferry Formation range from 4.4 to 6.2 million years, older by 2.1 million years than radiometric dates associated with other Blancan mammal faunas. Armstrong and others note that the two Glenns Ferry dates older than 4.5 million years are from basalts with unusually large atmospheric argon corrections.

Figure 7. Measured section at location PK4. Located in the SE¼NE¼ sec. 12, T. 5 S., R. 1 W., Owyhee County, Idaho. Base elevation is 2,900 feet.
The older potassium-argon dates could be caused by fractionation of atmospheric argon during its removal by a bake-out procedure, although Armstrong and others feel this effect is minor. If the basalts which they sampled flowed into a very deep lake, the rapid cooling and high pressures could also lead to a potassium-argon date older than the true age (Dalrymple and Lanphere, 1969).

In the Hagerman area, Armstrong and others (1972) dated the Banbury Basalt, formerly thought to be older than the Chalk Hills Formation, at 4.4 to 4.9 million years. These dates also cast doubt on dates of 4.4 to 6.2 million years for the Glenns Ferry basalts since the Banbury Basalt underlies the Glenns Ferry Formation. Armstrong and others felt these dates for the Banbury Basalt may be too young because of pervasive weathering, but the dates are consistent with all their evidence except their Glenns Ferry basalt dates.

The potassium-argon dates and the stratigraphic position of the Banbury Basalt suggest a period of volcanism between the deposition of the Chalk Hills and Glenns Ferry Formations. Other basalts are found in the western Snake River Plain in a similar stratigraphic position. In the Oreana area the Glenns Ferry Formation directly overlies a basalt that may itself overlie the Chalk Hills Formation (Anderson, 1965). In the Adrian area Glenns Ferry sediments, as determined by fish fossils, are underlain by the Blackjack Basalt. This basalt was named by Bryan (1929) and later mistakenly synonymized with the Owyhee Basalt. Although no correlations using fish fossils or volcanic ashes have been made with sediments directly below the Blackjack Basalt, fossil molluscan faunas and general stratigraphic relationships suggest that the sediments are part of the upper Chalk Hills Formation and that the basalt is roughly equivalent in age to the Banbury Basalt.

FISSION TRACK METHODS

Fission track dating can give the age of an unaltered, coarse-grained volcanic ash. The eleven ash samples dated in this study were collected from six ash layers in the Chalk Hills and Glenns Ferry Formations. Although one ash layer was sampled at five widely separated localities, the abundance of ash beds within measured sections and the lack of precision of the ash dates did not allow correlation among ash samples using fission track dating. Instead, correlation among ash layers is based on comparisons of ash chemistry and lithology. The fission track dates provide the time of deposition for these ash layers.

These ashes were dated using methods outlined by Boellstorff and Steineck (1975). Glass shards appropriate for fission track dating were separated from bulk samples by sieving, ultrasonic cleaning, and, where necessary, heavy liquid separation. These techniques were necessary to produce samples of large, clean, glass shards. Two aliquots of the treated ash were taken. One was irradiated with a thermal neutron dose of about 10^{12} neutrons/cm², along with a standard of known age and uranium content. The two aliquots were then etched under identical conditions in 24 percent reagent grade hydrofluoric acid for up to 2 minutes to enlarge fission tracks into etch...
Figure 9. Measured section at location PK7. This is the reference section for correlations involving the comparison of sequences of ash beds. Located in the NW¼SW¼ sec. 19, T. 7 S., R. 4 E., Owyhee County, Idaho. Base elevation is 2,930 feet.
The precision of each date is expressed as a 95 percent confidence interval. A normal distribution for the ages of ashes in this study was assumed. Samples used in the fission track dating were collected by G. P. Larson, field parties from the University of Michigan in 1975 and 1976, and the author. Localities and measured sections for most of the samples are given in Swirydczuk and others (1982 this volume). Additional localities and measured sections are given in Table 1.

The accuracy of these fission track dates may be affected by three factors. If the ash was heated after the time of deposition, the fission tracks in the glass shards may have been erased or annealed. The apparent age of the ash represents the time when the ash cooled enough for new fission tracks to form. Preliminary ages of 3.5-4.0 million years for some ashes in the Chalk Hills Formation near Oreana, Idaho, suggest that these ashes have been annealed, presumably by hydrothermal action. Partial annealing is suspected in an ash sample from Horse Hill (H1), which gives a date significantly younger than other ash samples in the same ash layer. Hydrothermal activity, which can cause annealing, is still present at Indian Bathtub hot springs, several miles to the south. Since other ashes dated in this study may also have been partially annealed, their ages must be regarded as minimum dates.

Contamination of one ash by shards from another ash could also affect the apparent fission track age of the ash, especially if the differences in ages of the two ashes were great. Shards which are more resistant to annealing could also affect the apparent age of the ash. Partial annealing is suspected in an ash sample from Horse Hill (H1), which gives a date significantly younger than other ash samples in the same ash layer. Hydrothermal activity, which can cause annealing, is still present at Indian Bathtub hot springs, several miles to the south. Since other ashes dated in this study may also have been partially annealed, their ages must be regarded as minimum dates.
Figure 10. Measured section at location PK8. Located in SE¼ sec. 3, T. 8 S., R. 5 E., Owyhee County, Idaho. Base elevation is 3,025 feet.

- ashly silts grading into pure volcanic ash
- volcanic ash (medium sand-silt) light gray-very light gray, Lower Horse Hill ash layer of Swartselzuk and others, 1982
- base of ash is burrowed (silts)
- 5 in. conglomerate with up to 2 in. pebbles of silstone (mutedated alive green) fining upward; fish and wood
- silstone
- covered
- coarse silt to fine silt with ashly layers containing plant and fish debris
- sandstone with basalt scoria cobbles
- basalt flow
- light tan silstone, massive bedded
- 4-in. gravel unit
- silstone
- light tan granule sandstone with wood, fish, and pumie, Faunal Sample L
- silstone
- sand and pebble cover
- 50
- 45
- 40
- 35
- 30
- 25
- 20
- 15
- 10
- 5
- 0
- ashy silts grading into pure volcanic ash
- volcanic ash (medium sand-silt) light gray-very light gray, Lower Horse Hill ash layer of Swartselzuk and others, 1982
- base of ash is burrowed (silts)
- 5 in. conglomerate with up to 2 in. pebbles of silstone (mutedated alive green) fining upward; fish and wood
- silstone
- covered
- coarse silt to fine silt with ashly layers containing plant and fish debris
- sandstone with basalt scoria cobbles
- basalt flow
- light tan silstone, massive bedded
- 4-in. gravel unit
- silstone
- light tan granule sandstone with wood, fish, and pumice, Faunal Sample L
- 1 in. medium gray ash, orange-stained (silt)
- 1/4 in. light gray ash (silt)
- silstone
- 1 in. impure tan ash (silt)
- silstone
- 1/2 ft. dark gray massive ash (silt)
- 6 in. light orange laminated ash (silt)
- erosional surface cut (below 157 ft. in places)
- silstone
- 1 in. light gray-tan ash (silt)
- silstone
- olive green sandstone
- orange-brown sandstone with fossil fish
- conglomerate with 4 in. quartzite cobbles-basal lacustrine sediments of the Glenns Ferry Formation
- ashy sandstone
- burrowing
- sandstone
- silstone
- 1 ft. salt-pepper light gray ash (fine sand-fine silt)
- silstone
- dark gray sandstone
- calcite-cemented sandstone
- interbedded silts and sands
- dark gray sandstone (medium sand) with biotite
- 1 in. gray calcite-cemented sandstone
- 1 in. medium gray calcite-cemented sandstone
- silstone
- 1 ft. medium-light gray ash (coarse-fine silt)
- silstone
- 6 in. light-very light gray ash (medium-fine silt)
- silstone
- 4 in. dark-medium gray ash (coarse sand-silt)
- 3 in. light gray-orange ash (coarse-fine silt)
- silstone

Figure 10. continued.
the glass age determinations. Boellstorff, who suggested the Borchers Ash as an interlaboratory standard, believes that calibration of the newer NBS standards may be at fault (Boellstorff and Alexander, 1980). If Seward is correct and the Borchers Ash has been annealed, dates determined using the Borchers Ash as a standard are too old. A comparison of ages calculated for the interlaboratory standard using the older NBS standard and the new NBS standards (Seward, 1979) reveals that dates using the Borchers Ash standard and assuming no annealing are 29 percent older than those dates calculated by assuming that annealing did take place. This correction factor can be used only if all samples of the Borchers Ash have been uniformly annealed, a likely assumption since workers have consistently reported similar fission track ages (Seward, 1979; Boellstorff and Steineck, 1975). Table 1 gives ages based on the Borchers Ash standard as well as ages corrected using Seward's data for the Borchers Ash to approximate use of the new NBS standard. The discussion below uses dates based on the Borchers Ash standard.

**FISSION TRACK RESULTS**

Two ash samples (F-2 and 19-A-02) from stratigraphic levels about 25 feet apart in the Glenns Ferry Formation give statistically identical dates (at .05 level) of 2.4 ± 0.2 and 2.5 ± 1.0 million years. Ash beds from the Poison Creek and Oreana areas were correlated by ash chemistry and lithology. Both ashes contain very thin glass shards which almost completely dissolve during 1 minute of etching in hydrofluoric acid. This lowered the number of fission tracks that could be counted for these samples, resulting in a large standard deviation for one of these dates.

A third ash (77-4) was sampled from sands just above the unconformity separating the Chalk Hills and Glenns Ferry Formations. This ash from the Oreana area gives a date of 3.23 ± 0.4 million years. Because this ash is found in transgressive beach sands at the base of the Glenns Ferry Formation, it may have been reworked from older annealed ashes in the Chalk Hills Formation. Reworking is unlikely, however, since the ash bed is very pure. Preliminary fission track dates of 3.8 and 4.3 million years for ashes nearby suggest that some annealing has occurred in this area and that the ash age must be considered a minimum age.

An ash layer in the upper Chalk Hills Formation...
was sampled in three of the four study areas from five separate sampling sites. Four of the dates are not statistically different (.05 level) from each other, giving an average age of 7.0 million years. The remaining ash, from the Horse Hill area near Hot Creek, gives a date of 5.9 million years and may be partially annealed. It is within 10 miles of a present-day hot spring and near another sampling site in the lower Chalk Hills Formation which has given a preliminary date of 3.3 million years.

Ash dates from the lower Chalk Hills Formation show greater standard deviations and less consistency than other ash dates. Three ash samples give dates of 7.9 ± 0.5, 8.5 ± 1.2, and 9.1 ± 0.7 million years based on the Borchers Ash standard. The oldest and youngest dates are from the same ash layer as correlated by ash chemistry (Swirydzuk, personal communication, 1981) and by ash lithologies between localities 1.5 miles apart. These fission track dates suggest that the lower Chalk Hills Formation is about 8.5 million years old. The large standard deviations for the dates may have been caused by variations in preparation and counting techniques or by altered distribution of uranium in the ashes. Annealing seems unlikely for three reasons: there is no evidence of hydrothermal activity, additional ashes (S3, S4) from the same area are not annealed, and the ashes showing different dates are found in close proximity to each other.

**TECTONIC SETTING**

Two generally accepted tectonic models have been proposed for the formation of the western Snake River Plain. One calls on rifting to create the western plain, the other calls on cooling and contraction of rocks in the wake of the Yellowstone Hotspot to form both the western and eastern Snake River Plain. Zoback and Thompson (1978) proposed that the formation of the western Snake River Plain was part of a larger pattern of extensional movement that also formed the northern Nevada aeromagnetic anomaly and influenced the northwest-southeast alignment of feeder dikes for the Columbia River basalts. Smith and Sbar (1974), Morgan (1971), Matthews and Anderson (1973), Eaton and others (1975), and Armstrong and others (1975) did not separate the formation of the eastern and western parts of the Snake River Plain, hypothesizing that all of the plain was formed by the passage of a hot spot now centered under Yellowstone Park.

The eastern Snake River Plain was probably formed by subsidence following the passage of the Yellowstone Hotspot. The magnetic and gravitational anomaly patterns suggest a series of volcanic centers cooling and sinking with time (Mabey, 1978). Armstrong and others (1975) show that the oldest silicic volcanic rocks increase in age away from Yellowstone Park along the eastern Snake River Plain. Seismic evidence suggests that the eastern plain is still active, particularly in the vicinity of Yellowstone. The western plain shows no evidence of seismicity or microseismicity, indicating neither nontectonic movement or very fluid conditions below the plain (Pennington and others, 1974).

Several lines of evidence suggest that the eastern and western plains were not formed by the same process. Gravitational and magnetic anomalies for the western Snake River Plain show a comparatively simple pattern, indicating a thick, dense layer of magnetic rock (Mabey, 1976), rather than the more complex pattern of local highs and lows of the eastern plain which indicate varying thicknesses of Cenozoic rocks (Mabey, 1978). The dense layer, up to 5 kilometers thick, may include basalts of the Columbia River Group (Mabey, 1976).

The structural geology of the eastern part of the Snake River Plain is also different from the western part. The eastern plain lacks bounding faults (Kirkham, 1931; Armstrong and others, 1975) and seems to have formed entirely by downwarping, while the western plain shows evidence for faulting as well as downwarping along its boundaries (Malde, 1959; Kirkham, 1931). The trend of the western plain is almost 90 degrees from that of the eastern plain. If both were formed by the same hotspot, they indicate either a drastic change in the direction of movement of the North American plate or a change in the direction of movement of the Yellowstone Hotspot.

Regional tectonic evidence does not suggest that the North American plate changed direction in the last 15 million years. Smith and Sbar (1974) show that the Yellowstone Hotspot has been fixed with respect to two other hotspots, the Hawaiian and Raton hotspots, for at least the last 10 million years. It is possible that the Yellowstone Hotspot was moving independently before 10 million years and then began moving in concert with the other two hotspots, but the difference between the eastern and western parts of the plain makes this hypothesis unlikely.

Other hypotheses for the formation of the western Snake River Plain are less likely. Hamilton and Meyers (1966) proposed that batholiths in the western United States serve as subplates. They postulated that the movement of the Idaho batholith to the northwest led to the rifting of the eastern Snake River Plain. Their theory does not explain the formation of the western Snake River Plain unless the batholith was heading to the northeast in the late Miocene. Their hypothesis predicts that the western Snake River...
The absence of earthquakes in the western Snake River Plain and along most of the eastern plain (Suppe and others, 1975; Pennington and others, 1974) argues against this hypothesis. In addition, Taubeneck (1971) has shown that structural and lithologic trends in the Idaho batholith continue across the western plain in granitic rocks on the southwest side, indicating that the Idaho batholith was cut by the rift, rather than causing the rift by its movement.

**DISCUSSION**

The two most likely tectonic models for the origin of the western Snake River Plain predict different patterns of sedimentation. If rifting formed the western Snake River Plain, one would expect to find the oldest lacustrine sediments near the location of the initial rifting. As rifting continued further along the axis of the western plain, the size of the basin would increase and younger lacustrine sediments would therefore be deposited over a wider area. Episodic rifting might have caused periodic draining and filling of the basin as faulting and volcanic activity modified the elevation of the drainage outlet from the plain.

If subsidence following the passage of a hotspot formed the western Snake River Plain, one would expect to find the oldest lacustrine sediments near the western outlet of the plain. Younger lacustrine sediments would be deposited farther to the east as crustal cooling behind the hotspot created a depression. Large permanent lakes would not be expected with such a model unless some additional tectonic activity raised the drainage outlet from the plain. Although not enough sedimentologic or stratigraphic data exist to reject either model, our data favor the rifting model.

As presently known, the minimum extent of younger lacustrine sediments in the western Snake River Plain is intermediate between distributions predicted by the two models. Only the eastern limits of lacustrine deposition are known. Additional delineation of the lacustrine/nonlacustrine boundary in the Glenns Ferry Formation may eliminate one of these tectonic models.

The presence of an unconformity between the Chalk Hills and Glenns Ferry Formations demonstrates that lake levels fell near the end of the Miocene, lowering or completely draining the lake. This period was ended by deposition of transgressive lacustrine sediments of the Glenns Ferry Formation. This drop in lake level may have been caused by climatic changes, tectonic activity, or erosion of the western outlet of the basin.

The sediments and fish faunas of the Chalk Hills and Glenns Ferry Formations show little evidence of climatic control of lake levels. Evaporite deposits have not been reported from lacustrine facies of the western Snake River Plain. The gypsum that is abundant in some areas may be an alteration product from volcanic ash. It is found in many places as a layer within ash beds. The basal oolite of the Glenns Ferry Formation, which might otherwise indicate increasing salinities during evaporitic conditions, was deposited as a progradational unit in an overall transgressive event (Swirydyczuk and others, 1980). In addition diverse fossil faunas just below and just above the boundary between the two formations contain families and genera of fish now found in cool or northern waters (Kimmel, 1979). Included are genera of minnows, salmon, and sculpins (Smith, 1975; Kimmel, 1975). These faunas suggest cooler climates rather than the warmer climates expected with a climatically caused fall in lake levels. The diversity of these faunas is much higher than expected for a lake with fluctuating salinities. Thus, climatically caused changes in lake levels seem unlikely.

The filling of the lake basin during the late Miocene and again in the Pliocene may be due to volcanic activity blocking the outlet of the plain. Volcanism occurred in the same area before and possibly during deposition of the Chalk Butte Formation, which is equivalent to the Chalk Hills Formation in Idaho. The Grassy Mountain Formation, which underlies the Chalk Butte Formation, consists of more than 1,000 feet of basalts interbedded with sediments. Thus it may have filled a previous western outlet from the western Snake River Plain, creating the lake which deposited the Chalk Hills lacustrine sediments. The Blackjack Basalt, overlain by Glenns Ferry lacustrine sediments, demonstrates that volcanic activity also occurred in the area of the outlet just before Pliocene lacustrine deposition. Volcanism was also occurring at about the same time in other areas of the western Snake River Plain. This widespread episodic volcanism can be explained by episodic rifting. It is not explained by the hotspot-passage theory.

Uplift or subsidence along the edge of the western Snake River Plain could create apparent changes in lake levels without additional climatic change. Subsidence and uplift at the outlet of the plain could also have caused the changes in lake levels. Examination of patterns of tectonic activity along the edge of the western Snake River Plain makes it possible to evaluate these two tectonic hypotheses.

Correlation of nearshore lacustrine sediments and ashes among different areas along the edge of the western Snake River Plain should make it possible
to determine whether significant subsidence has occurred. The elevation of each ash or sediment layer at the time of deposition varies with the shape of the lake basin. Figure 12 (and Tables 2 and 3) shows that the elevations of Chalk Hills ash layers in most areas decrease toward the axis of the western Snake River Plain. If the lake basin retained the same configuration between deposition of the Chalk Hills and Glenns Ferry Formations, the beds in both formations in the same area should show similar slopes toward the axis of the basin. Subsidence of the Chalk Hills sediments in the center of the basin or filling of the basin with sediments would result in Chalk Hills strata showing a steeper slope toward the axis of the plain than the Glenns Ferry strata. Uplift of the center of the basin or increased erosion there between deposition of the Chalk Hills and Glenns Ferry Formations would result in Glenns Ferry strata showing a steeper slope toward the center of the basin. As Figure 12 demonstrates, both Chalk Hills ashes and the basal Glenns Ferry lacustrine sediments from measured sections in the Horse Hill and Poison Creek areas decrease in elevation toward the axis of the basin. The Chalk Hills ashes show a slightly greater slope, suggesting minor subsidence or continued deposition along the axis during the late Miocene. The ashes of the Chalk Hills Formation in the Poison Creek area show a much steeper slope toward the axis than ashes from other areas, possibly because of variations in the palaeoslope of the Chalk Hills lake or because of greater subsidence in that area.

Considering only ash layers and sediments deposited in nearshore lacustrine environments provides a relatively small range of elevations, assuming that the sediments were deposited in one large lake. Several important ash correlations presented earlier use ashes associated with beach deposits. This combination of time indicators and shoreline indicators allows direct comparison of paleoelevations for some

Figure 12. Comparison of elevations of ash layers within the Chalk Hills Formation and elevation of the lowest lacustrine siltstones of the Glenns Ferry Formation versus distance from the axis of the western plain. Elevations of Chalk Hills strata are shown by solid symbols, and those of the Glenns Ferry strata by open symbols. Solid lines link strata from the same measured section. The basis for each correlation is given in Table 2. Squares are from the Oreana area, circles from the Poison Creek area, triangles from the Adrian area, and barred circles from the Horse Hill area. Table 2 gives sources for precise locality data. Table 3 gives additional locations.
beds. In only one area along the edge of the plain do we find evidence for major subsidence between deposition of the Chalk Hills and Glenns Ferry Formations. In the Adrian area localities less than 3 miles apart show Chalk Hills sediments more than 800 feet below Glenns Ferry sediments at about the same distance from the axis of the plain. This difference in elevation is probably due to a combination of initial differences in paleoelevations of the two localities, subsidence of the Chalk Hills sediments, and uplift of the Glenns Ferry sediments.

At least some of this difference must be due to subsidence after deposition of the Chalk Hills Formation since ashes and shoreline indicators are within inches of each other in the Adrian area, even though they are hundreds of feet lower than time-equivalent nearshore and beach sediments in the Horse Hill and Poison Creek areas. The Glenns Ferry sediments in the Adrian area are among the highest along the southwest edge of the plain and could have been deposited during the high-water stage of the Glenns Ferry lake. Only two thin ash beds are present in the sediments, and less than 50 feet of unquestionably lacustrine sediments are present, suggesting that the sediments were deposited over a short time during a high stand of the Glenns Ferry lake. The range of elevations present among the localities in this area, all at about the same distance from the axis of the plain, may be a result of an eastward-dipping paleoslope rather than one perpendicular to the axis of the plain.

Faulting could account for the difference between the elevation of the Glenns Ferry lacustrine sediments and those of the Chalk Hills Formation in the Adrian area and may have occurred at any time after the deposition of the Chalk Hills Formation. Although faults have been mapped in the Adrian area, no major faults have been mapped between the localities for the Chalk Hills and Glenns Ferry Formations (Bryan, 1929; Corcoran and others, 1962; Kittleman and others, 1967). If faulting is not responsible for the high elevation of the Glenns Ferry sediments, then the subsidence of the Chalk Hills sediments must have occurred in the late Miocene or early Pliocene, before deposition of the Glenns Ferry sediments.

Evidence for subsidence in the Adrian area is significant because it is near the Owyhee River, the proposed outlet for the Snake River Plain during the late Miocene and Pliocene by large lakes occupying much of the western Snake River Plain. Lacustrine deposition was preceded by volcanic activity in eastern Oregon near the Owyhee River, an area that may have been the outlet for the plain in the late Miocene and Pliocene. This volcanism may have created the lakes by blocking the outlet in the Miocene and again in the early Pliocene. Other basaltic activity of approximately the same ages suggests that the volcanism and the resulting lacustrine deposition are related to episodic rifting along the Snake River Plain rather than to subsidence following the passage of the Yellowstone Hotspot. Comparisons of present elevations of upper Chalk Hills nearshore sediments of the same age suggest that the area nearest the outlet underwent subsidence in the late Miocene. This may have caused the draining of the Chalk Hills lake. Diversion of the drainage of the Snake River Plain into the Columbia River drainage system and the subsequent erosion of a new, lower outlet from the plain may have caused the draining of the Glenns Ferry lake.

The draining of the Glenns Ferry lake may not be related to the tectonic activity. Wheeler and Cook (1954) suggest that drainage from the western Snake River Plain was diverted to the Columbia River by stream (lake) capture or by rising lake waters and that subsequent erosion at this new outlet drained the Glenns Ferry lake.

CONCLUSIONS

Glens Ferry and Chalk Hills lacustrine sediments were deposited in the late Miocene and Pliocene by large lakes occupying much of the western Snake River Plain. Lacustrine deposition was preceded by volcanic activity in eastern Oregon near the Owyhee River, an area that may have been the outlet for the plain in the late Miocene and Pliocene. This volcanism may have created the lakes by blocking the outlet in the Miocene and again in the early Pliocene. Other basaltic activity of approximately the same ages suggests that the volcanism and the resulting lacustrine deposition are related to episodic rifting along the Snake River Plain rather than to subsidence following the passage of the Yellowstone Hotspot. Comparisons of present elevations of upper Chalk Hills nearshore sediments of the same age suggest that the area nearest the outlet underwent subsidence in the late Miocene. This may have caused the draining of the Chalk Hills lake. Diversion of the drainage of the Snake River Plain into the Columbia River drainage system and the subsequent erosion of a new, lower outlet from the plain may have caused the draining of the Glenns Ferry lake.

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