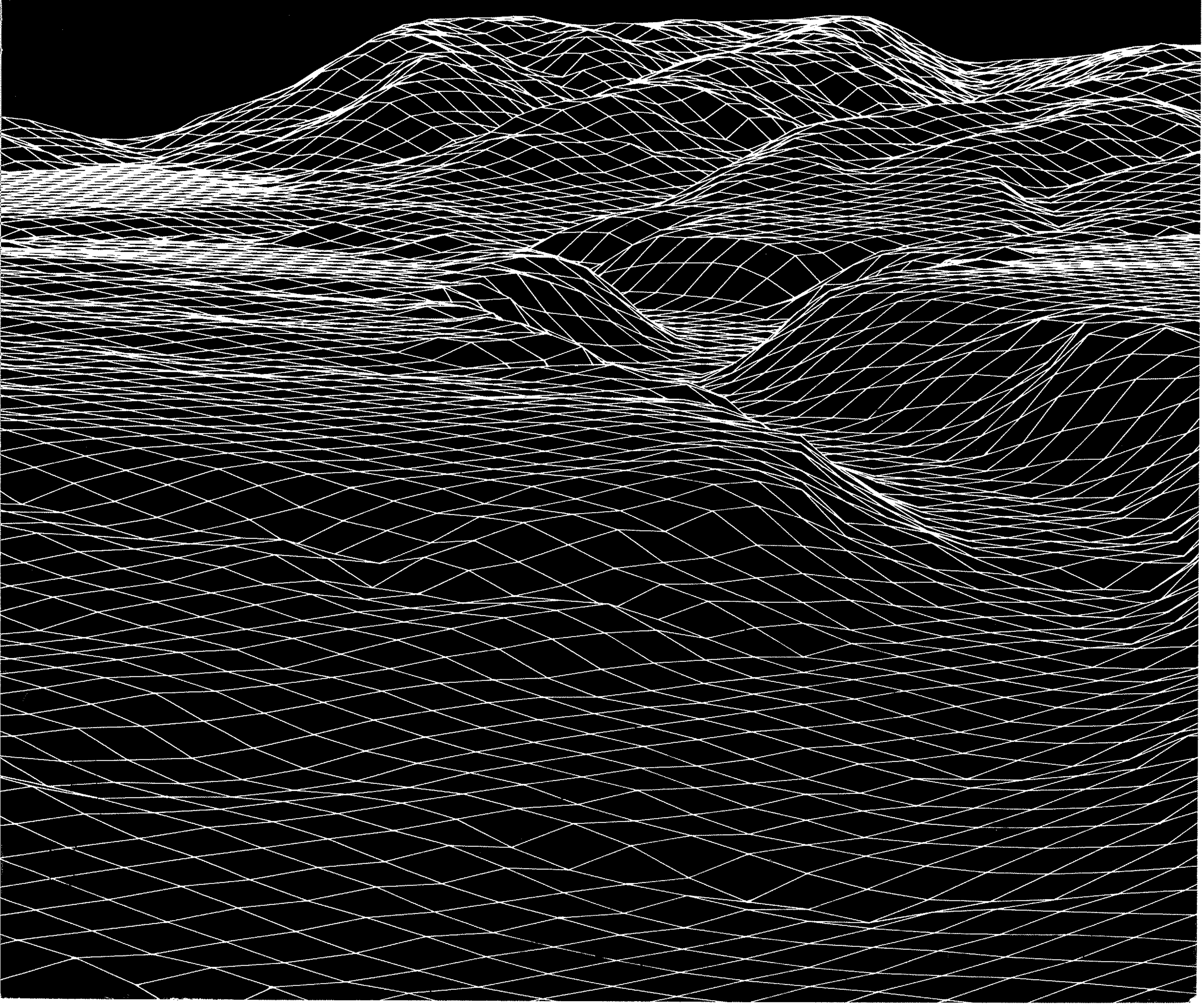
Geology and Geomorphology of the Boise Valley and Adjoining Areas, Western Snake River Plain, Idaho

KURT L. OTHBERG



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Cover: View looking southeast and upstream along the Boise River canyon toward Lucky Peak Dam. Wire-frame illustration prepared by L.R. Stanford at the Digital Mapping and Information Laboratory of the Idaho Geological Survey.

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Kurt L. Othberg[1]

ABSTRACT

The Pliocene and Pleistocene geologic history of the Boise Valley, Idaho, includes crustal rifting, basin filling, drainage capture, pervasive incision by rivers, eruptions of lava flows, and the catastrophic Bonneville Flood. During the Pleistocene, episodic downcutting of Tertiary basin-fill sediments produced terraces in the Boise Valley. Pleistocene basalt lava flows erupted onto several alluvial surfaces of the ancestral Boise River. Soils developed in thin loess on terraces whose ages span the Pleistocene. The increasing development of soil duripans corresponds with terraces of increasing age.

Fine-grained sediments deposited by the Bonneville Flood mantle the terrace surfaces below an elevation of 740 meters (2,430 feet) west of Caldwell. These slackwater deposits that date to 14.5 ka are the parent material for an important soil age marker, the Greenleaf Series.

Potassium/argon and argon-40/argon-39 ages of the basalts range from about 100 ka to about 1.6 Ma. These dates — plus magnetic polarities, the degree of soil development, and the stratigraphy of the terrace gravels with respect to the age of the Bonneville Flood sediments and the Glenns Ferry Formation — show that the age of the terrace sequence in the Boise Valley spans the entire Pleistocene.

Longitudinal profiles of the terraces reveal moderate changes in surface gradients over time. This evidence suggests that rift-basin faulting and warping continued into Quaternary time, but that little movement has occurred since about 100 ka.

The geomorphic history of the Boise Valley includes a Tertiary subsiding graben that was filling with fine-grained lacustrine and flood-plain sediments into the late Pliocene. A drainage diversion, probably by capture through Hells Canyon, provided a free-flowing outlet. Repeated periods of glacial climate, which may have started as early as 1.67-1.87 Ma, probably generated episodes of greater stream power and coarse-gravel sediment. Terraces were formed during glacial climates by rapid downcutting followed by coarse-gravel deposition. The Boise Valley terraces may correlate with several of the known glaciations in the northwestern United

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States and with certain marine oxygen isotope cold stages.

INTRODUCTION

The geology and geomorphology of the lower Boise River valley extends from the mountain front to the confluence with the Snake River (Figures 1 and 2). The river valley from the city of Boise to the mountain front is labeled "Boise Valley" on U.S. Geological Survey topographic maps. Savage (1958) expanded the name Boise Valley to cover the river valley west to the confluence with the Snake River. I generalize Boise Valley to include the terraces and upland surfaces that form the valley sides bordering the river bottomland. The geology and geomorphology of the Boise River valley in the western Snake River Plain includes adjoining areas in the study. The complete study area, shown in Figure 2, incorporates the valley bordering the east side of the Snake River valley, the southern part of the Boise Valley-Payette Valley interfluve, and the northern part of the zone of volcanic vents.

Much of Idaho's population is concentrated in the Boise Valley. Here, the growing cities of Boise, Meridian, Nampa, Caldwell, and others are interspersed within rich, irrigated farmland. At the turn of the century, this area was chosen for two of the U.S. Geological Survey Folios (Lindgren, 1898; Lindgren and Drake, 1904). The geology presented in the folios was significantly reinterpreted by Savage (1958; 1961). More recent interpretations that incorporate detailed study of the river terraces, lava flows, soils, and structure began with Wood and Anderson's (1981) work in the Nampa and Caldwell area. This research was followed by geologic mapping and related studies near the city of Boise by Wood and Burnham (1983), Wood (1984), Burnham and Wood (1985), Othberg (1986), Gallegos and others (1987), Wood and Burnham (1987), Othberg and Burnham (1990), Othberg and others (1990), Othberg and Stanford (1990), Othberg and Stanford (1992), and Burnham and Wood (in press).

As with Wood and Anderson (1981), I have interpreted the geology within geomorphic units such as river terraces and lava-capped surfaces. These landform units provide a framework that is applicable to the many soil, water, engineering, and general planning needs in this rapidly developing region.

Topographic maps and field reconnaissance reveal that multiple terraces are the dominant landforms in the Boise Valley. I was able to combine the studies of soils and terrace chronology because of previous research on Boise Valley soils (Sandoval and others, 1959; Stuart and others, 1961; Priest and others, 1972; Collett,1980). The results show that the ages of the terraces and associated soils spanned the Quaternary.

My work on the Boise Valley provides additional insights into the late Cenozoic geology of the western Snake River Plain, including observations on crustal rifting, basin filling, volcanic eruptions, ancient climate and ecological changes, dramatic drainage capture, pervasive incision by rivers, and the catastrophic Bonneville Flood. Covering the period from the late Pliocene through the early Holocene, my report emphasizes evidence for the changeover in the western Snake River Plain from basin filling to the stepwise incision that created the present Boise Valley. I describe the sediments, soils, and lavas that compose various geomorphic surfaces; interpret the stratigraphic relationships among the lithologic and morphologic units; and develop a chronology through dating, paleomagnetic studies, and correlation. To establish the events that shaped the landscape, I present the structural setting that shows the rift-basin and the effects of Quaternary faulting, interpret the geomorphic history, and correlate the terraces with episodes of glacial climate.

GEOLOGIC AND GEOMORPHIC SETTING

The Snake River Plain has physiographic continuity from eastern Oregon to Yellowstone National Park. Malde (1991) described the geology and tectonic origin of the western part of the Snake River Plain and distinguished it from the eastern part. The Snake River carries all surface waters from the Snake River Plain through Hells Canyon to the Columbia River. At the Idaho-Oregon border, the Owyhee, Boise, Malheur, and Payette rivers join the Snake River (Figure 1). These tributaries intersect the Snake River at nearly the same location and have contributed to the geomorphology of the western Snake River Plain.

The western Snake River Plain is a lowland in southwestern Idaho and eastern Oregon. It extends from about Twin Falls northwestward into Oregon. The plain is about 30 miles wide where the Boise River crosses from the city of Boise to the Snake River (Figure 1). The Boise River heads in the Sawtooth and Smokey Mountains of central Idaho. It drains an extensive area of high mountainous terrain. The river exits the mountains near

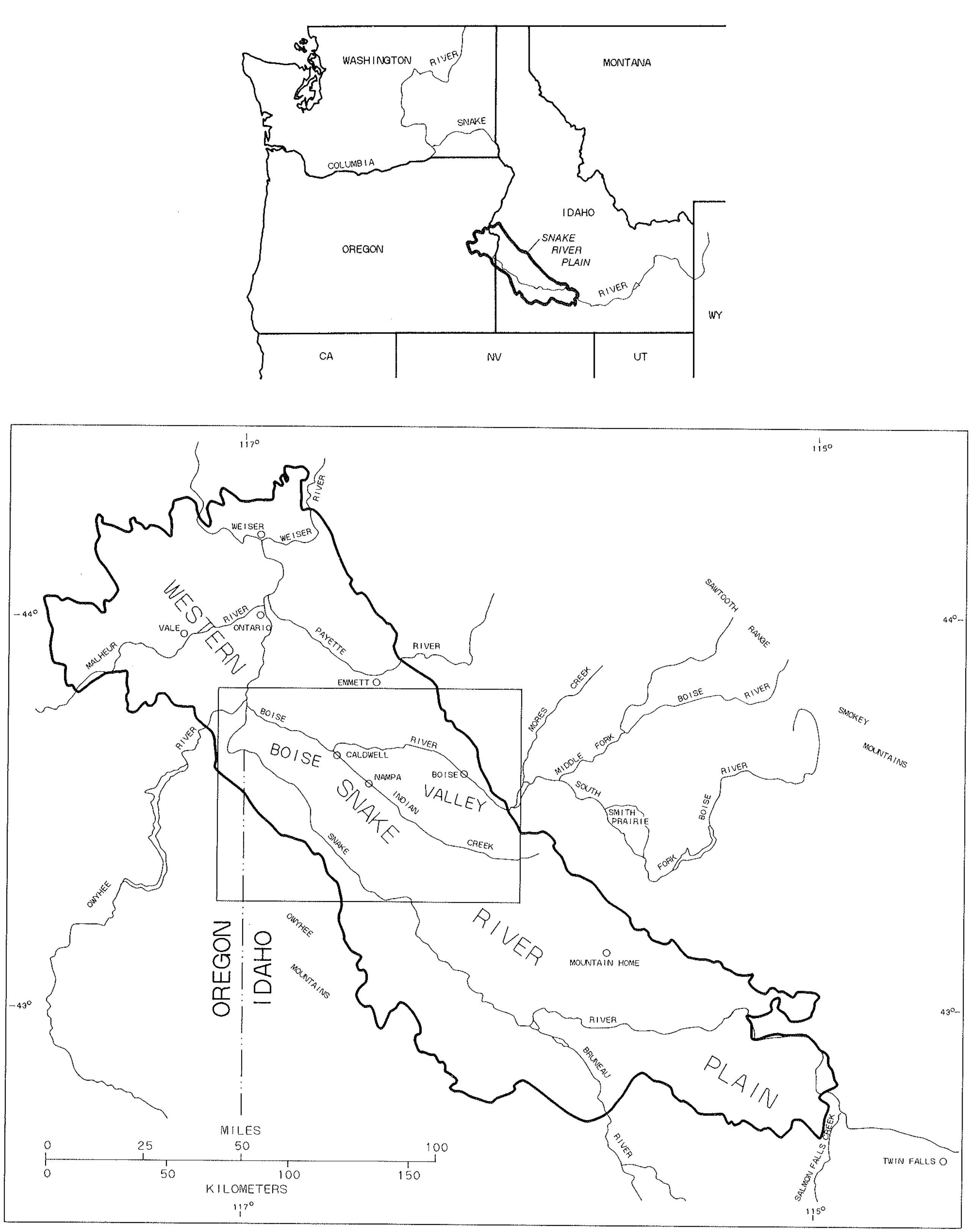

Figure 1. Large map shows the location of the Boise Valley within the western Snake River Plain. The rectangle outline inside the map encloses the study area shown in Figure 2. Map above shows the location of the western Snake River Plain in the Pacific Northwest.

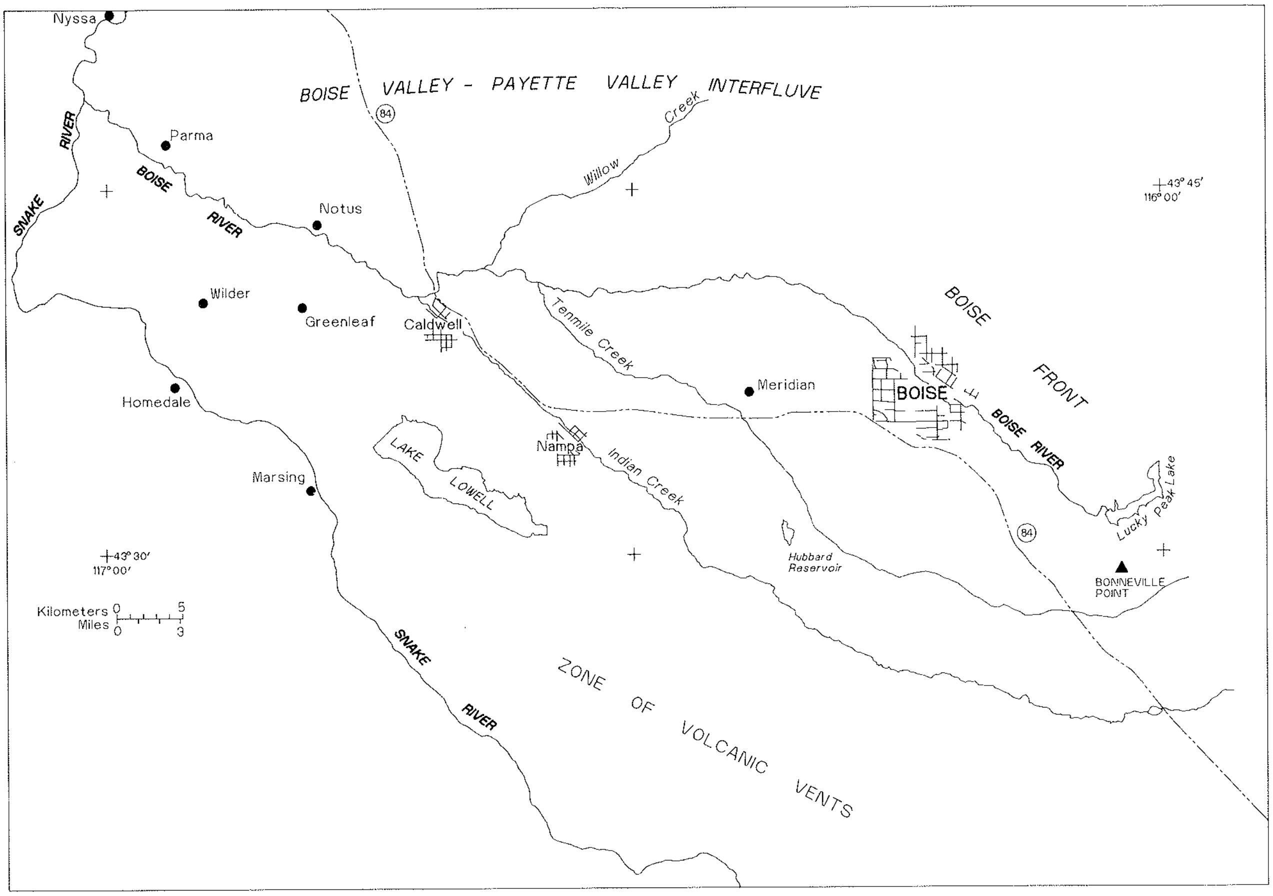

Figure 2. Map of the Boise Valley and adjoining areas.

Lucky Peak Dam southeast of the city of Boise (Figure 3) and flows about 50 miles northwestward across the western plain where it joins the Snake River (Figures 1 and 2). The Boise Front, the foothill area lying between the valley floor and the mountains, marks the trend of the mountain front separating the western plain from the central Idaho mountains (Figure 2).

Although the plain has little relief compared with the surrounding mountains, each of its river valleys is incised about 150 meters (500 feet). The western plain thus appears as broad uplands between major river valleys. It lacks prominent features, but the physiography reveals a fairly complete record for reconstructing late Cenozoic geologic and geomorphic history. A major upland, the interfluve separating the Boise and Payette rivers (Figure 3), approximates the maximum level to which the western plain was filled with sediment before Quaternary incision. Uplands and high terraces are broken by many small faults typically striking parallel to the northwest-southeast trend of the western plain. The adjoining river valleys, although broad and low in gradient, generally are benched with terraces. The most complete terrace sequence is near the south side of the city of Boise. South and southwest of the Boise Valley lie lava fields and a series of volcanoes that also align with the northwest-southeast trend of the western plain (Figure 3). Some volcanic rocks are studied in this report because several lava flows entered the lower Boise River valley and thereby affected its geomorphic history.

The western plain is both a northwest-trending physiographic lowland and a great structural basin separating the Cretaceous Idaho batholith of west-central Idaho from batholith outliers in southwestern Idaho. Although the eastern plain probably is crust partially melted by a hot spot moving toward the northeast where it is presently active in the Yellowstone National Park area, the western plain is a graben with features similar

Figure 3. View from the canyon rim, looking south-southeast, showing the Boise River and Lucky Peak Dam. Here the river exits the mountains and turns northwest to flow across the western Snake River Plain.

to continental rifts (Mabey, 1982; Smith and others, 1985; Rosendahl, 1987). The basin is a graben but structures include downwarping. Numerous marginal faults trend northwest-southeast and are faulted down toward the center of the basin (Malde, 1959, 1991; Wood and Anderson, 1981; Wood, 1989). Vertical displacement along the northern faults may be as much as 2,744 meters (9,000 feet). Much faulting took place in the early to middle Pliocene, but deformation probably began in the Miocene and continued into the Pleistocene. Rocks of early Pliocene and younger age appear to be displaced downward toward the center of the basin, but the magnitude of displacement diminishes with younger age.

The basin probably formed by isostatic compensation (Malde, 1991). Mabey (1982) suggested a slab of dense rock at intermediate depths is Miocene basalt. The rift may have begun to open about 17 Ma after which the subsiding basin was filled with both upwelling basalt and sediments shed from the surrounding highlands. Parts of the western plain may also have undergone silicic eruptions about 11 Ma (Malde, 1991; Wood, 1989). The late Tertiary geologic history of the western plain has been controlled by this rifting that caused subaerial and subaqueous basalts to be emplaced and sediments to be deposited in lake, fluvial, and alluvial fan environments (Middleton and others, 1985; Smith and others, 1985).

Soon after the thick, basal volcanic rocks were implaced, sedimentary deposits began to accumulate. Subsidence from rifting, augmented by basalt moving into the floor of the graben, generated a basin into which water and sediment had to accumulate. A Tertiary drainage outlet believed to exist to the west through eastern Oregon probably was interrupted by periods of volcanism (Kimmel, 1982; Malde, 1985, 1987, 1989). The rock record shows widespread filling of the basin by both sediments and basalt from the late Miocene through the late Pliocene. Although basalt eruptions continued into the Pleistocene and coarse sediments were transported from the mountains onto the plain during Quaternary glaciations, the filling of the western Snake River Plain was replaced by incision in the late Pliocene or early Pleistocene and continued to the present.

Today, climate in the Boise Valley and adjacent areas of the western plain is temperate and arid to semiarid. Average annual precipitation ranges from 15 to 20 centimeters (6-8 inches) near the Snake River and 25 to 31 centimeters (10-12 inches) in most of the lowland. Along the Boise Front, the orographic effect rapidly increases precipitation to 61 centimeters (24 inches) annually. Most precipitation falls during the colder months. Seasonal snowfall averages 58 centimeters (23 inches). Snow accumulation typically is light in the lowlands and usually melts soon after it falls (Savage, 1958, 1961; Priest and others, 1972; Collett, 1980). Winds vary over the area. Northwesterly winds are prevalent, but southeasterly winds are common during winter and spring. In cool periods, winds are southeasterly at the Boise International Airport because the cold, heavy air draining off the mountains into the Boise Valley is confined between the Boise Front and the upland of Bonneville Point (Figure 3) (Collett, 1980). During the Pleistocene, the climate probably was semiarid also, but as the mountains were glaciated, the western Snake River Plain experienced cooler temperatures, longer periods of snow accumulation, and greater runoff during a delayed, spring snowmelt (Pierce and Scott, 1982).

Soils in the western plain formed in a semiarid and temperate climate. They are associated with sagebrush vegetation and commonly have accumulations of silica and white calcium carbonate in the B horizon (illuvial). The soils are typically unleached, alkaline, and fertile. In areas of greater precipitation (generally higher elevations and northeast of the Snake River), soils have more organic matter in the A horizon (surface) and more calcium carbonate, silica, and clay in the B horizons (Priest and others, 1972; Collett, 1980). Due to the cool, semiarid climate, the soils have strongly developed horizons only where they have formed on old surfaces. Periods of cooler climates in the Pleistocene probably allowed greater soil moisture retention and augmented horizon development in older soils (Blank, 1987; Fosberg and others, 1991). As shown by this study, the ages of soils in the Boise Valley and adjoining areas range from Holocene to late Pliocene. The oldest soils have the greatest accumulations of clay, calcium carbonate, and silica in the B horizons.

SOIL CHARACTERISTICS AND DEVELOPMENT

Soil, as defined by soil scientists in the United States, is composed of natural earth materials that contain living matter and that are capable of supporting plants. According to a Soil Conservation Service agricultural handbook, "Soil includes the horizons near the surface that differ from the underlying rock material as a result of interactions among climate, living organisms, parent materials, and relief" (Soil Survey Staff, 1975, p. 1). Soil horizons form as climate and organisms act upon preexisting consolidated or unconsolidated earth materials (i.e., parent materials) exposed at the surface for thousands of years in a particular physiographic position (Soil Survey Staff, 1975; Birkeland, 1974, 1984). Soil formation involves both the geomorphic setting and the age of an exposed surface. Given the fairly uniform physiography within the western plain and the soil differences on various geomorphic surfaces, the amount of soil development generally is proportional to the age.

The geomorphic surfaces include the terraces of the Boise Valley. Over time, the physiography of any one terrace is changed by the interplay of younger deposition and erosion. Older surfaces not only stand at high elevations relative to the present stream grades but are also incised by gullies and valleys of local streams (relict in many places), which may also have formed adjacent alluvial fans. Loess influx mantled the terrace gravels with silt, and some lower terraces near the Snake River received thick deposits of Bonneville Flood slack-water sediments.

Subsequent erosion and deposition on the older topography complicates the distribution of soils, but differences in erosion and deposition help in determining the relative ages of surfaces, soils, and geologic events. To examine and use soils as clues to the ages of terraces (ancient alluvial surfaces) of the Boise River, it is necessary to find unmodified remnants of the terraces. This becomes increasingly difficult on older, more eroded landforms.

Loess is the major parent material of the soils deposited on the terraces of the Boise Valley and adjoining areas. As a thin surficial deposit, loess is ubiquitous on surfaces with little or no erosion. It is thinner on older surfaces but thicker as the distance from the Snake River decreases. The loess cap generally rests on gravel. The upper 1 to 2 meters (3-7 feet) of the underlying gravel deposits is characterized by oxidized gravel clasts and by coatings and void fillings of calcium carbonate accumulated during soil formation.

Below an elevation of about 740 meters (2,430 feet), but above the late Holocene flood plains, Bonneville Flood sediments reset the process of soil development wherever they were deposited. The thin-bedded sandy silt and fine sand deposits of the Bonneville Flood mantle three terraces and provide a 14,500-year-old marker (Scott and others, 1982; O'Connor, 1990). These sediments were deposited in the slack waters, or temporary lake, that formed as the catastrophic Bonneville Flood attempted to flow through the constriction of Hells Canyon.

Presently, the influence of temperature, moisture, landforms, and plants and animals on terrace soil development varies little in the study area. Soil age and development, however, vary considerably throughout the terrace sequence. Climate has varied over the thousands to hundreds of thousands of years these soils have been forming. The evidence of past glaciations and periods of larger lakes in the western United States indicates average temperatures colder than today's (Flint, 1971; Mears, 1981; Porter and others, 1983; Barry, 1983). Most Pleistocene alluvial fans were formed during times of glaciation in the mountains and under cooler temperatures that caused more effective retention of soil moisture and greater runoff during a later, more rapid seasonal snow melt (Pierce and Scott, 1982). A Pleistocene soil on an alluvial fan in south-central Idaho shows a complex development of horizons suggesting periods of cooler temperatures and greater soil moisture during its history (Blank, 1987; Fosberg and others, 1991). These conditions contrast with the present warmer and drier soils.

Soil development in the Boise Valley has clearly been affected during the Pleistocene by changes in soil moisture, vegetation, and soil temperature. The primary result of these changes is that older soils tend to have more complex profiles. Nonetheless, correlation based on soil characteristics is still valid because the soil history on stable parts of the same surface should be similar.

Changes in climate during the Pleistocene also affected rates of erosion and deposition. Malde (1964) and Fosberg (1965) both describe evidence that periglacial processes were active in southern Idaho during the Pleistocene. Pierce and Scott (1982) suggest that solifluction was an important surface process during times of cool, glacial climates. The patterned ground on higher terraces and uplands of the Boise Valley were caused by intense freeze and thaw cycles and the accompanying soil mass movements and differential erosion. Widely distributed small alluvial fans apparently formed during the Pleistocene in the Boise Valley. The alluvial-fan sands and gravels were likely deposited during the glacial climates that favored solifluction and greater runoff (Othberg, 1986; Othberg and Burnham, 1990; Othberg and others, 1990). Many of the gullies, ravines, and small drainageways present in the older terraces and uplands probably formed during these more severe climatic episodes.

Combining information about both geology and soils in the Boise Valley provides a better understanding of each. The relative and absolute ages of lithologic units and geomorphic surfaces help in estimating the time over which a soil forms and the rate at which soil features develop. Describing and mapping the soils of terraces reveals characteristics that can be used to correlate the terraces and their lithologic units. Measurable changes in soils that vary with age occur in the development of duripans (accumulation of silica and calcium carbonate) and argillic horizons (illuvial clay).

"CALICHE" AND DURIPANS

In the semiarid Boise Valley, soils form illuvial horizons of lime and silica commonly known as caliche. The term "caliche" (Blake, 1902) has been applied broadly to deposits of secondary calcium carbonate of various origins. It has been used without regard for genesis, physical and chemical characteristics, or geomorphic and stratigraphic relations. Although geologists in the United States generally associate caliche with soil carbonate, the term probably should be abandoned for scientific application owing to its varied usage (Goudie, 1973; Machette, 1985; Blank, 1987).

In place of caliche, more precise terminology is provided by the U.S. Department of Agriculture's Soil Conservation Service (Soil Survey Staff, 1975; Nettleton and Peterson, 1983; Fosberg and Falen, 1987) in which hardpan horizons of arid and semiarid soils are called "calcic," "petrocalcic," or "duripan" depending on the chemistry of the pan and the degree of horizon development. Caliches of Idaho, including the Boise Valley, fall within the criteria for duripan and calcic horizons.

Calcic soils show properties caused by the pedogenic accumulation of secondary calcium carbonate in soil horizons. Where sufficient precipitation and crystallization of calcium carbonate or silica produce an indurated, plugged horizon ("hardpan"), the terms petrocalcic or duripan, respectively, are applied. Although calcium carbonate is the prime constituent in Idaho caliches, a significant, associated chemical component is silica. U.S.D.A. soil scientists distinguish a silica-cemented hardpan, a duripan, where soils have distinct properties due to the presence of silica in the form of opal, sepiolite, and palygorskite (Fosberg and others, 1991).

Duripans of the western U.S. are associated with the accumulation of calcium carbonate. Calcite commonly augments or is dominant to silica cement. In these semiarid climates a gradation in soil horizons exists between those where calcium carbonate is the dominant cementing agent and those where silica assumes importance as a cementing agent (Blank, 1987). Silica content appears to progressively increase as mean annual temperatures decrease (M.A. Fosberg, oral commun., 1991).

Geologists may use the terms calcrete and caliche loosely to describe calcite-rich layers without implying anything about the degree of silica cementation. They typically make no distinctions such as "petrocalcic" and "duripan." Moreover, in studying the ages of surfaces, there may be no important need to recognize the differences. Blank (1987) postulated that calcrete and caliche are duripan analogues. A corollary seems to be that duripans in the semiarid Northwest United States are analogues of petrocalcics in the Southwest. Work on the soil-age and landscape relationships in the Southwest deserts (Gile and Hawley, 1966; Gile and others, 1965, 1966; Machette, 1985; McFadden and Tinsley, 1985) may apply to Idaho duripans as well. Soils older than late Pleistocene in the Boise Valley contain horizons of cemented silica and calcium carbonate structurally similar to petrocalcics of the Southwest. The aridisols in southern Idaho, however, have sufficient cemented silica to qualify as duripans (Blank, 1987; Fosberg and others, 1991).

Duripans are graded into three categories of increasing development which reflect an increase in soil age: (1) "duric horizon" — common durinodes[2] or nearly continuously cemented with silica (qualifies as a *Bq* but not a *Bqm*[3]); (2) "haplic or entic duripan" — either continuously cemented or composed of imbricated overlapping cemented lenses, which do not slake in water or HCl, but lacking a continuous laminar coating of opaline silica; and (3) "typic duripan" — continuous cement of opaline silica either as a continuous laminar coating or as imbricated overlapping coarse plates (Soil Survey Staff, 1975; Nettleton and Peterson, 1983). The U.S. Department of Agriculture's soil classification further states (Soil Survey Staff, 1975, p. 41):

> *[T]he strongly cemented duripans of arid climates are usually platy and the plates are roughly 1 to 15 cm thick. Pores and the surfaces of the plates are coated with opal and with some birefringent material that is probably a microcrystalline form of silica. Carbonates generally are present in small to large amounts. . . . Other duripans contain moderate amounts of accessory calcium-carbonate cement and are whitish-colored. These, and white duripans grading to petrocalcic horizons in carbonate content, have distinctively pustulose-pendant undersides and smooth, lamina-coated tops on the indurated coarse plates that occur at the top of such pans. The mixtures of carbonate-opal cement have distinctive, patchy or continuous, white and yellowish-green, pinkish, or brownish colors relative to whitish unopalized petrocalcic horizons. Where duripans grade to petrocalcic horizons in carbonate-cement content, they have a laminar upper subhorizon and they are called duripans, by definition, if at least half the subhorizon does not slake in acid.*

ARGILLIC HORIZONS

The accumulation of clay in the B horizon by the weathering of minerals and the translocation of clay particles is a strong indicator of soil age (Birkeland, 1974, 1984, 1985; Soil Survey Staff, 1975). B horizons with an increased clay content suggesting translocated clay are called "argillic" and are labeled *Bt* (Soil Survey Staff, 1975; Fosberg and Falen, 1987). In addition to stronger duripan development on terraces of increasing age, the soils on the terraces in the Boise Valley also show corresponding increases in the thicknesses of the argillic horizons and the percentages of clay.

SOILS IN BOISE VALLEY TERRACES

Of the many soil series described and mapped in the Boise Valley, five appear to best represent the sequence of soil ages (Othberg and Fosberg, 1989). These are, in order of increasing soil development and age, the Greenleaf, Power, Purdam, Elijah, and Chilcott Series (Priest and others, 1972; Collett, 1980). Figures 4 and 5 show typical distinguishing characteristics and laboratory data for these series.

The sequence of soil development represented by these five soil series demonstrates the growth of silica

[2]Durinodes are weakly to well-indurated cicada nodules containing silica cement.

[3]See Fosberg and Falen (1987) for letter codes used in field descriptions of soil profiles.

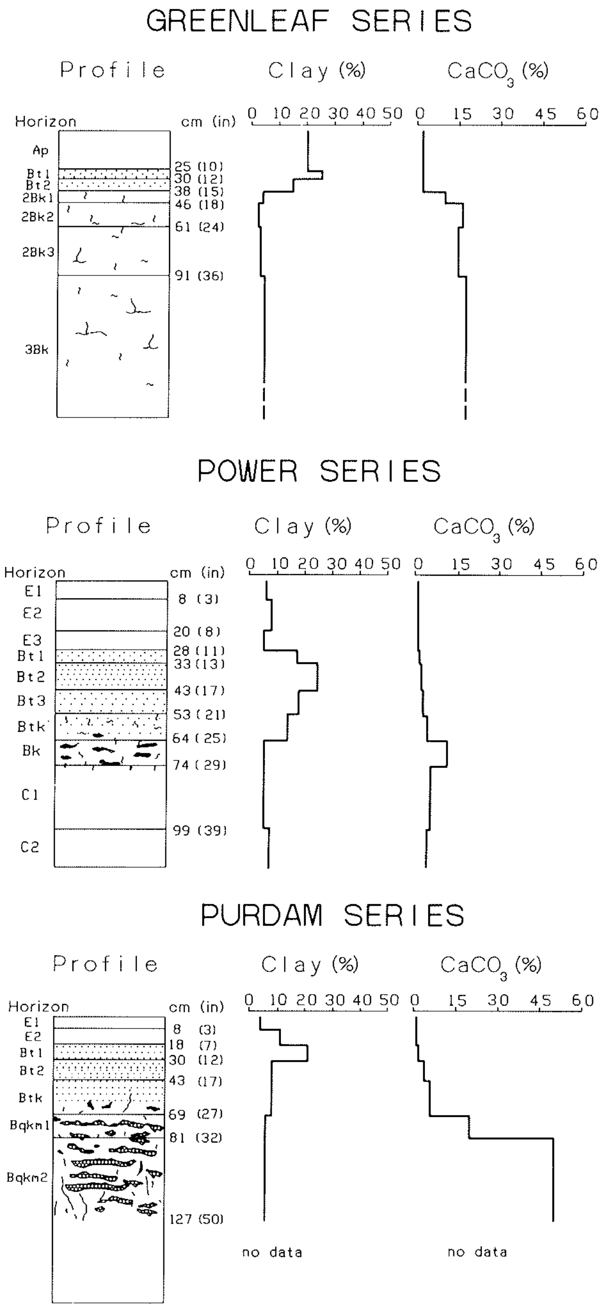

Figure 4.

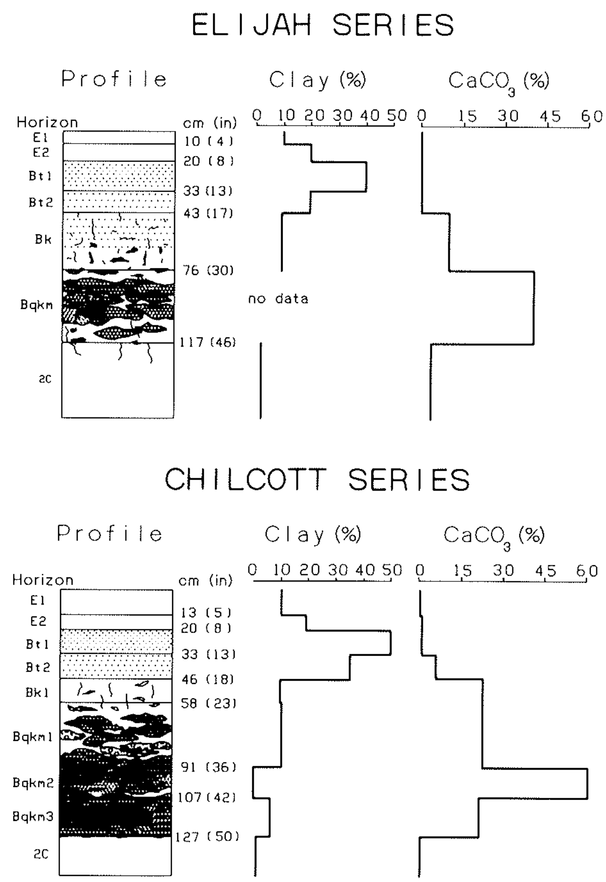

Figure 5.

Figure 4. Soil profile characteristics and percentages of clay and calcium carbonate for the Greenleaf, Power, and Purdam Series. Profile symbols: stipple pattern — pedogenic clay; other symbols — stringers, nodules, and plates of calcium carbonate and silica. Sources of data: *Greenleaf Series* — University of Idaho Soil Characterization Laboratory, sample 59Ida-1428, NE¼NW¼ sec. 4, T. 5 N., R. 5 W.; *Power Series* — University of Idaho Soil Characterization Laboratory, sample 56Ida-2317, NE¼NW¼NW¼ sec. 22, T. 7 N., R. 3 W.; *Purdam Series* — Stuart (1958), sample 57Ida-0140, NE¼NE¼ sec. 35, T. 3 N., R. 2 E.

Figure 5. Soil profile characteristics and percentages of clay and calcium carbonate for the Elijah and Chilcott Series. Profile symbols: stipple pattern — pedogenic clay; other symbols — stringers, nodules, and plates of calcium carbonate and silica. Sources of data: *Elijah Series* — Sandoval (1956), sample 55Ida-1414, SE¼ sec. 8, T. 5 N., R. 2 W.; *Chilcott Series* — Sandoval (1956), sample 55Ida-0122, NW¼ sec. 20, T. 2 N., R. 2 E.

(*q*) and calcic (*k*) horizons over time into platy duripans (*qkm*). Although not as dramatically revealed in soil profiles, the accumulation of pedogenic clay in the *Bt* (argillic) horizon, as well as its thickness, also increase with soil age. Figures 6 and 7 show the range in accumulation of calcium carbonate and silica in Boise Valley soils from weak calcic horizons to thick platy duripans.

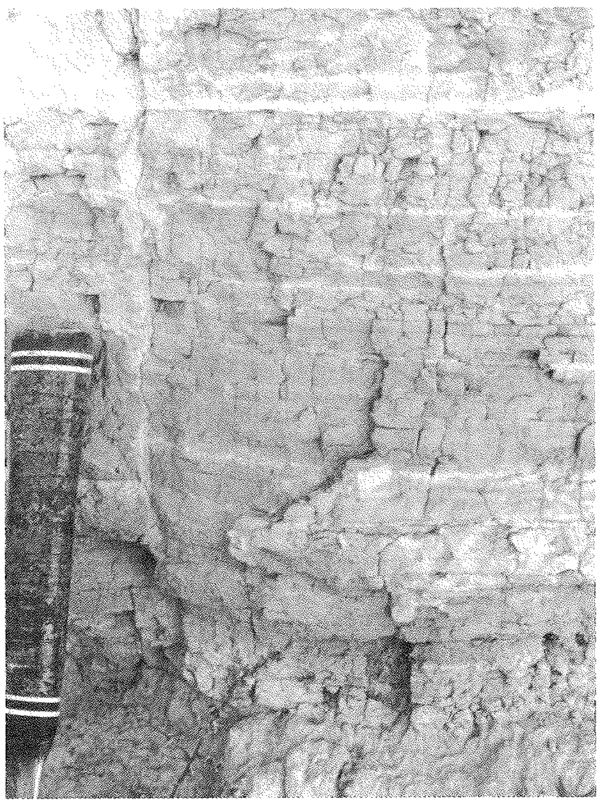

Figure 6. Close-up view of Greenleaf soil showing thin calcic layers formed in sandier portions of thin-bedded slack-water sediments and along vertical cracks. Handle of rock hammer for scale.

The study of soil development in the Boise Valley helps interpret a sequence of terraces covering a broad range of time. Identifying these soils can correlate surfaces within and outside of the Boise Valley. Fitting the soil characteristics into a larger geomorphic interpretation helps relate soil development to the geomorphic history of the region.

GEOCHRONOLOGY

Chronometric control for the Pliocene and Pleistocene primarily comes from radiometric and fission track

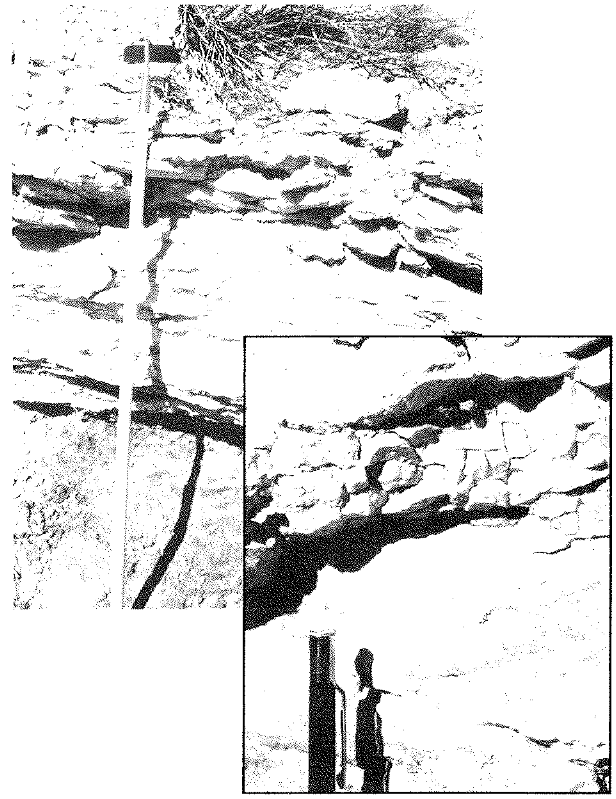

Figure 7. The thick, platy duripan of the Chilcott Series reflects its antiquity. Hoe is about 1.2 meters (4 feet) long. Closeup view (inset) of the duripan plates shows the pattern of calcium carbonate and silica cementation. Mechanical pencil for scale.

dates on volcanic rocks, tephra, organic remains, and carbonate accumulations. Potassium/argon and argon/argon dates in particular provide numerical ages for the magnetic polarity time scale, which in turn has proved valuable for dating rock units of this time span. Recent publications contribute important revisions to the time scale for the Pliocene and Pleistocene. The late Pliocene and Pleistocene part of the magnetic polarity time scale published by Mankinen and Dalrymple (1979) and Berggren and others (1985) was revised by Cande and Kent (1992) using astronomical calibration[4] that was partly confirmed with new argon/argon dates (Baksi and others, 1991; Izett and Obradovich, 1991). The volume of articles edited by Sibrava and others (1986) analyzes and revises glacial correlations regionally within the United States and for all the Northern Hemisphere. This publication correlates the marine oxygen isotope stages with terrestrial glaciations. The corre-

[4]Astronomical ages are based on variations in Northern Hemisphere summer insolation calculated from planetary mechanics. See Fullerton and Richmond (1986) and Johnson (1982) for details.

lations are based on stratigraphic and chronologic data (Fullerton and Richmond, 1986) that demonstrate the oxygen isotope record directly reflects the accumulation of ice on the continents (although the glacial maxima and the isotope maxima were not necessarily in phase). Revisions in the oxygen isotope stages (Ruddiman and others, 1986; Shackleton and others, 1990) may make the early Pleistocene glacial correlations more tenuous. Figure 8 shows the time divisions, time scale values, oxygen isotope stages, and age controls and correlations of glaciations in the Rocky Mountains, Yellowstone National Park, and Cascade Mountains.

The ages of major boundaries for Wisconsin and Illinoian time divisions are based on the oxygen isotope stage estimated astronomical age. The upper limit of the early middle Pleistocene is set by the potassium/argon age of the Lava Creek Tuff and Pearlette "O" ash (610 ka). The upper limit of the early Pleistocene is set by the astronomical age of the Matuyama-Brunhes magnetic polarity reversal. Argon-40/argon-39 dating of Hawaiian lavas, the Bishop Tuff, and the Cerro San Luis rhyolite confirms the astronomical age of 0.77-0.79 Ma for the Brunhes-Matuyama boundary (Baksi and others, 1991; Izett and Obradovich, 1991). Cande and Kent (1992) set the Brunhes-Matuyama boundary at 0.78 Ma. Through international agreement, the Pliocene-Pleistocene boundary is defined by the Vrica section in Italy, dated at 1.65 Ma; however, no physical record in the United States is known to correspond with this boundary.

RADIOMETRIC DATING AND MAGNETIC POLARITIES OF BASALTS

Potassium/argon dates were obtained for five of the basalt units that rest on terraces of the Boise River (Table 1). The basalt of Slaters Flat was also dated. It buries an alluvial surface of the ancestral Tenmile Creek. Eight argon-40/argon-39 dates were obtained on basalts emplaced in the area near Nampa and west to the Snake River valley (Table 1).

The magnetic polarities at outcrops of twenty-three basalts were determined in the field using a fluxgate magnetometer (Table 1). The magnetic polarities of sixteen samples were confirmed using the paleomagnetic laboratories at Eastern Washington University in Cheney, Washington, and at the U.S. Geological Survey in Flagstaff, Arizona. Figure 9 compares magnetic polarities and the potassium/argon and argon-40/argon-39 age ranges of the basalt units with the details of the magnetic polarity time scale for the late Pliocene and the Pleistocene.

STRATIGRAPHY

The structural evolution of the western Snake River Plain as a rifting basin has controlled the origin of the rock units that fill it. In addition to basalt, the plain is composed of sediments as much as 1.7 km thick (Malde, 1991; Wood and Anderson, 1981). Most of the sediments reflect lacustrine and fluvial environments of deposition within and along the borders of a subsiding basin (Middleton and others, 1985).

Cope (1883) named the Pliocene-Pleistocene sequence of sediments within the basin the Idaho Formation. Lindgren (1898a; 1898b) and Lindgren and Drake (1904a; 1904b), however, grouped the basin sediments, respectively, into the Payette Formation and the Payette and Idaho Formations undifferentiated; they were unable to distinguish between the two formations using lithologies. Although Kirkham (1931a) agreed that the basin sediments may be lithologically indistinguishable, he mapped the Payette Formation and the Idaho Formation separately based on their structure and distribution within the basin.

Malde (1959; 1991) and Wood and Anderson (1981), using geophysical data and deep drilling results as well as field evidence, interpreted the base of the fault-bounded plain to be composed of early-rift basalts as old as 17 Ma. The basin has had a long history of filling with both volcanic rocks and sedimentary deposits that probably include stratigraphic units as old as the Miocene Payette Formation and the Columbia River Basalt Group.

The extent of the Idaho Formation was altered by the work of Malde and Powers (1962). They defined a more detailed stratigraphy in which several formations of late Miocene through Pleistocene age compose the Idaho Group (Figure 10). Of the rocks in the Idaho Group, the Pliocene Glenns Ferry Formation contains the greatest volume and areal extent (Malde and Powers, 1962; Swirydczuk and others, 1982). The Glenns Ferry Formation chiefly consists of fine-grained sediments that mostly are lacustrine (Middleton and others, 1985).

Although one unconformity is present that suggests a period of incision, basin-filling was predominant in pre-Quaternary time (Malde and Powers, 1962; Kimmel, 1982; Middleton and others, 1985). In the more complete part of the rock record — in the Chalk Hills Formation and younger units — the geomorphic history of the western Snake River Plain can be separated into an extensive period of basin filling followed by the widespread entrenchment and removal of basin deposits.

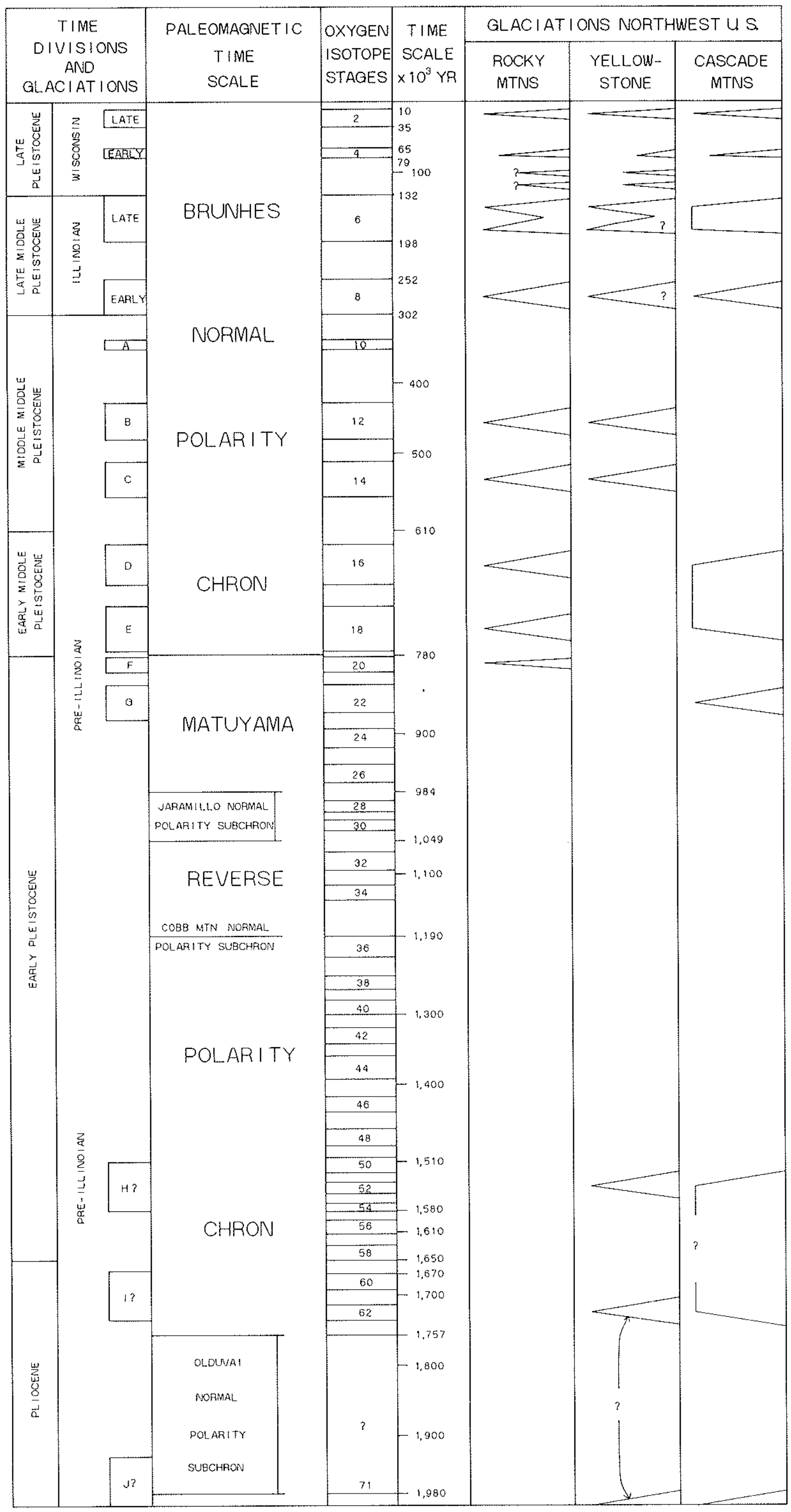

Figure 8. Glaciations of the northwestern United States correlated with the late Pliocene and Pleistocene time divisions, the Wisconsin, Illinoian and pre-Illinoian glaciations, and the marine oxygen-isotope cold stages 2-71 (determined from deep-sea core sampling). Adapted from Richmond and Fullerton (1986, Chart 1), Ruddiman and others (1986), Shackleton and others (1990), and Cande and Kent (1992).

Table 1. Magnetic polarities and potassium-argon and argon-40/argon-39 ages of basalts (potassium/argon dates and argon-40/argon-39 ages provided by the Berkeley Geochronology Center, Institute of Human Origins, University of California, Berkeley, California).

Rock Unit	Polarity	Latitude	Longitude	Age (Ma) [1] potassium/argon [2] argon/argon
Basalt of Mores Creek	N	43°31.52′	116°03.76′	0.107 ± 0.012 [1]
Basalt of Kuna Butte (South Side)	N	43°31.51′	116°32.03′	0.387 ± 0.031 [2]
Initial Point vent	N	43°22.32′	116°23.61′	0.414 ± 0.037 [2]
Basalt of Gowen terrace	N	43°31.33′	116°04.24′	0.572 ± 0.210 [1]
Basalt of Lucky Peak	N	43°31.85′	116°03.66′	1.364 ± 0.210 [1*]
Basalt of Long Gulch (upper)	N	43°32.31′	115°42.28′	
Basalt of Long Gulch (lower)	N	43°32.31′	115°42.28′	
Christmas Mountain vent	N	43°16.94′	116°06.91′	
Caldwell lava flow	R	43°41.31′	116°41.06′	0.799 ± 0.095 [2]
Basalt of Slaters Flat	N	43°27.54′	115°58.93′	0.907 ± 0.280 [1]
Upper Deer Flat lava flow	R	43°30.29′	116°34.38′	0.922 ± 0.184 [2]
Basalt of Fivemile Creek (old U.S. 30)	N	43°32.67′	116°09.38′	0.974 ± 0.098 [1]
Basalt of Fivemile Creek (vent)	N	43°30.27′	116°06.91′	
Basalt of Fivemile Creek (canyon)	N	43°31.52′	116°04.45′	
Basalt of Hubbard Reservoir	N	43°31.92′	116°20.20′	1.001 ± 0.098 [1]
Mason Creek lava flow	N?	43°33.72′	116°28.23′	1.231 ± 0.123 [2]
East Nampa lava flow	R	43°36.23′	116°31.12′	1.165 ± 0.125 [2]
Black Cat Road lava flow	R	43°31.43′	116°27.15′	
Kuna city lava flow	R	43°29.13′	116°24.43′	1.376 ± 0.205 [2]
Rawson Canal lava flow	R	43°34.09′	116°27.12′	
Missouri Avenue vent	R	43°28.74′	116°39.08′	
Basalt of Pickles Butte (canyon rim)	R	43°28.03′	116°44.99′	1.580 ± 0.085 [2]
Steamboat Rock Basalt	R	43°28.57′	115°37.77′	

* Stratigraphic relationships indicate the K/Ar age of the basalt of Lucky Peak is too old (Othberg and Burnham, 1990).

Malde and Powers (1962) subdivided the uppermost Idaho Group rocks into the Tuana Gravel, the Bruneau Formation, and the Black Mesa Gravel. These are overlain by the basalts of the Snake River Group that erupted from shield volcanoes and formed the surface of the center of the basin during the Pleistocene (Figure 10). Malde and Powers (1962) and Malde (1985, 1987, 1989, 1991) suggested that the Tuana Gravel was deposited not only after, but in response to, the drainage capture and downcutting, thereby a process that bevelled the basin-filling deposits. Using evidence in the northwestern part of the western Snake River Plain, I have suggested that the gravels deposited widely by high-energy braided streams ended the basin-filling sequence (Othberg, 1988) (Figure 10).

Wood and Anderson (1981) used Snake River Group terminology, but in the Boise Valley and adjacent areas no evidence exists to distinguish between sediments and lavas formed during entrenchment (Bruneau Formation) and those of the Snake River Group. Sediments of the Bruneau Formation were deposited during times of lava dams on the Snake River. Comparable deposits are absent in the Boise Valley where episodes of valley incision, deposition of terrace gravels, and emplacement of basalt flows occurred throughout the Pleistocene. Therefore, I have not used the Bruneau Formation and Snake River Group nomenclature (Figure 10).

LITHOLOGIC UNITS

In Figure 11, I subdivide the geology of the Boise Valley and adjoining area into general lithologic units. More detailed geologic maps are provided by Wood and Anderson (1981), Othberg and Burnham (1990), Oth-

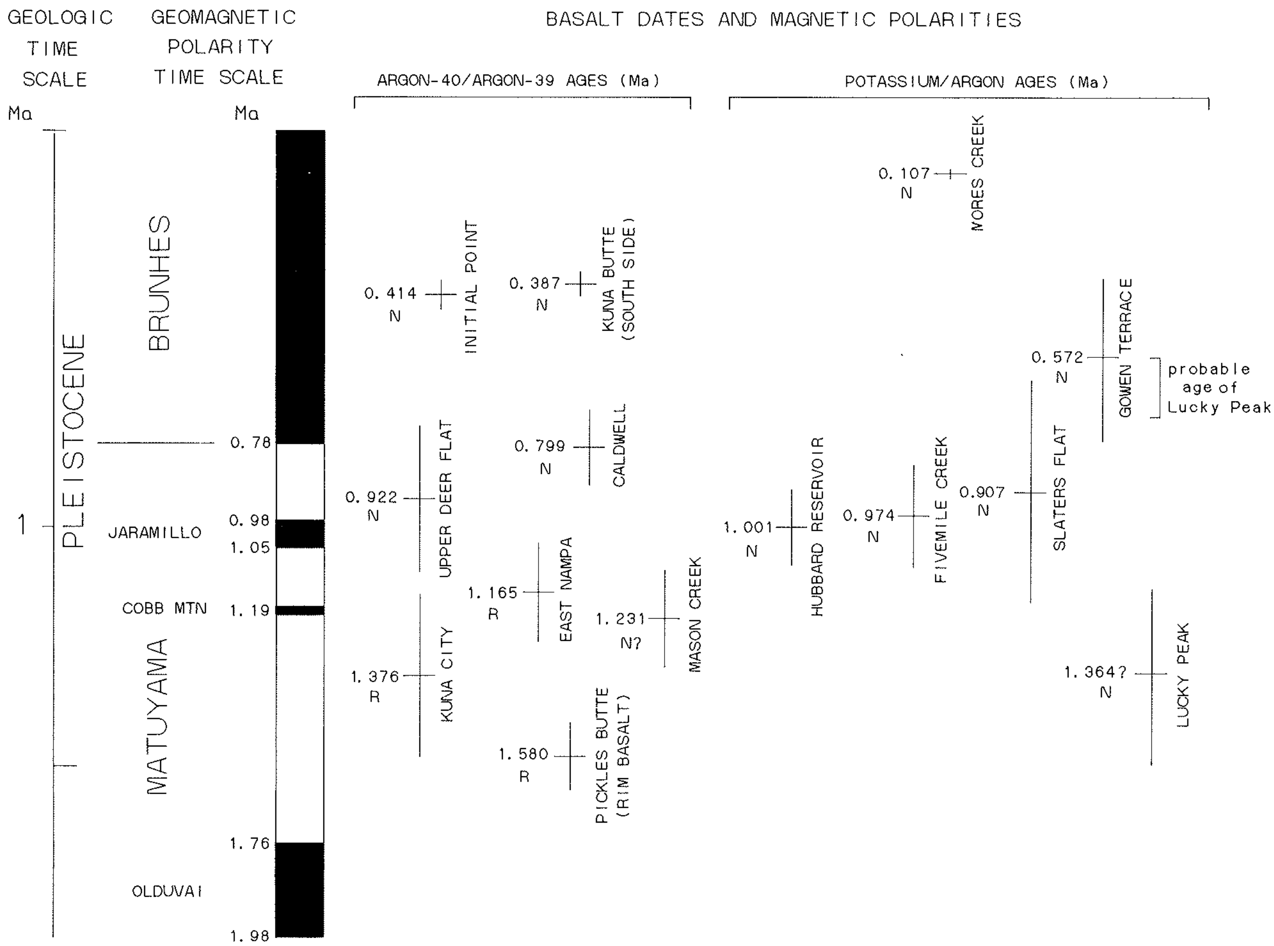

Figure 9. Results of dating of basalts in the Boise Valley and adjoining area. Argon-40/argon-39 and potassium/argon ages grouped separately. Magnetic polarities of each basalt shown by N or R (see Table 1). Time scales shown for reference. Geomagnetic time scale adapted from Mankinen and Dalrymple (1979) as modified by Shackleton and others (1990) and Cande and Kent (1992). Length of vertical age bar shows the precision limit of each date. The potassium/argon date of the basalt of Lucky Peak is unreliable; stratigraphy shows the age to be probably between that of the basalt of Gowen terrace and the beginning of the Brunhes Normal Polarity Chron (see text).

berg and others (1990), Othberg and Stanford (1990), and Burnham and Wood (in press).

Figure 11 shows seven general geologic units. Pre-Tertiary rocks include the Idaho batholith and the basin-fill sedimentary and volcanic rocks. The Idaho Group is represented by the gravel of Bonneville Point and the Tenmile Gravel, defined below. All younger units mostly correspond with the Snake River Group.

Pre-Tertiary Rocks

The Idaho batholith makes up the mountains to the northeast of the western Snake River Plain. The rocks of the batholith within and adjacent to the Boise Front are biotite granite and granodiorite (Anderson and Rasor, 1934) intruded by pegmatite zones and dikes of rhyolite and basalt.

Basin-Fill Sedimentary and Volcanic Rocks (Tertiary)

Rocks of the Idaho Group in the northern part of the western Snake River Plain lack the physical criteria for correlation with the Chalk Hills and Glenns Ferry Formations as described for the southeastern part by Malde and Powers (1962) and subsequent workers (Figure 10). As a result, local formations and informal stratigraphic units have been used in geologic mapping in the northern part of the plain. These include the Terteling Springs and Pierce Gulch Formations and an assemblage of ba-

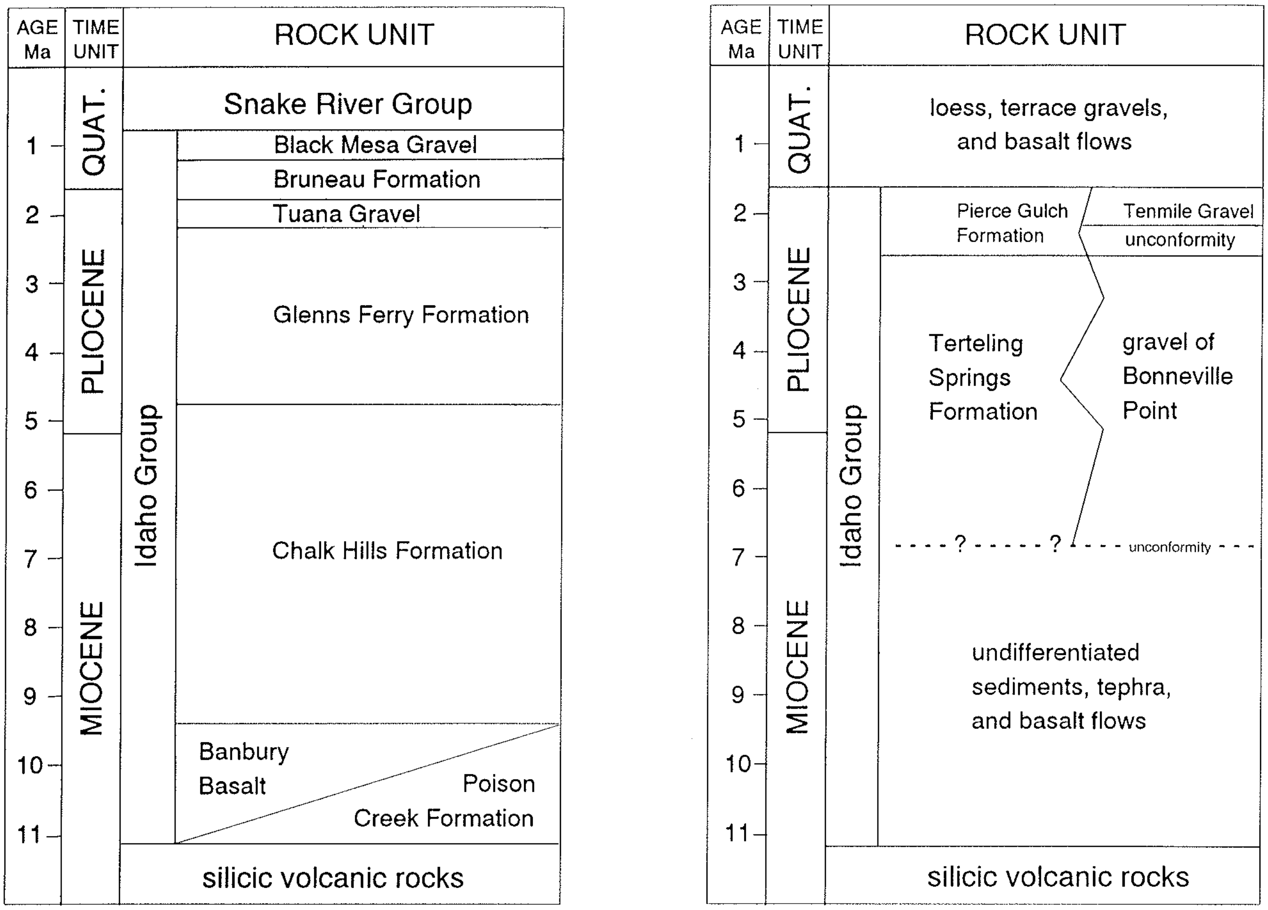

Figure 10. Stratigraphy of the southeastern part of the western Snake River Plain (modified from Malde, 1991) and the north part of the western Snake River Plain (adapted from Othberg and Burnham, 1990; Burnham and Wood, in press; and Malde, 1991).

salt flows and tuffs (Wood and Anderson, 1981; Wood and Burnham, 1983; Othberg and Burnham, 1990; Burnham and Wood, in press).

With the exception of Buwalda (1921) and Savage (1958, 1961), most geologists studying the basin sediments have regarded them to be predominantly lacustrine. Along the basin margins, there is a diversity of facies in the western plain. At the Boise Front, the textures, lithologies, and depositional environments of sediments were controlled by granitic mountains bordering the plain. In addition, a major river draining central Idaho mountains probably has emptied onto the plain at the Boise Front for perhaps several million years.

In the southeastern part of the western plain, Malde (1972) found that three principal facies — lacustrine, fluvial, and flood plain — exist in the Glenns Ferry Formation. A part of the fluvial facies was reinterpreted by Smith and others (1982) as shoreface sands. Middleton and others (1985) described several lithofacies in both the Chalk Hills and Glenns Ferry Formations. Their interpretations indicate varied basin-margin environments dominated by fluvial (including flood plain) and lacustrine deposition. In this southeastern part, sediments with the greatest volume and area represent deposition in a large lake system formed when subsidence in the rift created a basin. Drainage out of the basin, probably through eastern Oregon, may have been restricted by volcanism (Kimmel, 1982; Malde, 1991). Lithofacies representing a lake environment include massive and laminated mud, volcanic ash beds, oolitic limestone, and some ripple, cross-laminated sands. In addition, fine-grained sands and silts accumulated in beach and shoreface settings (Malde, 1972; Swirydczuk and others, 1979; Swirydczuk, 1980; Swirydczuk and others, 1982; Kimmel, 1982; Middleton and others, 1985). The bulk of the sediments are lacustrine in origin within the Glenns Ferry Formation. The flood-plain sediments (largely vertical accretion deposits), however, occur over

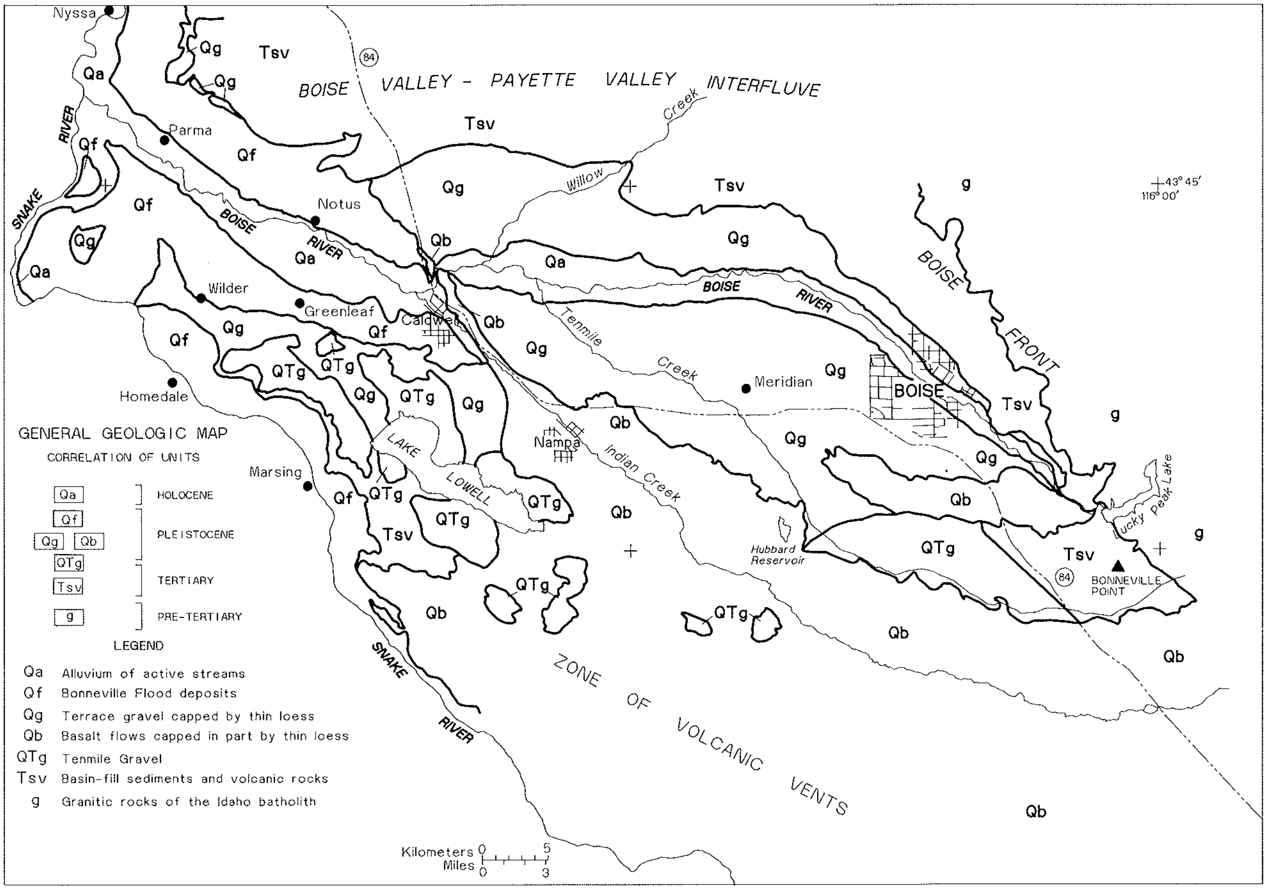

Figure 11. General geologic map of the Boise Valley and adjoining areas.

a large area, are intercalated with the lacustrine facies, and grade laterally into lacustrine deposits (Middleton and others, 1985).

In the Boise Front, Wood and Burnham (1983) and Gallegos and others (1987) described complex facies associations of silts, sands, oolitic beds, and coarse debris flows that probably represent shoreface, beach, deltaic, and fluvial environments along a lake margin. The varied lithofacies in the Boise Front were first recognized by Lindgren (1898a), but he called all of them "lake beds." Buwalda (1921) thought the relative abundance of coarse sand and pebbly beds indicated that the basin sediments were in large part flood-plain and slope deposits. Savage (1958) likewise believed that the widely distributed arkosic sands in the Boise Front and the foothills to the northwest were the result of an ancient river environment. Kirkham (1931a) believed that although lithofacies varied considerably in the basin margins, certain beds across the basin demonstrated the existence of a large body of water. Wood and Burnham (1983) were able to show that the sands replaced by silts toward the southwest from the Boise Front, suggested deepening water. Washburne (1909) noted that clay predominates over coarser materials in well records, in contrast to materials near the surface in which sandy and pebbly beds are more apparent.

Based on my study of well logs in the Boise Valley, the basin sediments that underlie the terrace gravels are conspicuously interbedded with and dominated by beds of sand and "clay" (well-drillers' vernacular for textures finer than sand). Exceptions include upland locations near the Snake River where well logs and field evidence reveal interbeds of gravel that have dark volcanic clasts characteristic of an Owyhee Mountains source. And, for sites closer to the high ridge south of Boise, well logs record interbed textures that progressively coarsen to the point where sand and gravel predominate at depth under Bonneville Point.

Subdividing the Tenmile Gravel

Othberg (1988) interpreted the change of depositional environments in the western Snake River Plain to represent the postulated capture of its drainage through Hells Canyon into the Columbia River basin. The change in depositional environment may have been a response to climate change in the Northern Hemisphere. Before the headward erosion initiated by the capture, the western plain had been filling. At the end of the aggradation, just before downcutting by the rivers, coarse gravel was deposited across the plain. These gravel deposits are distributed along the former courses of the major rivers and creeks that drain the adjoining uplands. The Tuana Gravel in the southeastern part of the western plain (Malde and Powers, 1962; Malde and others, 1963; Malde, 1985, 1987, 1989, 1991) is one example. The Tenmile Gravel, as restricted herein, probably was deposited at this time (Malde, 1985; Othberg, 1986, 1988).

Savage (1958, p. 26) renamed Lindgren's (1898a) "upper mesa gravel" to the "Tenmile gravel formation" owing to "some disagreement with the Lindgren description as to the upper and lower limits" (Table 2). Savage attributed these gravels to "torrential floods of meltwater coming from glaciated areas" in the early Pleistocene. He noted that the textures and sedimentary structures of these deposits were "similar to valley train material in regions adjacent to live glaciers." Savage may have intended to formalize the unit, but designated no type locality. By 1966 "Tenmile Gravel" was listed in the U.S. Geological Survey lexicon of geologic names (Keroher and others, 1966). Savage (1958) emphasized the higher terrace gravels in his usage of "Tenmile gravel formation."

A geologic map by Nace and others (1957) was available to Savage in 1958 (included in his list of references), but he used none of their terrace units. Although Nace and others provided the name "Tenmile terrace," Savage neither used the landform unit nor credited them with the name. Savage included the gravely deposits underlying the upland of Bonneville Point in the Tenmile gravel. However, these weathered, interbedded sand and gravel beds had been mapped as Neocene by Lindgren (1898a) and as Pliocene by Kirkham (1931a). Nace and others (1957) included these sand and gravel beds in their Quaternary-Tertiary "early terrace gravel" unit, and identified a "terrace" extending from Tenmile Creek to Bonneville Point (Figure 2).

Wood and Anderson (1981) and Wood and Burnham (1983) restricted the Tenmile Gravel in the Nampa and Caldwell area to gravel lithologies that clearly had a source in the Boise River drainage. They separated gravel deposits of younger surfaces from the Tenmile Gravel (Table 2). Subsequent geologic studies in the Boise area by Othberg (1986), Othberg and Burnham (1990), Othberg and others (1990), and Burnham and Wood (in press) maintained this restricted definition of the Tenmile Gravel but still included the sand and

Table 2. Late Cenozoic stratigraphy interpreted by previous authors in the Boise Valley for sedimentary units (excluding recent alluvium).

<table>
<tr><th>Period</th><th>Wood & Burnham (1983)</th><th>Savage (1958)</th><th>Lindgren & Drake (1904)</th><th>Lindgren (1898)</th></tr>
<tr><td rowspan="5">QUATERNARY</td><td>Whitney terrace alluvium</td><td>Nampa-Caldwell sediments</td><td>Late terrace gravels</td><td>Lower Mesa gravel</td></tr>
<tr><td>Sunrise terrace alluvium</td><td rowspan="3">Tenmile Gravel</td><td rowspan="4">Early terrace gravels</td><td rowspan="4">Upper Mesa gravel</td></tr>
<tr><td>Gowen terrace alluvium</td></tr>
<tr><td>sediments of the Deer Flat surface</td></tr>
<tr><td>Tenmile Gravel</td><td>Idaho Formation</td></tr>
<tr><td rowspan="2">TERTIARY</td><td>upper Idaho Group</td><td rowspan="2">Payette Formation</td><td rowspan="2">Payette and Idaho Formations undivided</td><td rowspan="2">Payette Formation (Payette gravels)</td></tr>
<tr><td>lower Idaho Group</td></tr>
</table>

gravel beds that Lindgren (1898a) believed were Tertiary.

A lower Tenmile Gravel forms the gravelly uplands near Lucky Peak Lake and is composed of 50 percent weathered clasts (Othberg, 1986). This unit contrasts with the overlying upper Tenmile Gravel which is less weathered. Othberg further recognized that the Tenmile Gravel was time transgressive, ranging in age from Pliocene to early Pleistocene. The contrasts in weathering also suggest that a major break in time is represented by the contact between the upper and lower Tenmile Gravel.

Gravel of Bonneville Point (Tertiary)

I herein provide the informal name, gravel of Bonneville Point (Figure 10) for the lower Tenmile Gravel of Othberg (1986) and Othberg and Burnham, (1990). The unit is composed of weathered, interbedded sands and gravels (Figure 12) that form the highly dissected upland of reversed topography on which Bonneville Point is located (Figure 11). The upland rises to about 1,257 meters (4,124 feet) in elevation south and southwest of Lucky Peak Lake and extends westward to about 976 meters (3,200 feet) in elevation where the lithologically distinct gravels of the Tenmile Gravel cap the newly designated gravel of Bonneville Point. The unit is exposed in gulches, in gravel pits, on eroded slopes near Bonneville Point, and on the north and west sides of Lucky Peak Lake (Figure 11). In addition to these exposures, water well logs show that this unit is a thick fill lying against the range-front fault boundary of the mountains. The well logs further suggest that the gravel of Bonneville Point grades northwest and west into the finer grained Terteling Springs Formation and intertongues with it (Figure 10). The gravel of Bonneville Point unconformably overlies the tilted basalt volcanic assemblage of the Boise Front into which an ancestral canyon was cut by the Boise River. The assemblage is in turn unconformably overlain by the Tenmile Gravel.

Figure 12. Borrow pit near Blacks Creek Road (NW¼SE¼ sec. 30, T. 2 N., R. 4 E.) showing interbedded sand and gravel of the gravel of Bonneville Point. Face of pit is about 6 meters (20 feet) high in center of photograph.

The gravel of Bonneville Point owes its preservation on the prominent upland of Bonneville Point in part to the greater resistance of the gravels to erosion compared with surrounding lithologies. Even the surface of the granite has been lowered by erosion more quickly than Bonneville Point (Figure 13). This greater resistance of a gravel is aptly described by Rich (1911).

Tenmile Gravel (Pliocene-Pleistocene)

The upper Tenmile Gravel of my former usage (Othberg, 1986; Othberg and Burnham, 1990) makes up a highly dissected terrace occupying the western end of the gravel ridge south of Boise. Remnants of the terrace occur along a westward linear trend that extends to the bluffs of the Snake River. I restrict my usage of the Tenmile Gravel to that distribution (Figure 11), and I abandon the informal name, upper Tenmile Gravel. The Tenmile Gravel's assemblage of gravel clasts is dominated by granitic rocks and porphyritic felsites that came from the central Idaho mountains. Measured azimuths of cross-bed dips within the Tenmile Gravel indicate a westward-flowing river. I retain Savage's interpretation that the gravels were deposited by high-energy meltwater streams. In addition, I follow the restrictions of Wood and Anderson (1981) and later workers that separate younger terrace gravels from the Tenmile Gravel.

The Tenmile Gravel is the highest terrace of the Boise Valley and was deposited as the former Boise River prograded across the filled plain (Othberg, 1988). Lateral to the course of the Boise River at the time of deposition were local streams that drained the foothills and mountain front. Based on investigations in the Boise Front and adjacent areas (Wood and Burnham, 1983; Gallegos and others, 1987; Burnham and Wood, in press), these deposits include arkosic sands and stream and fan gravels primarily composed of local granite clasts. One mappable unit in the Boise Front containing

Figure 13. View from Bonneville Point (SE¼ sec. 24, T. 2 N., R. 4 E.) toward the northeast up Lydle Gulch. Flat-topped summits on either side of Lydle Gulch are composed of the gravel of Bonneville Point, which is thinning in the direction of view. More eroded hummocky terrain in the distance is composed of granitic rocks of the Idaho batholith.

abundant gravel in its upper part is the Pierce Gulch Formation (Figure 10) (Burnham and Wood, in press). The Pierce Gulch Formation consists of arkosic sand overlain by a 9-meter-thick gravel cap composed of subrounded pebbles and cobbles of local granite and foothills basalt. The gravel occurs along ridge tops of similar elevation that are suggestive of terrace remnants. Burnham and Wood (in press) interpreted the sands of the Pierce Gulch Formation to be fluvial and deltaic and believed the sand deposits record the locations of range-front deltas prograding into the northeastern margin of a regressing lake shore. In their studies of fish biostratigraphy south of the Snake River, Smith and others (1982) identified regressive beaches from which they inferred a rapid drop in lake level. The overlying deposits suggest prograding fluvial environments in early Pleistocene time. I propose that the gravel cap of the Pierce Gulch Formation is correlative with widespread gravel deposition in the northwestern part of the western Snake River Plain in the late Pliocene or early Pleistocene. Thus, the gravel of the Pierce Gulch Formation and the Tenmile Gravel may be coeval.

Terrace Gravel (Pleistocene)

During the Pleistocene the Boise River cut at least eight terraces into the chiefly fine-grained Tertiary basin fill. All terrace deposits are pebble to cobble gravel with a coarse sand matrix (Figure 14). The gravels are poorly sorted and crudely bedded and include common thin lenses of sand. The sedimentary structures are typical of braided-stream deposits. The stones are imbricated and their grain sizes decrease downstream. At the mountain front, sparse boulders occur in the deposits, whereas near the confluence with the Snake River cobbles are absent. The gravels are so similar from terrace to terrace that texturally they are virtually indistinguishable. Since the terrace gravels are essentially the same sedimentologically, similar cutting and filling by a relatively high energy river occurred episodically throughout the Pleistocene. All but the oldest Pleistocene terrace deposits show a similar suite of gravel lithologies. The oldest terrace gravels lack the component of Pleistocene basalt clasts that make up to 10 percent of the clasts in the younger terrace gravels (a relative-age measure of the onset of basalt eruptions that affected the Boise River drainage). On the north side of the Boise Valley, local tributary streams contributed sandy sediment contemporaneous with gravel deposition by the Boise River. Terrace gravels north of the Boise River, therefore, grade into sand deposits in the Pleistocene terraces, incised alluvial fans, and valleys fills of those tributaries.

Local streams, mostly active during past climates that caused greater runoff, deposited sand and gravel valley

Figure 14. Close-up view of typical gravel pit wall showing the range of gravel clast sizes and lenses of sand (SE¼ sec. 10, T. 4 N., R. 1 E.).

fills and alluvial fans. In the Boise Front, the valley fills and alluvial fans are composed of coarse-grained arkosic sand deposits. Adjacent to the Bonneville Point upland and the Tenmile terrace, local streams built coalescing alluvial fans of reworked older sand and gravel. North of the Boise River, local streams formed valley fills and alluvial fans of reworked Tertiary arkose.

Thin wind-blown deposits differentially cover the surfaces of the terraces. These deposits are principally loess, but dune sand is present locally on bluffs and terraces near the confluence with the Snake River. Based on soil development, the loess deposits vary in age, but the loess is too thin to reveal any sequence of loess deposition. In most areas, the loess has accumulated in minor amounts, and typically the terrace remnants reflect long-term stability shown by the increasing soil development on successively older terraces.

Basalt Flows (Pleistocene)

Shield volcanoes, basaltic cones, and lava flows form much of the surface of the western Snake River Plain south and southeast of the Boise Valley. They are part of the Idaho Group and Snake River Group in the southeastern part of the western plain but are included in the Idaho Group and Pleistocene basalt flows in the northern plain (Figure 10). Basaltic volcanism is widespread in the western plain, and these volcanic rocks are common in the stratigraphic record.

Several basalt lava flows bury former alluvial surfaces in the Boise Valley and adjoining areas. The flows erupted from three sources: Smith Prairie on the South Fork of the Boise River (Figure 1), the range-front fault zone southeast of the Boise Front, and the northwest-southeast aligned system of volcanic vents in the center of the western Snake River Plain. Figure 15 shows these sources and the approximate flow directions of lavas within the western plain.

All these lavas are medium to dark gray olivine basalts with varying sizes and amounts of phenocrysts. Most of the flows are thin, reaching 4 meters (13 feet) in thickness. Thin deposits of loess differentially cover the surface of the lava flows and typically show an increase in soil development with age.

Howard and Shervais (1973) and Howard and others (1982) identified and traced lava flows of several canyon-filling basalts that erupted from vents at Smith Prairie. Two of these basalts flowed down the Boise River as far as the northeastern edge of the western plain. As each lava flow left the canyon, it spread onto a different level of the Boise River alluvial plain (Figures 15-18). One unit is the basalt of Lucky Peak, named by Howard and others (1982) for a single thick flow just downstream from Lucky Peak Lake. The other unit, locally called the basalt of Gowen terrace (Wood and Burnham, 1983; Burnham and Wood, in press; Othberg and others, 1990), was correlated by Howard and others (1982) with the Steamboat Rock Basalt in Smith Prairie.

Howard and others (1982) traced the Steamboat Rock Basalt downstream to Lucky Peak Reservoir and beyond to the Gowen terrace. Their mapping criteria were lithology, flow morphology, and position with respect to the basalt of Lucky Peak. The correlation of the basalt of Gowen terrace with the Steamboat Rock Basalt is suspect, however. Laboratory-measured magnetic polarities of the two units differ; samples from the basalt of Gowen terrace are normal polarity whereas Steamboat Rock Basalt samples, collected at the type locality at Smith Prairie, are reversed (Table 1). Howard and others' (1982) correlation is in part based on the altitude of the unit in the canyon with respect to the altitude of the basalt of Lucky Peak. The basalt of Lucky Peak,

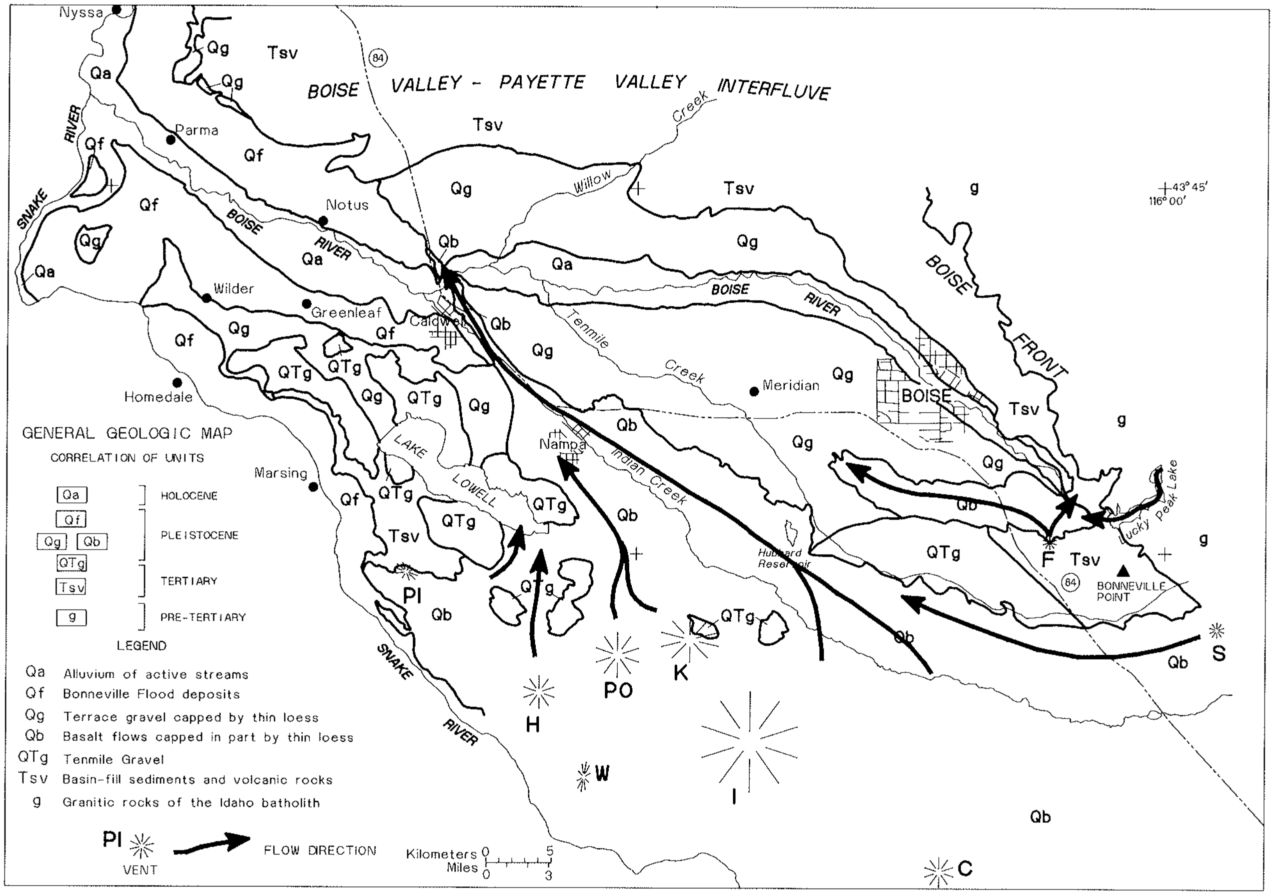

Figure 15. Locations of selected volcanic vents and flow directions of basalt flows emplaced on terraces of the Boise Valley: C, Christmas Mountain; F, Fivemile Creek; H, Hat Butte; I, Initial Point; K, Kuna Butte; PI, Pickles Butte; PO, Powers Butte; S, Slaters Flat; W, Walters Butte.

however, has not been identified in the valley of the South Fork of the Boise River or at Smith Prairie (Howard and Shervais, 1973). Its value, therefore, as a stratigraphic marker is questionable. Furthermore, the potassium/argon dates for the basalt of Gowen terrace and the Steamboat Rock Basalt also differ considerably. Steamboat Rock Basalt's K/Ar age is about 1.8 Ma (Howard and others, 1982), whereas the basalt of Gowen terrace is about 572 ka (Table 1). More work is needed to resolve the correlation discrepancy. Meanwhile, the basalt of Gowen terrace apparently does not correlate to the Steamboat Rock Basalt.

The other two basalts shown in Figure 18 are the late Pleistocene basalt of Mores Creek and the early Pleistocene basalt of Fivemile Creek. A vent for the basalt of Mores Creek has not been identified, but its source clearly resides within the Mores Creek drainage, a tributary of the Boise River (Figure 1). Geologic mapping (Othberg and Burnham, 1990) reveals that the basalt of Fivemile Creek probably erupted from a small vent at the north edge of the Bonneville Point upland (Figure 15). This basalt and the Basalt of Slaters Flat erupted from vents on the fracture system associated with the range-front fault zone of the Boise Front. Lava of the basalt of Fivemile Creek flowed north and northwest into the Boise River alluvial plain and made one of the early northward diversions of the Boise River.

Other basalt volcanic eruptions affected the Boise Valley and adjoining areas along the present drainage of Indian Creek and to the south of Lake Lowell. Vents for these basalts form a northwest-southeast trend of volcanoes in the center of the plain and can be traced from outside the study area near Mountain Home (Figure 1) northwest to Marsing. These basalts erupted from shields and vents such as Christmas Mountain, Initial Point, Kuna Butte, and Powers Butte (Figure 15). Many of these rocks have been sampled for magnetic polarity and radiometric dating (Table 1). The morphologic

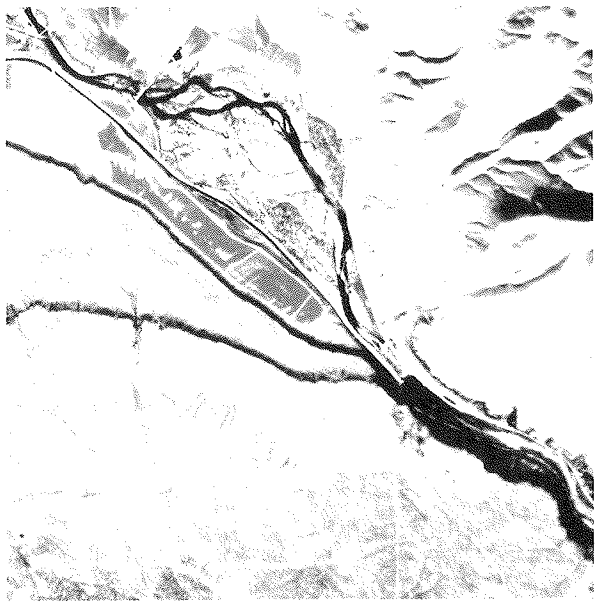

Figure 16. Vertical aerial photograph of southeast Boise showing terrace-edge escarpments caused by lava flows emplaced on terraces. North is toward top of page. Interstate 84 is in lower left corner. Location of canyon shown in Figure 17 is in lower right corner.

(landform) unit for these basalts is undivided, because there is a lack of detailed geologic mapping that separates the units.

Figure 17. View northwest of canyon cut by the Boise River through lava flows emplaced on terraces. Location noted in Figure 16. See Figure 18 for interpretation of stratigraphy.

Lava flows from one or more shield volcanoes in the center of the plain caused a major westward diversion of the Snake River a few miles south of Initial Point (Malde, 1985, 1987, 1989). Indian Creek now follows the drainage course along which several lavas flowed. This route may have been that of the ancestral Boise River before the basalts inundated the flood plain and forced the river northward near its present course. The basalt of Hubbard Reservoir, like the basalt of Fivemile Creek, probably contributed to the diversion of the

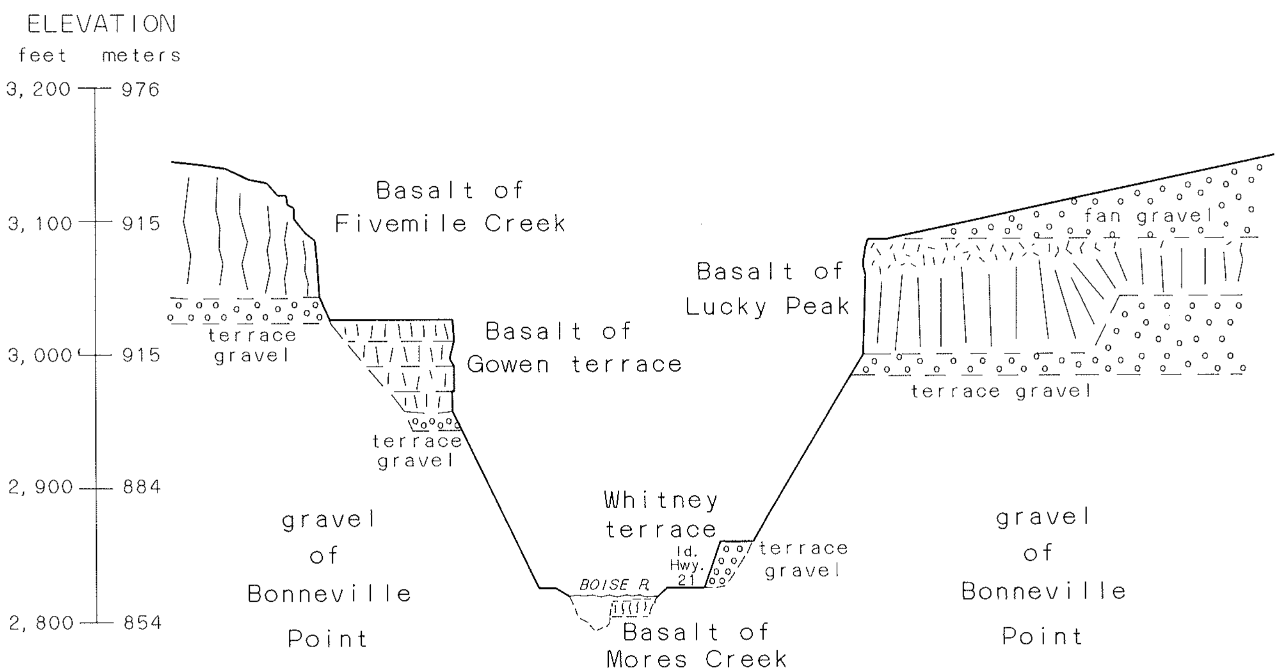

Figure 18. Profile and cross section of the Boise River canyon near Lucky Peak Dam showing stratigraphy of lava flows and buried terrace gravels. Stratigraphy of basalt units, oldest to youngest: basalt of Fivemile Creek, basalt of Lucky Peak, basalt of Gowen terrace, and basalt of Mores Creek.

Boise River northward about 1 Ma. This happened about the time estimated by Malde (1985, 1987, 1989) for the westward diversion of the Snake River by lavas erupting from Initial Point and nearby vents.

Bonneville Flood Sediments (Pleistocene)

Pleistocene Lake Bonneville in northeast Utah inundated an enormous area of terrain characterized by internal drainage (Morrison, 1965; Scott and others, 1983; Currey and Oviatt, 1985; Currey, 1990). Beginning its expansion about 28 ka, the lake reached its maximum level about 15 ka. Water then spilled northward across a low divide called Red Rock Pass in southeastern Idaho, and the lake first drained externally into the Snake River basin (Malde, 1968; Scott and others, 1982; O'Connor, 1990), but the lake remained stable (Currey, 1990). The level of Lake Bonneville remained near the 1,552-meter (5,092-foot) level and had an outlet at Red Rock Pass for about 1,100 years (15.3-14.2 ka). An accelerating erosion of the threshold produced the Bonneville Flood (Malde, 1968; Jarrett and Malde, 1987; O'Connor, 1990) about 14.5 ka and lowered the lake 108 meters (354 feet) (O'Connor, 1990) to the Provo level at 1,444 meters (4,738 feet).

The changes that precipitated the flood are unclear, but the rapid erosion of unconsolidated sediments in Red Rock Pass allowed an increasing discharge that culminated in a catastrophic flow of water cascading down the Snake River. In some places water escaped the river channel and spread across adjacent parts of the plain (Jarrett and Malde, 1987). The great erosive power of the flood easily removed deposits of loess and other sediments and in many places differentially eroded columnar basalt, forming irregular surfaces or "scablands."

When this flood was constricted by Hells Canyon, a lake temporarily formed and inundated adjacent valleys in Idaho and Oregon to an estimated elevation of 747 meters (2,450 feet) (O'Connor, 1990). Relative to the flood waters rushing freely through channels, these "slack waters" were calm. Unlike the erosive, high velocity waters, the slack waters were turbid with mud from upstream erosion that precipitated laminated to thin-bedded clayey silt and fine sand (Figure 19).

The Bonneville Flood slack water upstream from Hells Canyon probably filled the Snake River valley from at least Marsing downstream and the lower Boise Valley westward from Caldwell. Downstream from Caldwell in the western Boise Valley, the surfaces of terraces below 740 meters (2,430 feet) in elevation are mantled with thin-bedded silt and fine sand of the Bonneville Flood (Figures 11 and 20). The slack-water sediments become finer grained and thin eastward up the Boise Valley. Flood sediments are unknown upstream from Caldwell. Although the highest stand of the slack water should have reached a point just east of Caldwell, the constriction of the river at Caldwell probably limited upstream water flow; most water upstream from Caldwell was from the relatively clear Boise River. Moreover, the highest stand of slack water may have been short lived. O'Connor (1990) calculated the attenuation of the Bonneville Flood discharge at the Hells Canyon constriction. His calculations led to estimates of the flood's duration in selected reaches of the Snake River. O'Connor (1990) determined the Bonneville Flood lasted about 12 weeks in the western Boise Valley.

Typical thicknesses of the Bonneville Flood slack-water sediments range from 3 meters (10 feet) at Wilder to 6 meters (20 feet) near Nyssa. The sediments tend to be thickest near the Snake River. In exposures 1.6-2.1 km (1-2 miles) southeast of Parma, the lower part of these deposits show climbing ripple-drift cross-lamination that indicates rapid deposition by turbid water (Jopling and Walker, 1968) flowing southeastward up the Boise River valley[5] (Figure 21).

Mapping the terraces is more difficult where the Bonneville Flood slack-water sediments mask terrace escarpments, bury older soils, and increase the elevations of the mantled terrace surfaces. The terraces can be traced, however, now that the Bonneville Flood sediments in this area are identified and mapped (Othberg and Stanford, 1992). Buried duripans help to correlate these terraces with the eastern terrace sequence near Boise.

Alluvium and Colluvium (Holocene)

The channel alluvium of the Boise River is a predominant Holocene deposit. Its sandy pebble and cobble gravel texture grades downstream and westward into a sandy pebble gravel near the confluence with the Snake River. The gravel deposits underlie the flood plain to depths of 7-11 meters (23-35 feet) and overlie a surface cut by the river into the Tertiary basin-fill sediments (Othberg and Burnham, 1990; Othberg and Stanford, 1990). The lithologies of the gravel clasts consist of granitic rocks and porphyritic felsites derived from the Idaho batholith and associated rocks of the central Idaho mountains. Gray unweathered basalt eroded from Pleistocene lava flows make up to 10 percent of the gravel. Like the terrace deposits,

[5]Similar sedimentary structures are exposed outside the study area in the upper part of a section in a drainage ditch along highway U.S. 95 twelve miles south of Homedale.

Figure 19. Thin-bedded clayey silt and fine-sand partings of the Bonneville Flood slack-water sediments (silage-pit exposure in SW¼NW¼ sec. 2, T. 4 N., R. 5 W.). Handle of rock hammer for scale.

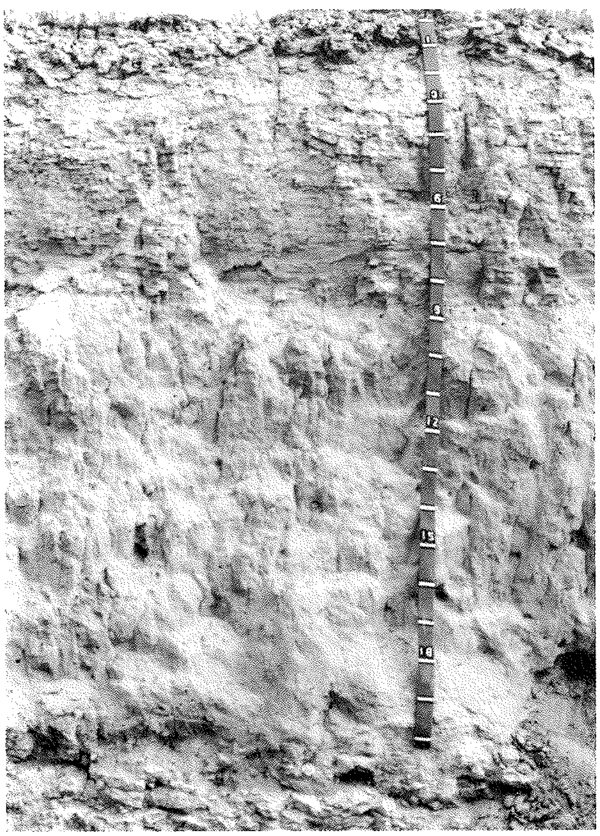

Figure 20. Silage-pit exposure on the Wilder terrace (SW¼NW¼ sec. 2, T. 4 N., R. 5 W.). Thin-bedded Bonneville slack-water sediments overlie bed of unweathered loess, which, in turn, overlies buried duripan. Scale shown by tape marked in decimeters.

Figure 21. Bonneville Flood slack-water sediments showing ripple-drift cross-lamination in sand and coarse-silt beds which grade upward to thin beds of clayey silt. Trowel for scale. Roadcut at the junction of U.S. 95 and U.S. 20/26 (SE¼ sec. 15, T. 5 N., R. 5 W.).

the texture of the channel alluvium of the Boise River is a coarse-grained gravel. This similarity in texture suggests the same depositional environment, at least episodic, throughout the Quaternary. Holocene colluvium largely consists of landslide deposits in the Boise Front and rock-fall and rock-slide colluvium composing the talus at the base of lava bluffs and ledges.

MORPHOLOGIC UNITS

The term "morphologic unit" has both a geomorphic and a stratigraphic meaning. Geomorphically, a morphologic unit is a surface, either depositional or erosional, that is recognized by its topographic character (Bates and Jackson, 1987). "Geomorphic surface" has been used synonymously with morphologic unit. Some morphologic units employ the descriptive term "surface" (as in Fivemile Creek surface) instead of a genetic landform term (as in Whitney terrace).

"Morphologic unit" also is an abbreviated form of "morphostratigraphic unit," an informal stratigraphic unit defined by Frye and Willman (1962). Gile and others (1981, p. 24), in describing the specialized stratigraphic needs in mapping geomorphology and soils, stated: "Earth materials genetically related to a constructional phase of a geomorphic surface are often conveniently mapped as a *morphostratigraphic unit.*" According to Frye and Willman (1962, p. 112), a morphostratigraphic unit is an informal stratigraphic term used to designate "a body of rock[6] that is identified primarily from the surface form it displays."

Morphostratigraphic units have not been formally adopted in the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983). The code, however, provides for formal stratigraphic designation of such mappable units in the more general category, allostratigraphic unit. Sequences of alloformations are not strictly superposed with respect to one another, but we still apply stratigraphic principles in interpreting the relative positions of these other classes of rock bodies. For example, an alloformation differs from a formation in that it is defined on the basis of its bounding discontinuities instead of a distinctive lithology. Gravel units, for example, with identical lithologies but in different terrace positions can be given separate stratigraphic names.

No alloformations have been established in the Boise Valley. Only a few mappable units such as the Tenmile Gravel have been given formation status. Currently, the terrace deposits have names tied to morphologic units (Table 3).

In this report, which emphasizes geomorphology, I use morphologic units (Table 3). To tie the landforms to earth materials and geologic history, morphologic units are chosen and commonly named on the basis of their genesis.

Morphologic units must be placed in a chronology to analyze properly the geomorphic history. The relative ages of landforms typically are determined by topographic position, unit boundaries, surface morphology and physical characteristics, and cross-cutting relations among the morphologic units. The minor addition or removal of material that degrades the original, constructive form (such as gullying, stream incision, the deposition of loess and colluvium, and the building of small alluvial fans) is less important than the degree of

[6] "Rock" in this context includes unconsolidated as well as indurated earth materials.

Table 3. Morphologic units of the western and eastern Boise Valley.

WESTERN BOISE VALLEY			EASTERN BOISE VALLEY			AGE OF LITHOLOGIC UNIT
Morphologic Unit	Features	Lithologic Unit	Morphologic Unit	Features	Lithologic Unit	
Bottomland	Stream channel and flood plain	Alluvium of active streams	Bottomland	Stream channel and flood plain	Alluvium of active streams	Holocene and late Pleistocene
Boise terrace	1st terrace above Boise River	Buried by Bonneville Flood sediments	Boise terrace	1st terrace above Boise River	Gravel of Boise terrace	Late Pleistocene
Whitney terrace	2nd terrace above Boise River	Buried by Bonneville Flood sediments	Whitney terrace	2nd terrace above Boise River	Gravel of Whitney terrace	Late middle Pleistocene
Wilder terrace	3rd terrace above Boise River	Buried by Bonneville Flood sediments	Sunrise terrace	3rd terrace above Boise River	Gravel of Sunrise terrace	Late middle Pleistocene
			Gowen terrace	4th terrace above Boise River	Gravel of Gowen terrace	Middle middle Pleistocene
			Lucky Peak surface	Lucky Peak lava flow (buries 5th terrace)	Basalt of Lucky Peak	Early middle Pleistocene
			Fivemile Creek surface	Fivemile Creek lava flow (buries 6th terrace)	Basalt of Fivemile Peak	Early Pleistocene
Basalt surfaces undivided	South Side lava flow	Basalt of Kuna Butte	Basalt surfaces undivided	Hubbard Reservoir lava flow	Basalt of Hubbard Reservoir	Early Pleistocene
	Mason Creek lava flow	?		Slaters Flat lava flow	Basalt of Slaters Flat	
	Kuna City and Black Cat Road lava flow	?				
	Caldwell, east Nampa, and Rawson Canal lava flows	?				
	Upper Deer Flat lava flow	?				
	Pickles Butte lava flow	Basalt of Pickles Butte				
Deer Flat terrace	4th (and 5th?) terrace above Boise River	Gravel of Deer Flat terrace	Amity terrace	7th terrace above Boise River	Gravel of Amity terrace	Early Pleistocene
Tenmile terrace	6th terrace above Boise River	Tenmile Gravel	Tenmile terrace	8th terrace above Boise River	Tenmile Gravel	Early Pleistocene
			Bonneville Point upland	Dissected upland of reversed topography	Gravel of Bonneville Point	Pliocene
Ridge and valley uplands	Eroded interfluve	Basin-fill sediments	Ridge and valley uplands	Eroded interfluve and foothills	Basin-fill sediments and volcanic rocks	Tertiary

soil development that takes place on the more stable surfaces.

There are three major reasons for using morphologic units and their stratigraphic relationships in a study of geomorphology. First, morphologic units are records of geomorphic processes and are indispensable for reconstructing events. Second, a stratigraphic approach to the study of landforms allows the geomorphic events to be interpreted historically. Third, the age of soils on landform surfaces helps one to interpret the morphostratigraphy. For the most part, Quaternary lithologic units in the Boise Valley and adjoining areas have characteristic landforms, for example, "gravel of Sunrise terrace."

Lindgren (1898a) first mapped terraces in the Boise Valley using the local names, "upper mesa" and "lower mesa." Lindgren and Drake (1904a) and Kirkham (1931a) dropped the topographic designations and used the lithologic names, "early terrace gravels" and "late terrace gravels." Nace and others (1957), although maintaining the terrace gravel lithologic units, superimposed terrace landform names on their geologic map to further subdivide the various elevations of the surfaces of the two gravel units. They recognized seven terraces of which I retain four with slight modification: Whitney terrace, Sunrise terrace, Gowen terrace, and Tenmile terrace. Three of their terrace names, "Broadway," "Eightmile," and "Meridian," have been abandoned.

Wood and Anderson (1981) relied on geomorphic relationships to define and map certain units in the Nampa and Caldwell area. They mapped the Whitney terrace and named a new geomorphic unit, the "Deer Flat surface." Wood and Burnham (1983) mapped alluvial deposits of the Whitney, Sunrise, and Gowen terraces as well as sediments of the Deer Flat surface in the Boise area and placed these lithologic units in a stratigraphy based on geomorphic succession. The Deer Flat surface is composed of terrace gravel deposits and intercalated basalt lava flows. In some areas basalt immediately underlies the thin loess in which the surface soils have formed. I distinguish between the basalt surface and the terrace that occupies the topographic position of the Deer Flat surface. I name the terrace morphologic unit the Deer Flat terrace. Many lava flows compose the basalt surface. Contacts for individual basalt units have not been mapped. Therefore, I have combined the basalt surfaces into one unit, basalt surfaces-undivided.

Othberg (1986) examined the geomorphic relationships between basalt flows, terraces, and the Tenmile Gravel (renamed the gravel of Bonneville Point herein) near Lucky Peak Dam. Othberg and Burnham (1990), Othberg and others (1990), Othberg and Stanford (1990), and Burnham and Wood (in press) described and mapped five terraces of the Boise River in the metropolitan Boise area. These studies emphasized the age, correlation, and stratigraphy of the geomorphic surfaces as a means to better interpret and map the lithologic units. For example, the gravel of Whitney terrace is the second river terrace above the present bottomland of the Boise River. Table 3 lists the morphologic units for the western and eastern parts of the Boise Valley, the characteristic features for each, the corresponding lithologic units, and the estimates of their age.

Of the fourteen morphologic units shown in Table 3, all but four originally were alluvial surfaces formed by the Boise River. The youngest of these is the present river bottomland. The oldest is the Bonneville Point upland. The remaining alluvial surfaces are terraces, two of which are completely buried by lava flows. Terraces are ranked by their topographic position relative to the Boise River. I recognize six terraces of the Boise River in the Boise and Meridian area of the eastern Boise Valley (Figure 22) and five or six terraces west of Nampa and Caldwell in the western Boise Valley (Figure 23). The Boise terrace is the lowest and first terrace above the Boise River, whereas the Tenmile terrace is the highest and sixth terrace. The nonalluvial morphologic units are represented by basalt surfaces and the eroded uplands of Tertiary basin-fill sediments — the ridge and valley uplands.

Figures 22 and 23 also show the association between soil development and the relative age of terraces. The increase in calcium carbonate and silica from a calcic horizon to a duripan 1 meter or more thick occurs in steps that match the change in morphostratigraphic position. This match also is true of the increase in clay in argillic horizons, but the increase is not as dramatically represented. Table 4 lists distinctive clay, calcic, and duripan horizons and the taxonomic classifications of the U.S. Department of Agriculture's Soil Conservation Service for representative soil series mapped on geomorphic surfaces of increasing age. The classifications show the sequence of change in the soil profiles with age. Steps in the sequence are marked by (1) the initial calcic (*Bk*) horizon in the Bram Series, (2) the initial argillic (*Bt*) horizon in the Greenleaf Series, (3) the initial duripan (*Bqkm*) in the Purdam Series, (4) the appearance of coarse laminar plates of silica and carbonate in the duripan of the Elijah Series, and (5) the accumulated clay in the argillic (*Bt*) horizon exceeding 35 percent in the Chilcott Series.

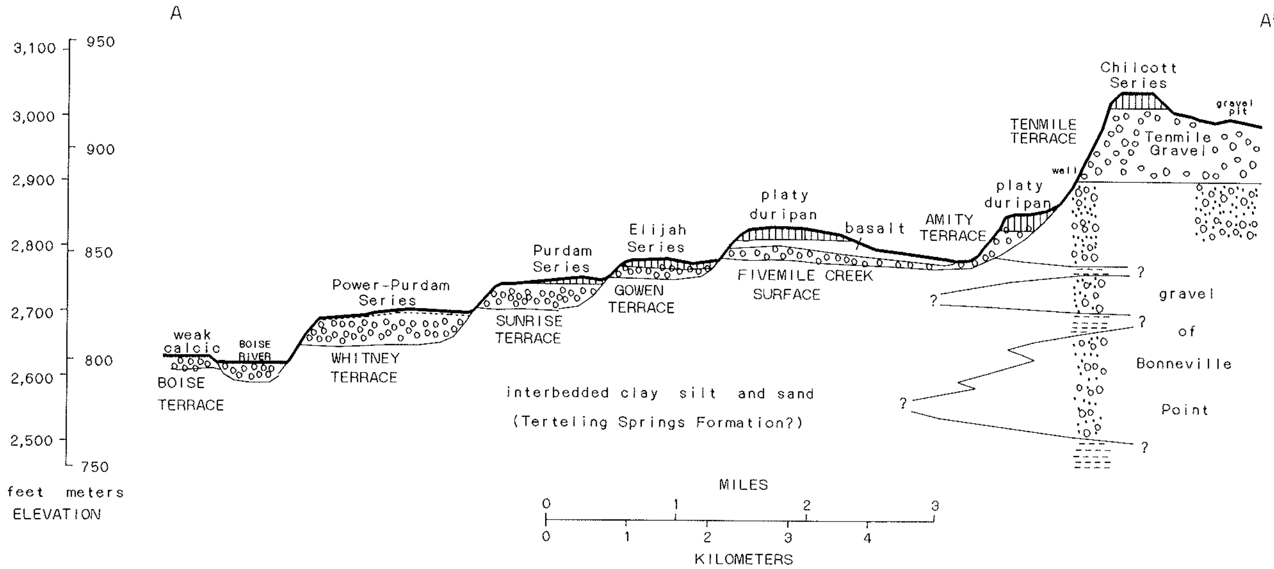

Figure 22. Diagrammatic profile and cross section of the eastern Boise Valley showing soil series or duripan characteristics on different terraces. Symbols: circles — gravel; dots — sand; dashes — silt and clay; vertical bars — duripan; dotted line — calcic horizon. A-A' shown for cross reference with Figures 26 and 28.

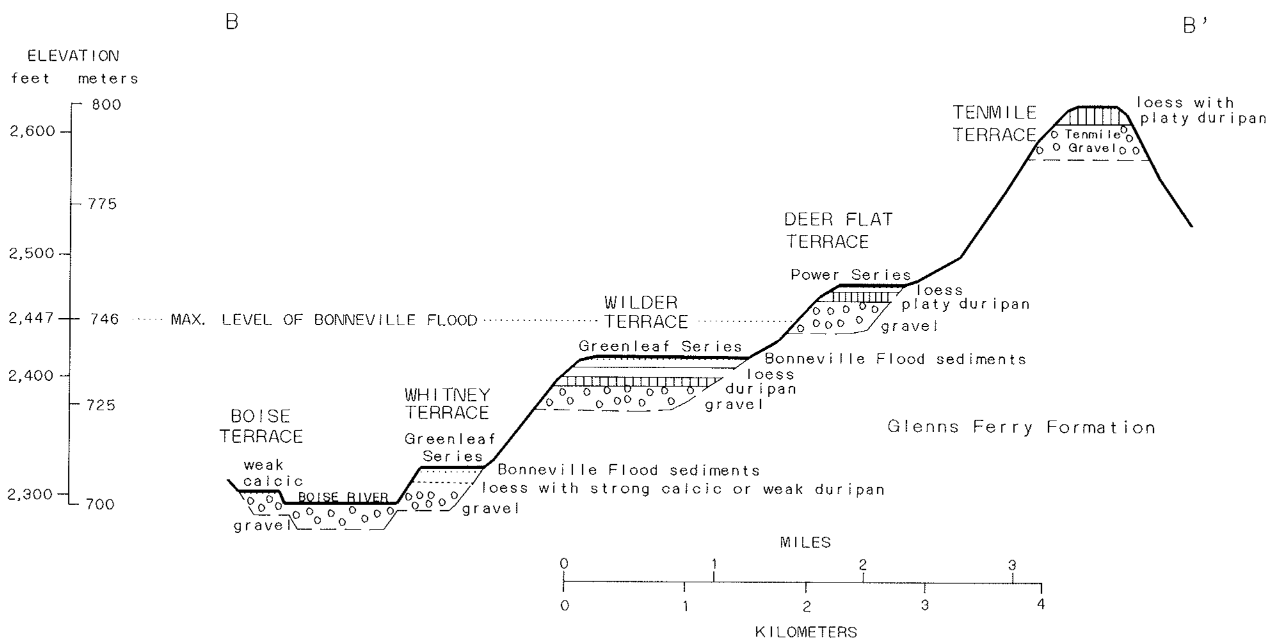

Figure 23. Diagrammatic profile and cross section of the western Boise Valley showing soil series or duripan characteristics on different terraces. Level of the Bonneville Flood (O'Connor, 1990) shown for reference with the Boise, Whitney, and Wilder terraces. Symbols: circles — gravel; vertical bars — duripan; dotted line — calcic horizon. B and B' are shown for cross reference with Figure 28.

Table 4. Distinctive soil horizons and subgroup classifications of representative soil series in a sequence based on geomorphic age in the Boise valley (interpreted from Priest and others, 1972; Collett, 1980; and field observations).

<table>
<tr><th>Morphologic Unit</th><th>Series</th><th>Horizon</th><th>Classification</th></tr>
<tr><td>bottomland</td><td>Falk</td><td>none</td><td>Xerorthents</td></tr>
<tr><td>Boise terrace</td><td>Bram</td><td>Bk</td><td>Xerollic Calciorthids</td></tr>
<tr><td>Bonneville Flood sediments</td><td>Greenleaf</td><td>Bk</td><td>Xerollic Haplargids</td></tr>
<tr><td>Whitney terrace</td><td>Power</td><td>Bt and Bk</td><td>Xerollic Haplargids</td></tr>
<tr><td>Sunrise terrace</td><td rowspan="2">Purdam</td><td rowspan="2">Bt and Bqkm (thin)</td><td rowspan="2">Haploxerollic Durargids</td></tr>
<tr><td>Wilder terrace (buried)</td></tr>
<tr><td>Gowen terrace</td><td>Elijah</td><td>Bt and Bqkm (plates)</td><td>Xerollic Durargids</td></tr>
<tr><td>Deer Flat terrace (buried)</td><td></td><td>Bqkm (plates, very thick)</td><td></td></tr>
<tr><td>Amity terrace</td><td rowspan="2">Chilcott</td><td rowspan="2">Bt (clay >35%)
Bqkm (plates, very thick)</td><td rowspan="2">Abruptic Xerollic Durargids</td></tr>
<tr><td>Tenmile terrace</td></tr>
</table>

The terraces are best preserved and defined by their locations and relative vertical positions near the city of Boise (Figures 24 and 25). Figure 26 is a stereoscopic oblique view of the terraces that illustrates their positions with respect to the Boise River in the foreground and the high Tenmile terrace in the background.

Listed in order of position above river level, the terraces of the eastern Boise Valley are the Boise terrace, Whitney terrace, Sunrise terrace, Gowen terrace, Amity terrace, and Tenmile terrace (Figure 22 and Table 3). In addition, the basalt-buried Lucky Peak and Fivemile terraces lie at levels between those of the Gowen terrace and the Amity terrace. Terraces of the western Boise Valley are the Boise terrace, Whitney terrace, Wilder terrace, Deer Flat terrace, and Tenmile terrace (Figure 23 and Table 3). Two additional terraces, one buried under the basalt of Fivemile Creek and the other under the basalt of Lucky Peak, are identified but not named because their original alluvial surfaces have no direct topographic expression.

No morphologic unit corresponding with the Tenmile Gravel was previously recognized; rather, a nongenetic topographic term, "Tenmile ridge," was used by Wood and Anderson (1981) and later workers. In this report I do not use the name Tenmile ridge because I distinguish between the high terrace, Tenmile terrace (modified from Nace and others, 1957), and the upland composed of the gravel of Bonneville Point (see *Bonneville Point Upland*, page 30).

Downstream of Caldwell the Bonneville Flood slackwater sediments mantle the Boise, Whitney, and Wilder terraces and are the parent material for the Greenleaf Series soil. This is best seen just south of Wilder where the escarpment of the Deer Flat terrace, which lacks a cover of Bonneville Flood sediments, rises above the Wilder terrace.

CHRONOLOGY OF MORPHOLOGIC UNITS

Ridge and Valley Uplands

The ridge and valley uplands morphologic unit consists of stream-incised hills and ridges separated by long valleys. It forms the broad interfluve between the Boise Valley and the Payette Valley as well as the foothills of the mountains. The rocks of this unit include Tertiary sedimentary and volcanic rocks as well as the Cretaceous granite. Deformation of these rocks has resulted in many tilted beds, fault scarps, and fault zones of weakened rock. Erosion of the foothills, therefore, has produced structural benches, dip slopes, and fault-controlled valleys. These features and relationships between landform and rock units extend along the Boise Front from Lucky Peak Lake northwest into the uplands of the

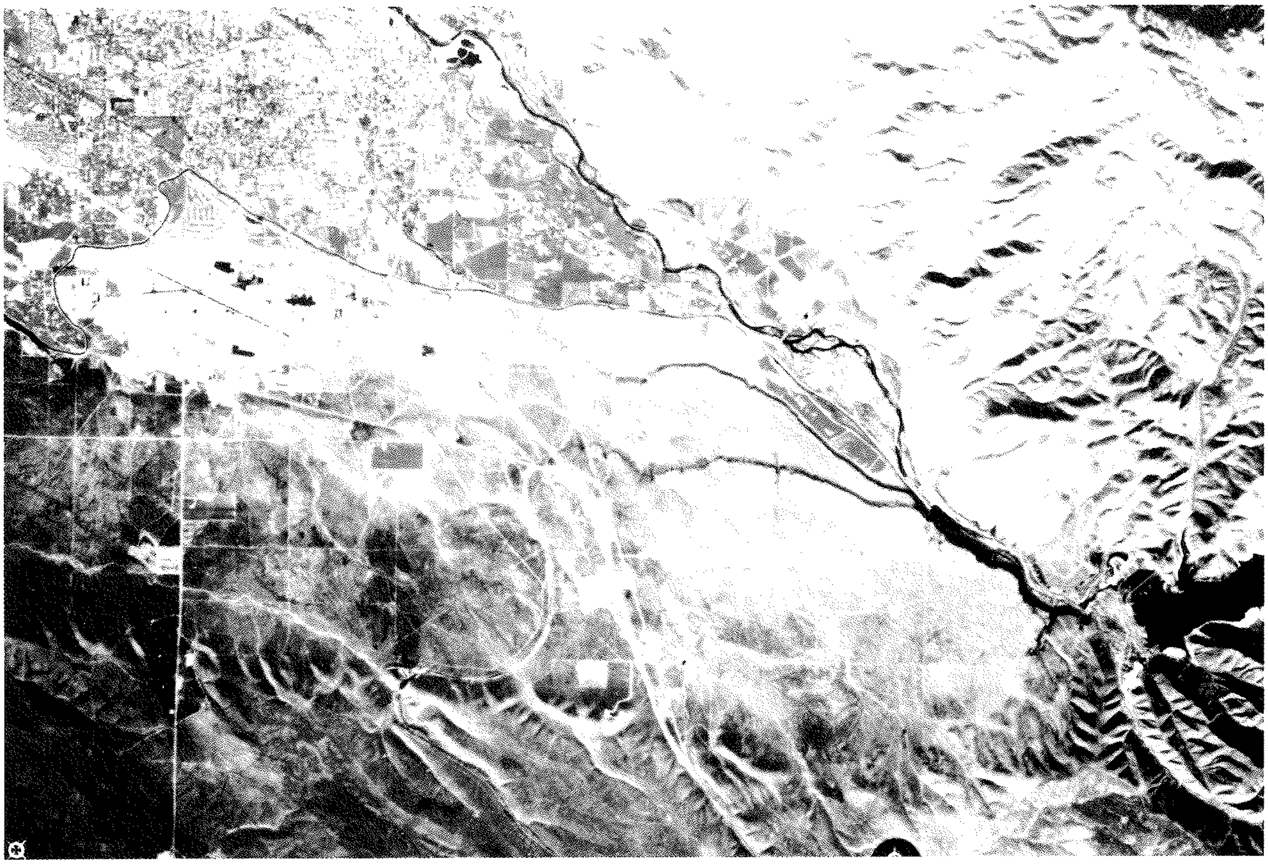

Figure 24. Vertical aerial photograph of south Boise showing location of preserved terraces. North is toward the top. Airport (left center) lies on Gowen terrace. Eroded upland in lower edge of photograph is Tenmile terrace. Photograph shown in Figure 25 was taken from Table Rock (top center).

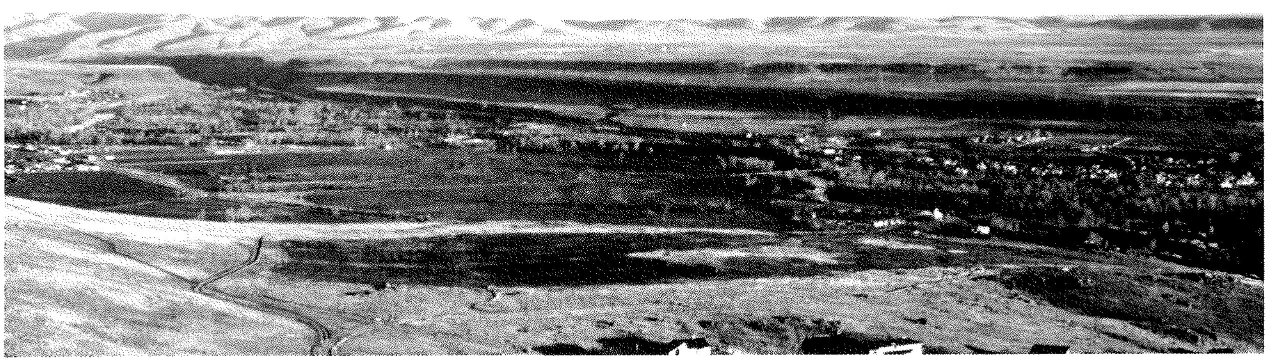

Figure 25. View of terraces in south Boise looking south from Table Rock (see Figure 24).

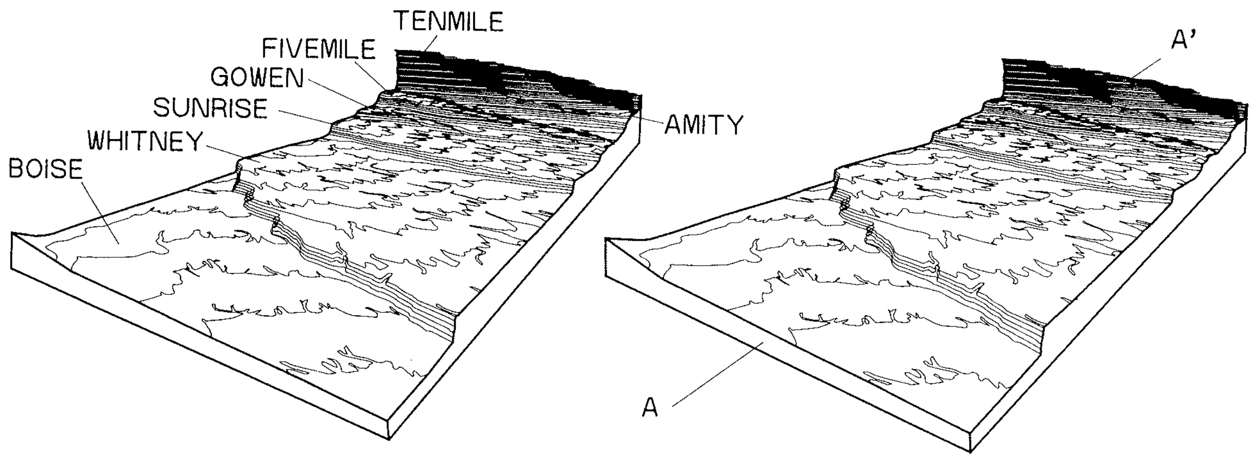

Figure 26. Stereopair of a block diagram showing the sequence of terraces in the eastern Boise Valley (courtesy of L.R. Stanford, Idaho Geological Survey). A-A' shown for cross reference with Figure 28.

Figure 27. Close-up view of the gravel of Bonneville Point showing highly weathered, decomposing clasts (borrow pit, NW¼NW¼ sec. 14, T. 2 N., R. 3 E.). Tape measure for scale.

Boise Valley-Payette Valley interfluve. The ridge and valley uplands formed by erosion throughout the Quaternary as the incision of the western Snake River Plain progressed. Evidence of modern erosion is minimal and, based on current knowledge and inferences about Pleistocene climatic conditions, most of the erosion that produced the ridge and valley uplands in their present form probably occurred during the wetter and more severe Pleistocene glacial climates.

Bonneville Point Upland

The Bonneville Point upland is a broad, faulted and dissected ridge of reversed topography composed of the gravel of Bonneville Point. The gravel of Bonneville Point consists of permeable coarse arkose and pebble to cobble gravel and is relatively resistant to weathering and erosion compared with the granitic rocks in the adjacent mountain front. Although the arkose and gravel were deposited in the ancestral valley of the Boise River where it exited the mountains, differential erosion has formed an upland composed of these alluvial sediments. Part of the upland relief is caused by the pervasive northwest-southeast faulting along the northeast edge of the western Snake River Plain. The coarse sediments represent a former alluvial surface that rises to the east as high as 1,256 meters (4,120 feet) in elevation on either side of Lucky Peak Dam. The surfaces of the granite body and other rocks of the mountain front, now in the lower slopes adjacent to the gravel of Bonneville Point, must have originally formed uplands that surrounded the ancestral river valley in which the coarse sand and gravel of the gravel of Bonneville Point were deposited. Soils in the Bonneville Point upland contain some of the greatest accumulation of illuvial clay and silica seen in the study area (M.A. Fosberg, oral commun., 1990). Stones in the subsoil are highly oxidized and crumbly, and the entire formation shows a degree of weathering greater than in any other gravel deposit (Figure 27). Large soil mounds, 10-15 meters (33-50 feet) in diameter, and broad, stony intermound areas form a patterned ground with the greatest relief and widest distribution in the study area. The Tenmile terrace abuts the Bonneville Point upland, and the Tenmile Gravel buries the gravel of Bonneville Point to the west. The Bonneville Point upland was present, albeit less eroded and probably less deformed by faulting, when the Tenmile Gravel was deposited.

Tenmile Terrace

The Tenmile terrace consists of a highly dissected and structurally deformed upland that is the eighth terrace above the Boise River in the eastern Boise Valley. In the western part of the study area, however, it is the fifth or sixth terrace above river level (Figure 28). Tenmile terrace is most prominently displayed south of Boise where its maximum altitudes are 137-146 meters (450-480 feet) above river level. Its morphology is largely dominated by ravines and small valleys. This erosional topography has been influenced by northwest-southeast trending faults, of which several are exposed in gravel pits and roadcuts.

To the east the Tenmile terrace borders the Bonneville Point upland. The Bonneville Point upland has a steeper slope, more developed, patterned ground, and soil characteristics that suggest it is older than Tenmile terrace. Maximum soil development on Tenmile terrace is represented by the Chilcott Series (M.A. Fosberg, oral commun., 1990; Collett, 1980). This well-developed soil has a large accumulation of pedogenic clay in the B horizon and a platy duripan at least 1 meter thick (Figures 5 and 7). The deposit composing the Tenmile terrace is the Tenmile Gravel.

Remnants of Tenmile terrace have been mapped as far west as the bluffs of the Snake River (Othberg and Stanford, 1992). These remnants lie 79-149 meters (260-490 feet) above river level and have deep erosion features such as small valleys aligned with the northwest-southeast structural trend (Wood and Anderson, 1981). The maximum soil development on these western remnants is represented by the Minidoka Series (Priest and others, 1972). Typically, the soil horizons above the thick platy duripan in the western outcrops have been stripped by erosion, and younger windblown sand and loess form thin surface deposits.

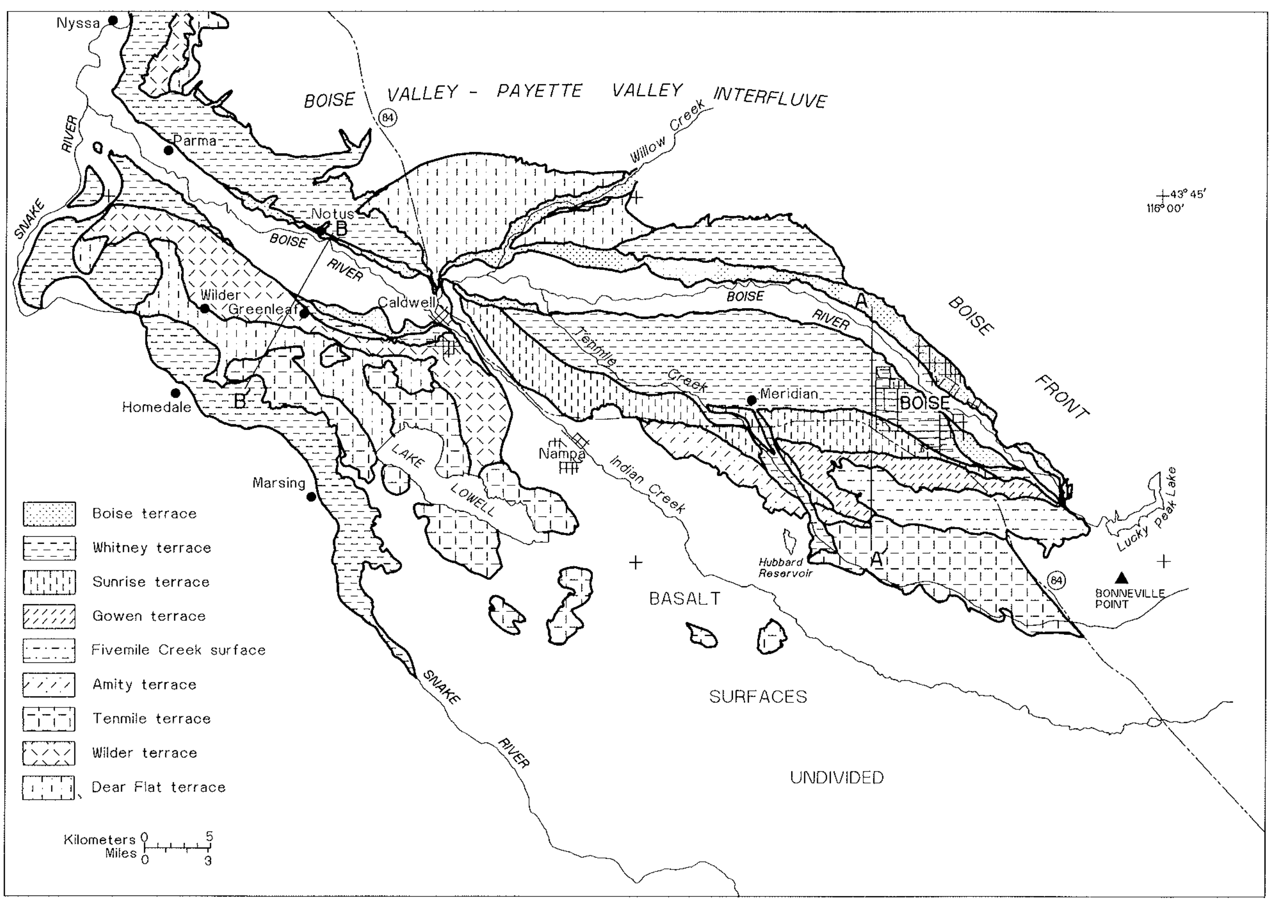

Figure 28. Distribution of Boise Valley terraces within the study area.

The Tenmile Gravel, as defined in this study, may correlate in part with the Tuana Gravel of the southeastern part of the western Snake River Plain (Malde, 1985, 1987, 1989, 1991). Stratigraphically, the Tuana Gravel lies between the Glenns Ferry Formation and the Bruneau Formation. Malde (1991) reviewed the stratigraphic relationships and the potassium/argon dates that narrow the possible range in age of the Tuana Gravel. Bracketing the potassium/argon dates suggests that the Tuana Gravel was deposited at about 2 Ma.

In the Boise Valley and adjoining areas, the age of the Tenmile Gravel is not well constrained. Stratigraphically, the Tenmile Gravel is younger than the Glenns Ferry Formation and older than both the Deer Flat terrace and the Amity terrace. Studies of the magnetic and fossil stratigraphy provide age control for the Glenns Ferry Formation exposed in the Chalk Hills bluffs near the site of the abandoned Froman Ferry on the Snake River. The beds contain an assemblage of late Blancan (~2.6 to ~1.9 Ma) vertebrate fossils with one exception, an immigrant microtine rodent that is an indicator species for Irvingtonian time (~1.9 to 0.9 Ma) in this part of North America (Van Domelen and Rieck, 1992; Ted Weasma and Charles A. Repenning, oral and written commun., 1992-1993). A search for the Olduvai Normal Polarity Subchron, formerly thought to range from 1.87 to 1.67 Ma, revealed that the sampled sediments are all reversed magnetic polarity (Van Domelen and Rieck, 1992). Thus, Van Domelen and Rieck do not recognize an Olduvai Normal Polarity Subchronozone in the section. The revised polarity time scale (Cande and Kent, 1992) gives an age of 1.76 Ma for the polarity reversal at the top of the Olduvai Normal Polarity Subchron. An early Irvingtonian age for the Chalk Hills section fits the post-Olduvai limiting age provided by the magnetic polarities. A minimum age for both the Tenmile terrace and the Tenmile Gravel is the argon-40/argon-39 date of 1.590 ± 0.085 Ma from the valley-rim basalt of Pickles Butte that caps a terrace probably correlative with the Deer Flat terrace. These dates and stratigraphic relationships suggest that the Tenmile Gravel was deposited in the early Pleistocene. The river incision that formed the Tenmile terrace occurred before the Pickles Butte eruption, about 1.58 Ma.

Deer Flat Terrace

The Deer Flat terrace is named for the terrace that extends from Lake Lowell northwest to the area just south of Wilder (Figure 28). The Deer Flat terrace consists of both an abandoned channel confined between hills surrounding Lake Lowell and the fourth terrace (or a combination of the fourth and fifth terraces) above the Boise River west of Nampa. Like Amity terrace, the Deer Flat terrace should represent the first level of Quaternary incision in the Boise Valley.

Altitudes above the Boise River at various locations suggest that the Deer Flat terrace either is two separate alluvial surfaces or is faulted. Altitudes of the terrace above the river occur as follows: about 61 meters (200 feet) at the northwest end of the terrace; about 50 meters (165 feet) at Greenleaf; about 48 meters (160 feet) northwest of Lake Lowell; and about 34 meters (110 feet) north of Caldwell near Interstate 84. The Deer Flat terrace is further complicated by basalt lava flows that were emplaced on the alluvial surface from the south and southeast and are known to interbed with the sediments (Wood and Anderson, 1981).

Northwest from Lake Lowell the Deer Flat terrace is buried by thicker deposits of loess. An exposure in a drainage ditch near Wilder shows a thick, platy duripan buried by loess. Most of the soils mapped in this area by Priest and others (1972) have incipient and thin duripans formed in the loess overlying the thick buried duripan. The age of the soils in the loess is similar to that of the soils formed on the Whitney terrace near Boise. The age of the buried duripan, however, represents the age of the Deer Flat terrace.

North of Caldwell, remnants of Deer Flat terrace also have thick duripans. The relative age for these soil duripans is probably equivalent to that of the Elijah Series or older. This soil evidence suggests Deer Flat terrace is at least as old as Gowen terrace, but it must be older because the basalts in Caldwell and east Nampa have reversed magnetic polarities whereas the basalt of Gowen terrace has normal polarity. Furthermore, the Caldwell lava flow yielded an argon-40/argon-39 age of 0.799 Ma (Table 1). This corroborates the minimum soil age, but also suggests that the Deer Flat terrace, as described, is a complex of multiple surfaces. Parts are equivalent to the Amity terrace and the terrace buried by the basalt of Pickles Butte, and may be about 1.6 Ma in age. Other parts represent younger terraces. The complexity of sorting out terrace levels and ages in the Nampa-Caldwell area helps confirm the vertical deformation along faults suggested by the northwest-southeast trends in the topography (see *Structure*, page 36).

Amity Terrace

The Amity terrace is the fifth terrace above the modern Boise River in the eastern Boise Valley. It is about

61 meters (200 feet) above river level. The terrace is the somewhat flat high surface bordered on its north and northwest sides by a high escarpment located about 2 miles south of Meridian (Figure 28). It is named for Amity Road that runs east-west across the terrace. Where buried by a lava flow in east Nampa, the terrace is 31 meters (100 feet) above the Boise River, a height similar to that of the Deer Flat terrace at Caldwell. The terrace extends northwest from the west end of Tenmile terrace to within 4 miles of Nampa. East of Tenmile Creek, remnants of Amity terrace are faulted and rise as high as 79 meters (260 feet) above the Boise River. The basalt of Hubbard Reservoir laps onto the gravel of Amity terrace from the south. The basalt has a potassium/argon age of 1.001 ± 0.098 Ma. Several lava flows occur in the broad, flat Indian Creek lowland that lies between Amity terrace and the city of Kuna (Figure 2). Argon-40/argon-39 dates on four of the lavas give ages ranging from 1.165 to 1.231 Ma. These basalts represent some of the area's earliest lava eruptions, which post-date the Amity terrace and helped to divert the Boise River northward.

The terrace is modified extensively by erosion, and its surface appears offset by faults, especially near Tenmile Creek. Major northwest-southeast linear topographic trends are reflected in the orientation of ravines, low valleys, and the escarpment on the northeast side of the terrace (Othberg and others, 1990). The upper, least eroded parts of Amity terrace are mantled with loess 0.5-2 meters (1.6-7 feet) thick.

Typical soil development on Amity terrace is at least equivalent to the Elijah Series, but due to erosion, the evidence of clay accumulation and thick duripans is preserved only in isolated areas. In isolated exposures where erosion has been minimal, the platy duripan developed on Amity terrace is as thick as in the Chilcott Series. Based on the highly developed soils and the radiometric ages of the basalt of Hubbard Reservoir and associated lava flows, Amity terrace is early Pleistocene in age. Although unclear from Wood and Anderson's (1981) geologic map whether the sediments of Deer Flat terrace extend east into the Meridian and Tenmile Creek area, Wood and Burnham (1983) correlated a part of the surface I call Amity terrace with Deer Flat terrace. Like Deer Flat terrace, the stratigraphic position of Amity terrace suggests it represents the first level of Quaternary incision of the Boise Valley. Owing to their physical separation, the effects of structural deformation, and their respective differences in morphology and thicknesses of mantling younger deposits, Amity terrace should be correlated with Deer Flat terrace until more data suggest otherwise.

Basalt Surfaces-Undivided

The basalt surfaces-undivided (Figure 28) is composed of basalts that flowed from the Slaters Flat volcano and the eruptive zone in the center of the plain (Figure 15). Several lava flows of varying ages form the lava field that parallels Indian Creek and lies south and southeast of Lake Lowell. Both normal and reversed magnetic polarities and a wide range of ages are represented by the flows (Table 1). The primary significance to terrace chronology is the normal-polarity basalt of Hubbard Reservoir and the reverse-polarity east-Nampa lava. Both rest either on the downfaulted southwest side of Amity terrace or on an alluvial surface incised into Amity terrace, providing a minimum age for the terrace. Other apparently distinct lava flows in the Indian Creek drainage are both normal and reversed polarity (basalt of Kuna Butte, South Side lava flow, and lava flows of Mason Creek, Kuna City, Caldwell, Rawson Canal, and Black Cat Road) and range in age from about 0.387 Ma to 1.376 Ma (Table 1 and Figure 9). All lava flows sampled south and southwest of Lake Lowell — Upper Deer Flat, Missouri Avenue vent, and Pickles Butte rim — are reverse polarity and range in age from about 0.922 Ma to 1.580 Ma.

With the exception of the basalt of Kuna Butte (South Side), soils developed on the basalt surfaces-undivided indicate ages at least as old as the Gowen terrace. Uneroded surfaces of reversed-polarity basalts exposed in canals typically have platy duripans as thick as those found in the Chilcott Series. Where argillic horizons are preserved, illuvial clay is more than 35 percent.

Stratigraphy and magnetic polarities suggest the range of ages represented by the basalt surfaces-undivided must be large. Some of the normal polarity lava flows may be less than 780 ka (Brunhes Normal Polarity Chron). The reversed polarity basalts must be at least 780 ka (upper limit of Matuyama Reversed Polarity Chron). The Tenmile terrace is younger than the top of the Olduvai Subchron. The reversed-polarity basalts are older than Tenmile terrace and younger than 780 ka. The radiometric dates are in accordance with these constraints and therefore seem reliable.

Fivemile Creek Surface

The Fivemile Creek surface (Figure 28) is composed of the basalt of Fivemile Creek, which probably erupted from a small vent on the southeast side of the surface (Figure 15). To the east in the Boise River canyon, a single lava flow overlies the surface of an alluvial gravel at about 927 meters (3,040 feet) in elevation (Figure 18). Along the north escarpment near Interstate 84, at least three thin flows outcrop and the base of the lava is well exposed at 911 meters (2,989 feet) in elevation. Water-well logs show the surface of the buried gravel is not uniform in elevation, and thus more than one alluvial surface may have been present at the time of burial by the basalt. In one exposure near I-84, the basalt and gravel are separated by a clastic deposit composed of water-altered basalt fragments and scoriaceous pebbles (hyaloclastite). This evidence suggests the lava flowed onto an active flood plain. The basalt of Fivemile Creek and the terrace it buries probably are coeval.

Soils on the Fivemile Creek surface developed in both loess and basalt. A well-defined stream drainage in the basalt's surface forms a relief of about 18 meters (60 feet). Some drainages, especially westward on the surface, appear controlled by faulting (Othberg and others, 1990). The Fivemile Creek surface ends near Tenmile Creek where it appears offset by faults (Othberg and others,1990). Soils formed in thick loess on the least-eroded areas. The most widespread soil has an argillic horizon with more than 35 percent clay and a platy duripan up to 1 meter thick. Duripans are found at 0.5-1 meter in depth, and stringers of white calcium carbonate extend into the upper part of the basalt. The typical soil is the Chilcott Series (Collett, 1980). A patterned ground of small circular mounds of soil material and loess 2-4 meters (7-13 feet) in diameter may have formed during Pleistocene periglacial conditions (Malde, 1964). The patterned ground is best seen on aerial photographs. The Fivemile Creek surface probably has an age within the Jaramillo Normal Polarity Subchron (Figures 8 and 9) based on soil properties, stratigraphic relationships, and a potassium/argon date of 0.974 Ma for the lava flow.

Lucky Peak Surface

The Lucky Peak surface is composed of the basalt of Lucky Peak, which is a canyon-filling lava that probably originated in Smith Prairie (Howard and others, 1982). Exposures southeast of Boise near Lucky Peak Lake show that the lava flowed onto an alluvial surface composed of about 3 meters (10 feet) of relatively unweathered channel gravel (Othberg and Burnham, 1990; Figure 18). This gravel lies at 909 meters (2,980 feet) in elevation and was probably the active flood plain when the Lucky Peak lava was emplaced. Lucky Peak lava also engulfed a gravel deposit lying 18 meters (60 feet) higher, about the level of the terrace buried by the basalt of Fivemile Creek (Figure 18).

Soils in the Lucky Peak surface primarily developed in gravelly alluvial-fan deposits. The gravels are reworked from the erosion of the gravel of Bonneville Point in the adjacent hills. Because the fan gravels are younger than the basalt of Lucky Peak, the soils provide little help in establishing a relative age for the Lucky Peak surface. The greater than 1 Ma potassium/argon dates for the basalt of Lucky Peak appear unreliable based on stratigraphy, paleomagnetic polarities, and dates from adjacent lava flows (Figures 9 and 18). Physical stratigraphy demonstrates that the basalt of Lucky Peak is older than the basalt of Gowen terrace but younger than the basalt of Fivemile Creek. Loss of argon due to the texture and mineralogy of this rock may contribute to inaccurate potassium/argon dates[7] (Carl Swisher, Berkeley Geochronology Laboratory, oral commun., 1989). The basalt of Lucky Peak may correlate more closely with the basalt of Long Gulch in Smith Prairie, dated by Howard and others (1982) at 0.68 Ma. The Lucky Peak surface probably has an early middle Pleistocene age of between 572 ka and 780 ka (Figures 8 and 9).

Gowen Terrace

The Gowen terrace is the fourth terrace above the modern Boise River in the eastern Boise Valley. The terrace ranges from 49-58 meters (160-190 feet) above river level; the variation mostly is due to minor gullying. This terrace extends from the Boise River canyon downstream to within 3 miles of Meridian (Figure 28). To the east it is buried by the basalt of Gowen terrace, which consists of canyon-filling lava flows (Figure 18). The lavas inundated this level's alluvial surface from the opening of the canyon to within 1 mile of where Interstate 84 crosses the terrace. Near Meridian, Gowen terrace appears truncated and possibly tilted by faulting (Othberg and others, 1990). The surface of the terrace is mostly mantled by 1-2 meters (3-7 feet) of loess and thin alluvium in minor drainageways. Maximum soil development on Gowen terrace is represented by the Elijah Series (M.A. Fosberg, oral commun., 1990; Collett, 1980). These soils have argillic B horizons and platy duripans 0.5-1 meter thick. Duripans are found at about 1 meter in depth, and some of their white calcic properties extend into the underlying

[7] A date reported by Howard and others (1982) was too old and also very imprecise: 2.1 ± 0.5 Ma.

gravel (Figure 5). Based on the soil development and a potassium/argon age of 0.572 ± 0.210 Ma for the basalt of Gowen terrace, the Gowen terrace is middle middle Pleistocene in age (Figure 8).

Sunrise Terrace

The Sunrise terrace is the third terrace above the modern Boise River in the eastern Boise Valley. The terrace is about 35 meters (115 feet) above river level. It extends from east Boise to Caldwell where its surface nearly merges with the Whitney terrace (Figure 18). In this area, near the drainage of Tenmile Creek, faulting has probably truncated and tilted the terraces of Sunrise and older age (Othberg and others, 1990). Sunrise terrace is slightly gullied by erosion, and the surface is mantled by loess 1-2 meters (3-7 feet) thick. The maximum soil development on the terrace is approximately represented by the Purdam Series (M.A. Fosberg, oral commun., 1990; Collett, 1980). The B horizons are both argillic and calcic, and a weakly to moderately developed duripan is common (Figures 4 and 5). Based on soil characteristics and the stratigraphic sequence of terraces in the Boise Valley, the Sunrise terrace may be correlative with the Wilder terrace.

Wilder Terrace

The Wilder terrace is named for the flat terrace 40 meters (131 feet) above the Boise River on which the town of Wilder is located (Figure 28). It is easily traced east to Caldwell and west to the bluffs of the Snake River valley. South of Caldwell the Wilder terrace is more difficult to distinguish, but it may extend to Lake Lowell. One remnant occurs north of Parma.

Wilder terrace is composed of Bonneville Flood slack-water sediments that mantle a sequence of deposits consisting of a thin loess, a thin duripan, and a gravel several meters thick. These relations are exposed in artificial cuts and eroded slopes in a gulch 6.5 kilometers (4 miles) north of Wilder. The loess appears to have been unweathered when it was buried by the Bonneville Flood sediments. This suggests that loess deposition was active in the west Boise Valley in late Wisconsin time. The loess overlies a duripan formed in the terrace gravel. Soil horizons above the duripan have been eroded. Considerable time must have transpired between depositions of the gravel and the loess — enough time to form a duripan soil equivalent to the Purdam Series and to erode the terrace surface to the level of the relatively resistant duripan.

The character of the duripan of Wilder terrace, although buried by slack-water sediments, suggests that the terrace is about as old as the Sunrise terrace to the east. However, the gradients of the Sunrise and Wilder terraces do not match. If Wilder terrace is a westward extension of Sunrise terrace, then the difference in the gradients helps demonstrate the amount of Quaternary deformation that has occurred in the Nampa-Caldwell area (see *Structure*, page 36).

Whitney Terrace

The Whitney terrace is the second terrace above the modern Boise River (Figure 28). It is 24-31 meters (80-100 feet) above river level at the east end of the Boise Valley and about 18 meters (60 feet) above river level near the confluence with the Snake River (Figure 18). Whitney terrace is the most extensive of the Pleistocene surfaces. Although mantled with sediments of the Bonneville Flood west of Caldwell, the terrace is traceable downstream to the bluffs of the Snake River. North of the study area, the main terrace in the Payette River valley probably correlates with the Whitney terrace. The Whitney terrace extends upstream into the Boise River canyon near Lucky Peak Lake to a maximum elevation of 878 meters (2,880 feet). At 1.2 miles farther upstream, the surface of the basalt of Mores Creek is exposed at about 860 meters (2,820 feet) in elevation during times of low water (Figure 18). Whitney terrace lies at a higher position and is, therefore, older than the basalt of Mores Creek, which has a potassium/argon age of about 0.107 Ma (Table 1). The surface of Whitney terrace has been little modified by erosion but is mantled by loess up to 2 meters (7 feet) thick. The maximum soil development on this surface is represented by the Power and Purdam Series, the soils of which exist in a complex pattern of distribution on the terrace (Priest and others, 1972; Collett, 1980; M.A. Fosberg, oral commun., 1990). The soils have argillic and calcic B horizons and, locally, a weak duripan (Figure 4 and 5). Based on this minimum age and the soil development on Whitney terrace, the age is late middle Pleistocene (Figure 8).

Boise Terrace

The Boise terrace is the first terrace above the modern Boise River (Figure 28). Named by Wood and Burnham (1983), it consists of a low surface, about 3 meters (10 feet) above the river level, situated predominately on the northeast and north side of the river (Figure 18). Much of downtown Boise is built on this terrace. The surface is virtually undissected, and the most developed soils on the Boise terrace lack a duripan, although such soils have either a calcic horizon or a weak argillic horizon. The classification and inferred age of these soils are similar to the Greenleaf Series that formed on slackwater sediments of the Bonneville Flood. Thus, the Boise terrace was formed in the late Wisconsin (Figure 8).

Bottomland

The bottomland unit includes the channel and flood plain of the modern Boise River. The river is underfit today, probably because dams and irrigation projects have dramatically reduced the peak-flow discharge.

STRUCTURE

Lindgren (1898b) and Russell (1902) recognized that high-angle faults produced the abrupt escarpment along the northern boundary of the western Snake River Plain. Kirkham (1931b), on the other hand, proposed gentle downwarping as the form and cause of the entire Snake River Plain and relegated the contribution of faulting to small discontinuous faults. Savage (1958) followed Kirkham's ideas and described the western plain as part of the Snake River Plain "downwarp." Malde (1959), however, presented evidence supporting the early interpretations of a fault-bounded northeast boundary for the western plain. Geologic mapping by Malde and others (1963) and studies by Wood (1989) show basin-margin faults on both sides of the southeastern part of the plain. Most of the faults are displaced down toward the center of the plain. Ekren and others (1981) mapped faults that form the border between the Owyhee Mountains (Figure 1) and the plain. These border faults have been present since 16 Ma and have remained active into the Quaternary (Ekren and others, 1984). Faults in the Boise Front that mark the basin margin were mapped by Wood and Burnham (1983), Burnham and Wood (in press), Othberg and Burnham (1990), Othberg and Stanford (1990), and Othberg and Stanford (1992).

Using oil-exploration well logs, geophysical data, and geologic mapping, Wood and Anderson (1981) and Wood (1984) interpreted some subsurface details of the western plain between Boise and the Snake River. Wood and Burnham (1983, 1987) described the relationships between the range front fault zone and the geothermal water system in the Boise area. Geologic mapping near Boise identifies many of the high-angle faults (Othberg and Burnham, 1990; Othberg and Stanford, 1990; Burnham and Wood, in press). Faults were observed in all rock units of Sunrise terrace age and older. Geologic mapping near Meridian and Tenmile Creek (Othberg and others, 1990) corroborates some of the fault trends interpreted by Wood and Anderson (1981) near Nampa and Caldwell.

Figure 29 shows structural cross sections interpreted by Wood (Wood and Anderson, 1981, p. 14-15). The cross sections depict normal faults of both senses of motion, that is, antithetic faults, in acoustic basement rocks thought to be Miocene basalt. Motion on these faults has produced at least 1,220 meters (4,000 feet) of total downward displacement and about 610 meters (2,000 feet) to the highest point on the Miocene basalt near the center of the plain (structural high into which J. N.

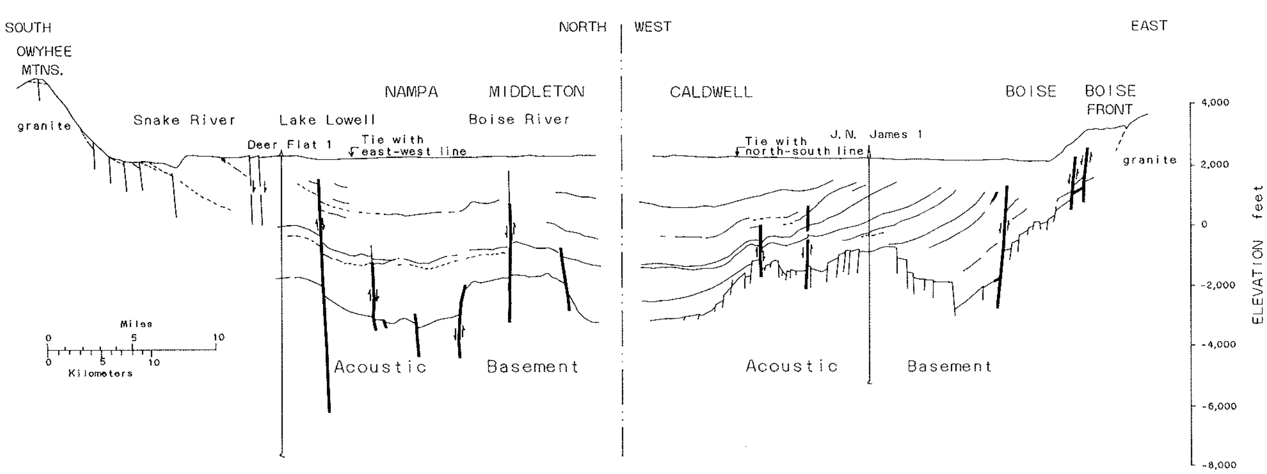

Figure 29. Cross sections showing basin structure as interpreted from geophysical data and oil exploration wells. Adapted from Wood and Anderson, 1981.

James No. 1 well was drilled — see Figure 29). My interpretation of the fault zones that form the basin margins and bound the central high are shown in Figure 30. Faulting is less prominent in younger rocks, but surficial mapping tends to corroborate the trends interpreted from geophysical data (Wood and Anderson, 1981; Burnham and Wood, in press; Othberg and Burnham, 1990; Othberg and others, 1990; Othberg and Stanford, 1992).

A comparison with models of continental rifts (Rosendahl, 1987; Morley and others, 1990; S.H. Wood, oral commun., 1988) suggests, at least for the acoustic-basement rocks, that the western Snake River Plain formed through half-graben propagation and that the central high is a "hinged high" formed through relative movement of a family of antithetic faults. That this style of rifting continued into the Pliocene and Pleistocene is less clear, but seismic reflection data as well as geologic mapping seem to confirm the interpretation of the structural features. From west to east, these features are (1) a northeast-dipping high with faults showing movement down to the northeast (Lake Lowell area), (2) a basin nearly centered under Indian Creek lying between Nampa and Caldwell, (3) a structural high with a major fault zone following Tenmile Creek, and (4) the broad range-front fault system of the Boise Front. The sedimentary units overlying the acoustic basement show many of the same faults but also are warped down toward the basin.

Figure 30 shows the locations of the Boise River and its terraces with respect to these major structural trends. Although the river's course has changed somewhat during the Quaternary, a comparison of the gradient of the present river flood plain with the gradients of terrace surfaces provides some insight into possible river profile changes and tectonic tilting and faulting of terrace surfaces. Figure 31 shows longitudinal profiles for the terraces and the Boise River flood plain. In the eastern Boise Valley, gradients steepen with the increasing height or age of the terrace. In the western Boise Valley, however, gradients decrease with the increasing height of the terrace. Figure 32 is a plot of gradient versus age

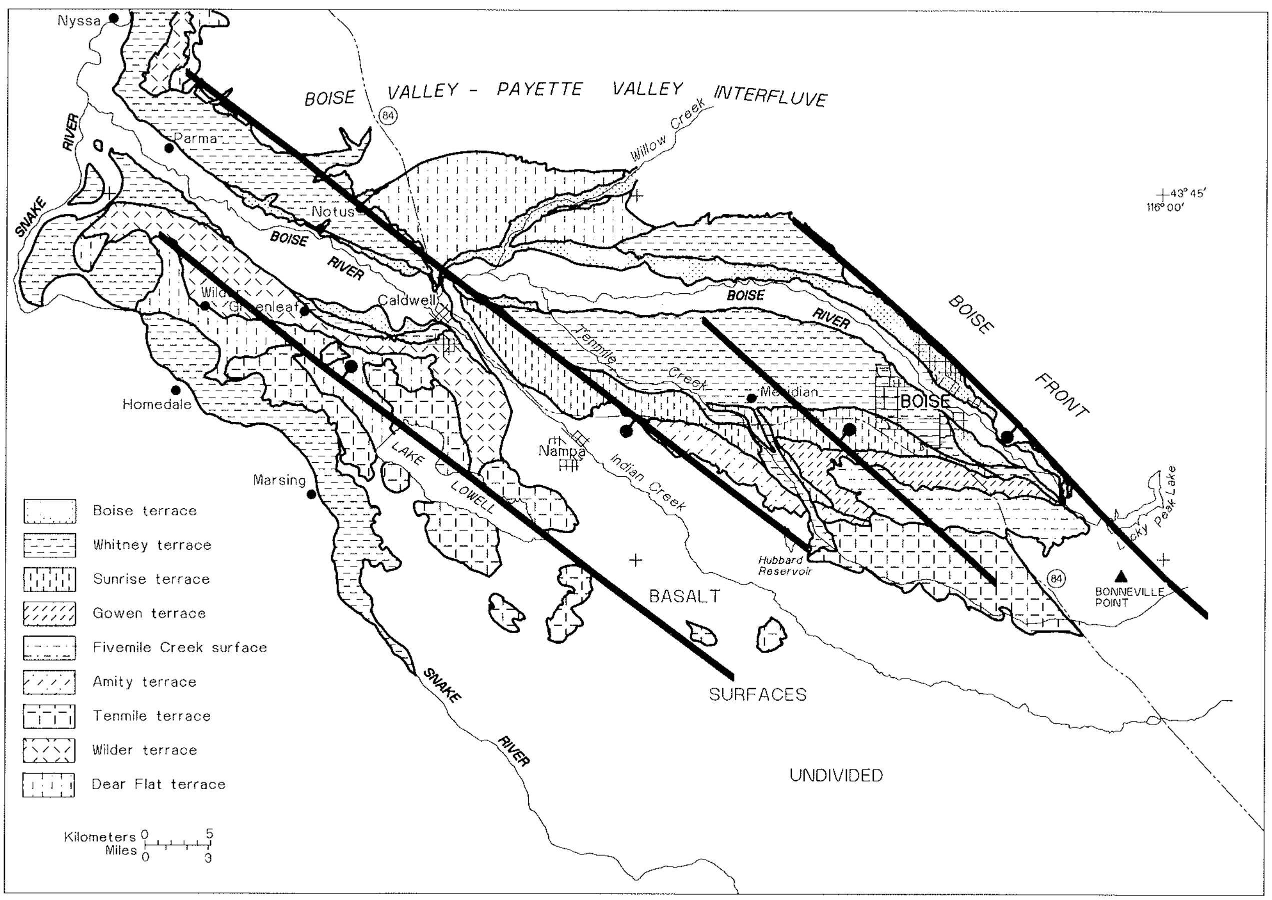

Figure 30. Approximate locations of major fault zones in the acoustic basement within the Boise Valley and adjoining areas. Ball and bar on downthrown side. The fault zones mark the boundaries of postulated half-graben structures in this part of the western Snake River Plain.

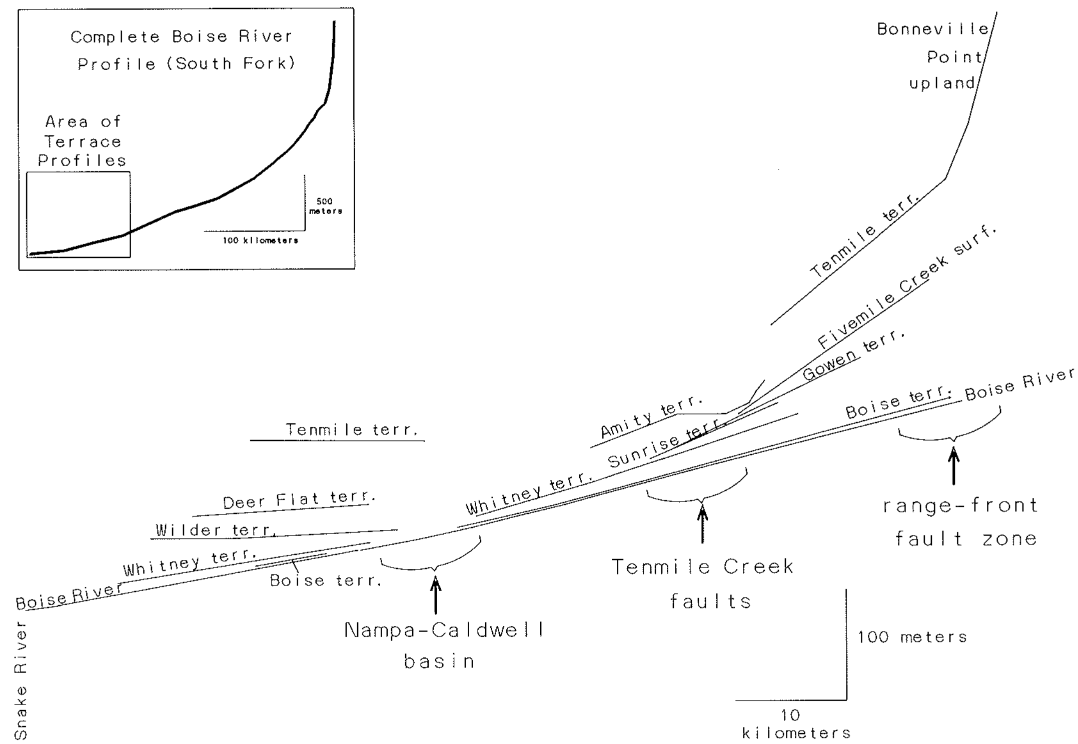

Figure 31. Plot of longitudinal profiles of Boise Valley terraces and the Boise River flood plain.

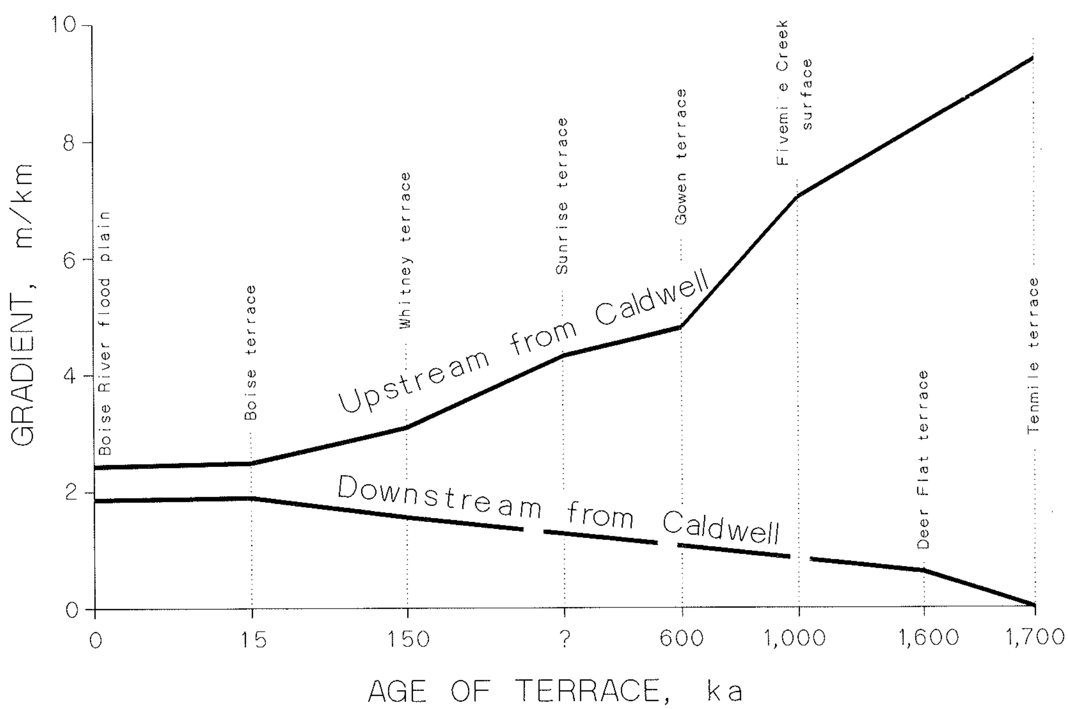

Figure 32. Plot of longitudinal gradient versus age for Boise Valley terraces and the Boise River flood plain.

for the eastern and western groups of terraces picked for their locations upstream or downstream of Caldwell. For each group, the gradient changes with time but in opposite directions.

Field evidence supports the idea that the changes in gradients over time resulted from tectonic movements of terraces rather than changes in stream profile. The grain size of channel deposits of the Boise River has not changed significantly from the time of the Tenmile Gravel to the present. Each lithologic unit shows a normal decrease from large cobble and pebble gravel near the mountain front to small- to medium-sized pebble gravel near the Snake River. This consistency in lithology indicates the channel gradients of the Boise River remained much the same at each time of gravel deposition. In addition, as terrace age increases, physical evidence of faulting and warping increases. Many faults have been mapped in the Tenmile Gravel, and the Tenmile terrace has many fault-controlled valleys and gullies. By contrast, no faulting has been documented on the Whitney terrace or younger surfaces.

The evidence suggests, therefore, that differences in gradients (Figures 31 and 32) are due mostly to tectonic movements within Quaternary time.[8] Specific responses of terraces to continued basin movements primarily occurred in three areas: (1) near the range front where upward warping and faulting exist along and near the basin margin; (2) near Tenmile Creek where faults and fault-line trends have been mapped and at which the levels of the Fivemile, Gowen, and Sunrise terraces appear to converge; and (3) near the Nampa-Caldwell basin (Figure 29) toward which older surfaces appear to have been warped or faulted. Placing approximate ages on the terrace levels based on dating the basalts demonstrates that little change has occurred during the last 100,000 years and that most of the movement took place before 600,000 years ago.

GEOMORPHIC HISTORY

After the initial rifting and subsidence of the western Snake River Plain, about 17 Ma, the downdropping and downwarping basin probably began to receive more sediment than any out-flowing water carried away. Indeed, much of the sedimentary record is lacustrine (Middleton and others, 1985), indicating that the basin was a sediment trap. The early drainage history of the western plain is poorly known, but fossils and the texture, lithology, and structure of the thick and fine-grained Miocene and Pliocene sediments suggest a complex lake system and accompanying flood plains into which much detritus was shed from the surrounding highlands by major streams (Malde, 1972; Smith and others, 1985; Middleton and others, 1985). Facies represent deep water, near shore, deltaic, beach, and stream environments. Except in times of major transgression, lake margins near tributory rivers probably retreated as deltas and flood plains prograded basinward. Beach and stream environments would have also prograded basinward if lake levels lowered.

A major unconformity separates the Miocene Chalk Hills Formation from the Pliocene Glenns Ferry Formation (Malde and Powers, 1962; Swirydczuk and others, 1982; Kimmel, 1982). Apparently, the cutting of the basin outlet allowed at least a partial draining of the lake. Downcutting in the Boise River drainage at this time may be represented by the depth of the ancestral canyon filled by the gravel of Bonneville Point.

The subsequent lake transgression, represented by the lower part of the Glenns Ferry Formation, probably began in response to continued subsidence in the basin and volcanism at the drainage outlet (Wheeler and Cook, 1954; Kimmel, 1982). At this time the western Snake River Plain probably drained through southeastern Oregon, northern Nevada, and northern California. The similarity of mammals in the Seven Devils and Wallowa Mountains suggests that no barrier, such as Hells Canyon, existed between these mountain ranges until the Quaternary (Cook and Larrison, 1954). Furthermore, faunal evidence from the Owyhee desert suggests that a barrier to species migration, such as an ancestral Snake River, existed in the Pliocene. Taylor (1960, 1985), using the distributions of fossil and relict mollusks and fishes, found biogeographic evidence for a Pliocene aquatic connection between the western Snake River Plain and northern California.

Sediment in the western plain continued to accumulate because of subsidence in the graben. In addition to the subsidence, drainage obstructions caused by volcanism in southeastern Oregon probably helped to maintain a relatively high, restricted outlet for water leaving the western plain (Kimmel, 1982). By 3.4 Ma, worldwide climate also began to change enough to cause cyclical variations in oceanic temperatures — the onset of peri-

[8] West of Caldwell, the burial of the Wilder and younger terraces by Bonneville Flood slack-water sediments has also decreased their gradients, because the thickness of the slack-water sediments increases westward, tending to flatten the downstream slope of the terrace. The actual surface of the Whitney terrace probably closely parallels that of the Boise River flood plain. The gradient of the buried surface of the Wilder terrace has not been measured, but judging from trends in the area, its slope probably is intermediate between that of the Deer Flat terrace and the Whitney terrace.

odically cooler climate that in the Pleistocene record correlates with continental glacier-ice accumulations (Schackleton and Opdyke, 1977; Loubere and Moss, 1986; Fullerton and Richmond, 1986). Fossil fish and predominantly clastic lake sediments indicate cool, fresh waters. Therefore, the Glenns Ferry transgression in part may have been a response to a change toward a cooler climate.

Malde (1972) attributed the three major sedimentary facies in the Glenns Ferry Formation to a diverse depositional environment that included a river, lakes, and broad flood plains. Kimmel (1982) and Smith and others (1982) suggested, however, that a large Glenns Ferry lake existed. They based their conclusions on studies of sections that are northwest of the area investigated by Malde, and they reinterpreted Malde's flood-plain facies as sands of a lake shoreface. The large lake hypothesis is supported, they argue, by correlations of lithologies and fossil fish and is consistent with the existence of a rift-valley lake (Smith and others, 1985). In addition, Smith and others (1982) recognized lake facies replaced by flood-plain facies prograding northwestward. They correlated sections that showed regressive beach deposits underlying flood-plain sediments near the center of the basin, and they attributed the change in depositional environment to a lowering of the lake level. Because they found a reduced number of fossil fish species, especially lake species, and many modern fish in the flood-plain sediments, they concluded the lake lowered in the early Pleistocene and suggested the regression marks the time of capture of western Snake River Plain waters as proposed by Wheeler and Cook (1954).

Most Glenns Ferry Formation sediments indicate deposition in an extensive lake system, but the view of a single transgression followed by a rapid regression and change to fluvial environments may be too simplistic. The complex interplay of depositional settings is demonstrated by the presence of flood-plain deposits throughout the Glenns Ferry Formation and by the transition of flood-plain facies into lacustrine deposits (Malde, 1972; Middleton and others, 1985). A complex paleogeographic history of the Glenns Ferry Formation seems likely and when better understood will reflect the interplay of subsidence, volcanism, and stream-sediment influx. The levels of lakes may vary for many reasons, and the replacement of lake environments by fluvial environments may be unrelated to base level changes. In any case, the youngest Glenns Ferry sediments were apparently deposited in a flood-plain environment, which, as described below, continued the process of basin filling.

The Glenns Ferry Formation exposed within the study area in the eastern bluffs of the Snake River valley mostly consists of flood-plain overbank deposits.[9] These predominantly fine-grained sediments appear to represent conformable aggradation. Laterally restricted river channel sand and gravel occur high in the section in several localities. The gravels were mapped by Wood and Anderson (1981) as Tuana Gravel where they are exposed on the eastern bluffs of the Snake River valley northwest of Lake Lowell. In more recent field examinations of these sections by H. E. Malde (written commun., 1987), he reinterpreted the gravels as intraformational channel deposits of the Glenns Ferry Formation. I found similar deposits and stratigraphic relationships at these localities and similar sections north and south of Marsing. I believe the deposits represent a single meandering channel. As observed by Wood and Anderson (1981), H. E. Malde, and myself, the suite of lithologies, and in particular the presence of tan quartzite pebbles, defines the channel as that of the ancestral Snake River.

Along the canyon rim of the eastern Snake River valley southeast of Lake Lowell, the flood-plain sediments are unconformably overlain by an alluvial gravel which is, in turn, conformably buried by a basalt flow. South of Marsing (outside the study area) exposures in bluffs show these basin-fill sediments truncated by fan gravels. The fan gravels probably grade to the level of the gravel underlying the basalt of Pickles Butte that forms the eastern rim of the Snake River valley. An argon-40/argon-39 date for that rim basalt is about 1.58 Ma.

In the bluffs north and northeast of Marsing, the Glenns Ferry Formation is overlain by coarse arkosic sand and coarse gravel of the Tenmile Gravel. Vertebrate fossils and reversed magnetic polarity suggest this part of the Glenns Ferry Formation is younger than the Olduvai Normal Polarity Subchron, that is, less than 1.76 Ma (Van Domelen and Rieck, 1992; Ted Weasma and Charles A. Repenning, oral and written commun., 1992-1993). The Glenns Ferry Formation and the Tenmile Gravel were deposited before the early Pleistocene Deer Flat terrace was cut and the Pickles Butte rim basalt was emplaced at 1.58 Ma. I am unaware of studies of fish fossils in these sections, but the sediments and fossil fish fauna from Guffey Butte[10] are described by

[9]Middleton and others (1985) believe the preponderance of overbank deposits in the fluvial facies of the Glenns Ferry Formation is best explained by the subsiding nature of the basin. In this setting, streams became relatively fixed in their channels and with frequent flooding and periods of subsidence, thick beds of silts and clays accumulated across the flood plain.

[10]Guffey Butte is outside the study area. It is located at the Snake River southwest of Walters Butte (Figure 9).

Smith and others (1982). They interpret them to be Pleistocene flood-plain deposits. The Guffey Butte deposits may correlate in part with the flood-plain sediments near Marsing.

At the end of this basin-filling episode in the western plain, possibly between 1.6 and 1.7 Ma, every major river emptying onto the western plain began to prograde coarse-braided channel gravel deposits across the broad, nearly flat surface of the plain. Remnants of these relatively high-elevation gravel deposits occur in many locations that border the valleys of the Snake, Boise, Owyhee, Payette, and Malheur rivers. The extent of the gravels indicate the once vast expanse of the surface at this level now greatly incised into wide terraced valleys and broad interfluves. For example, Tenmile terrace ranges in elevation from 818 meters (2,684 feet) near the Snake River to 990 meters (3,250 feet) at its eastern margin. Over the same distance, the Boise Valley bottomland ranges in elevation from 700 meters (2,296 feet) to 840 meters (2,755 feet). Approximate altitudes of these high gravels in the region range from 118 to 183 meters (390 to 600 feet) above the present rivers; that is, when the high gravels were deposited, river flood plains were at least 152 meters (500 feet) higher than present levels.

In the Boise Valley and adjacent areas, the Tenmile Gravel and probably the gravel cap of the Pierce Gulch Formation at the Boise Front represent this time of deposition. High gravel deposits with similar altitudes on the north side of the Payette River valley are probably correlative with the Tenmile Gravel. Remnants of other coarse gravels cap many ridge tops at elevations of about 845 meters (2,800 feet) in the western Snake River Plain of Oregon (Othberg, 1988).

Within the study area, only exposures in the Boise Front show clear evidence of Tertiary beach and shoreface lake deposits (Gallegos and others, 1987). Evidence for a large lake environment is less clear in sediments of the early Pleistocene upper part of the Glenns Ferry Formation. Evidence of aggradation in relatively low-energy environments predominates, however. Many sections coarsen at the top and culminate in the coarse gravels which were prograded across the plain. The gravels represent a dramatic change in stream regimens in which meandering stream and flood-plain overbank deposition was replaced by coarse-grained, braided-stream channel deposition. Subsequently, the aggradation of the basin was replaced by the episodic incision of valleys.

In the Boise Valley, the first known incision was at least 68 meters (223 feet) deep and established the alluvial level now represented by the Amity terrace and the Deer Flat terrace. This depth differs from that interpreted for the Snake River canyon upstream from the study area. Malde (1985, 1987, 1987, 1989, 1990, 1991) describes early Pleistocene canyon cutting of the Bruneau Formation in the southeastern part of the western Snake River Plain. In the first downcutting documented by Malde, the Snake River incised its valley about 190 meters (623 feet). This and subsequent canyon cutting occurred between 1 and 2 Ma, based on the potassium/argon age dates of Bruneau Formation basalts. Malde (1991) estimates that the Snake River valley was incised as much as 40 meters (131 feet) below the present river during the third canyon stage. He speculates that following the filling of the fourth canyon with basalt, the ancestral Snake River flowed north from Walters Butte to Nampa (Figure 15), depositing gravel and eroding some of the upland capped by the Tenmile Gravel. Thereafter, the Snake River was turned westward into the present channel.

The separate interpretations of the Bruneau canyon stages and of the terraces in the Boise Valley seem to be in conflict, assuming the Boise River was at grade with the Snake River. The Bruneau-age incision reported by Malde (1991) would require that the Boise Valley be cut at least as deep as the present river after the Tenmile terrace was formed but before the gravels of the Amity and Deer Flat terraces were deposited. However, no evidence for early Pleistocene incision below the level of those terraces has been found in the Boise Valley. Whereas the Snake River canyon apparently experienced dramatic changes in river levels during the early Pleistocene, the Boise Valley underwent episodic but incremental downcutting throughout the Pleistocene. Evidence to reconcile the separate interpretations might yet be found in geologic mapping, well logs, and geophysical data between Walters Butte and Nampa.

For the Boise Valley, the first incision into the basin fill began a pattern that continued throughout the Quaternary. Periodically, increased downcutting in Hells Canyon caused episodes of base-level lowering for the western Snake River Plain and, in turn, terraces to form in the Boise Valley. Times of more rapid downcutting in Hells Canyon may correlate with periods of glacial climates, which also caused the deposition of the gravels composing the terraces.

CAPTURE OF WESTERN SNAKE RIVER PLAIN DRAINAGE

Lindgren (1898a) recognized that basin filling was replaced by river entrenchment following the deposition of the Miocene and Pliocene sediments. He and Livingston (1928), however, thought the downcutting of lava dams brought the demise of the "lake." Livingston proposed that the outlet was through northeastern Oregon connecting northward through the Grande Ronde River. Wheeler and Cook (1954) argued that the Grande Ronde route was unlikely. They proposed that the western Snake River Plain drainage connected with the Columbia River basin through capture near the Oxbow of the Snake River in Hells Canyon. Using remnants of old erosion surfaces above 915 meters (3,000 feet) in elevation and stream-course patterns in Hells Canyon, they suggested that a tributary of the Salmon River eroded headward, south toward the western plain, first cutting northern Hells Canyon and then capturing south-flowing streams. This process, they believed, best explained the presence of the barbed tributaries to the Snake River in southern Hells Canyon, the formation of the Oxbow, and the apparent drainage reversal of Pine Creek near the Oxbow. They submitted that the rising "Idaho Lake" level in the late Pliocene or early Pleistocene spilled across the divide. The downcutting of the outlet then lowered the lake and diverted the entire drainage of the Snake River northward into the Columbia River basin.

Cook and Larrison (1954) altered the idea. They associated the diversion of western plain waters northward with the presence of high gravels resting on fine-grained sediments, and suggested that the gravels were deposited during a "pre-Wisconsin glacial age."

Malde (1985, 1987, 1991) argued that the capture and initial incision at Hells Canyon coincided with the deposition of the Tuana and Tenmile Gravels. In his view, the change to a high-energy drainage system represented by those formations was a response to downcutting. Malde (1991, p. 253) wrote:

> [W]*hen compared with underlying fine-grained deposits, these gravels clearly represent a high-energy drainage system, graded to an unobstructed outlet — presumably Hells Canyon. . . .* [B]*oth* [the Tuana and Tenmile Gravels] *appear to be graded to a base level below the inferred level of spillover at the head of Hells Canyon.*

He asserted that downcutting must have been underway during the deposition of the Tuana and Tenmile Gravels.

In my studies on the Tenmile Gravel and other high gravel deposits that may be correlative (Othberg, 1988), the streams depositing these coarse sediments show little or no evidence of valley incision. For example, the Tenmile Gravel in the western Boise Valley caps sections that coarsen upward from greenish gray silts of the Glenns Ferry Formation to coarse arkosic sands and then to the Tenmile Gravel. The character of these upper Glenns Ferry Formation sediments represents aggradation, but not necessarily impoundment. In addition, the gravel channel facies of the Glenns Ferry Formation indicate a through-flowing stream. The presence of the Tenmile Gravel overlying these flood-plain sediments suggests an increase in stream discharge and bed load — alterations from the source areas in the mountains. The direct result of a lowered base level at Hells Canyon would have been progressive incision headward by each stream course, that is, degradation, not aggradation.

The change to the widespread deposition of gravel represents an increase in the grain size of stream bed loads and a change to braided channels. These hydraulic alterations must have been a function of discharge and the availability of coarse detritus in the upper parts of the drainage basin. Given a late Pliocene to early Pleistocene timing of this change in stream regimen, the cause is likely the increased snow packs, the higher peak-discharge runoffs from the snowmelt, and the advance and retreat of glacier ice in the mountains.

Othberg (1988), like Cook and Larrison (1954), suggested that the capture of western Snake River Plain waters coincided with a glacial climate that produced a change in stream regimen and facilitated capture. I now believe evidence from the Boise Valley cannot prove that capture occurred then, only that the first major incision took place after the Glenns Ferry Formation was deposited. Drainage may have already occurred from the western plain through Hells Canyon, but deep, rapid downcutting happened later, probably coincident with a glacial climate that produced high-energy streams.

I have tried to separate the evidence of the basin's incision from the concept of capture through Hells Canyon. As I suggested earlier (Othberg, 1988), documenting a changeover from basin filling to incision in the western Snake River Plain seems more fruitful than evaluating whether a lake spilled across a divide into the predecessor of Hells Canyon. Accordingly, the first effective downcutting in the Boise Valley in response to the erosion of the Hells Canyon outlet occurred not only after Glenns Ferry time but also after late Tenmile

Gravel time. This interpretation requires that incision started near the Pliocene-Pleistocene boundary.

It may be reasonable to envision both a Glenns Ferry lake spillover and draining and a later beginning to the effective downcutting of Hells Canyon. Such a capture may have occurred as Wheeler and Cook (1954) and Smith and others (1982) perceived it, that is, at the end of a transgression followed by a rapid regression. A change in the drainage-basin connection is further suggested by changes in fossil fish assemblages within the upper Glenns Ferry Formation (Smith and others, 1982). If drainage diversion occurred in Glenns Ferry time, then a more complex geomorphic interpretation may be required. This idea may involve capture followed by the draining of a large lake slowly enough to allow wave action to generate the regressive beach deposits. If an outlet was achieved but flood-plain aggradation in the center of the basin continued, then perhaps the erosion of a threshold in Hells Canyon may not have been sufficiently deep to cause an incision of the lowest reaches of the subsiding basin.

TERRACES AND THE SEQUENCE OF INCISION OF THE BOISE VALLEY

Basin aggradation probably gave way to valley cutting in the early Pleistocene. Terraces and their remnants provide the evidence for the history of incision. Every major river valley in the western Snake River Plain is terraced, but no other valley equals the Boise Valley in preserving this geomorphic record. The record is more complete not only in the numbers of terraces (Table 3) but also in the length of time represented by those landforms. Age controls suggest a record of incision throughout the Pleistocene. The terraces are well presered because the basalt lava flows have protected the buried alluvial surfaces from erosion. The lavas diverted the Boise River northward, forcing it to cut new valleys. Structure also guided the Boise River from an originally single westward segment to today's three-segment course of northwest through Boise, west to Caldwell, and northwest to the Snake River (Figure 2).

Multiple terraces in the Boise Valley record successively lower and younger levels of former alluvial surfaces of the Boise River. Evidence from roadcuts, exposures in gravel pits, and well drillers' logs shows that each terrace and the river flood plain consist of a river-cut surface with an accumulation of coarse gravel. In forming the alluvial surfaces represented by each terrace, the Boise River cut down into the basin fill sediments. Several meters of gravel buried each cut surface through braided-channel deposition. Both the downcutting and the gravel deposition were accomplished at times of very high discharge in the river.

Downcutting followed by gravel deposition was a process that operated periodically throughout the Pleistocene in valleys carrying glacial meltwaters. This process apparently was tied to the timing of an increase in the sustained peak discharge of rivers and the availability of coarse gravel in source areas. These characteristics suggest terracing was in phase with, and caused by, the climatic processes responsible for glaciations (Figure 8).

The terrace sequence in the Boise Valley is best preserved southwest of Boise (Figures 22 and 26). The sequence there, in decreasing age, is the Tenmile terrace, the Amity terrace, the Fivemile Creek surface, the Lucky Peak surface, the Gowen terrace, the Sunrise terrace, the Whitney terrace, the Boise terrace, and the bottomland of the Boise River. Although faulting especially disrupts these surfaces in the area of Tenmile Creek (near the west border of the illustration in Figure 26), the stratigraphic relationships suggest that the Amity terrace is the first in the incising sequence. I tentatively correlate the Amity terrace with the Deer Flat terrace on the basis of stratigraphic positions and elevations. The Deer Flat terrace also appears to represent the first record of an alluvial level formed after major incision by the Boise River. The argon-40/argon-39 date of about 1.58 Ma from the valley-rim basalt of Pickles Butte provides a minimum age for this period of incision.

The ages of the remaining terraces in the sequence are also based on radiometric dates from basalt lavas that flowed onto former alluvial surfaces of the Boise River. The date of about 974 ka for the basalt of Fivemile Creek provides an age for the alluvial surface it buries. Hyaloclastite at the base of the flow near Interstate-84 suggests that the lava erupted onto an active flood plain. This evidence indicates a similar age for the alluvial surface. The flood plain probably formed during the Jaramillo Normal Polarity Subchron, 1.05-0.98 ka (Figure 9).

The next terrace below the Fivemile Creek surface southwest of Boise is the Gowen terrace (Figures 22, 26, and 28). But in the sequence near Lucky Peak Lake, the Lucky Peak surface occurs stratigraphically between the Fivemile Creek surface and the Gowen terrace (Figure 18). The normal magnetic polarity of the basalt of Lucky Peak suggests an age less than 780 ka. The age of the Lucky Peak surface probably is between that of the Gowen terrace and 780 ka (Figure 9).

The age of the Gowen terrace is based on potassium/argon date for the basalt that buries a few miles of the eastern extent of the terrace. The age of 572 ka for the lava is consistent with its normal magnetic polarity (Brunhes Normal Polarity Chron) and indicates the surface formed in the middle middle Pleistocene (Figure 8).

The age of the Sunrise terrace is poorly constrained. No lava flows provide age control for this surface. Its age is bracketed only by the older Gowen terrace and the younger Whitney terrace. The Wilder terrace may correlate with the Sunrise terrace based on soil characteristics exposed beneath the Bonneville Flood sediments that bury the Wilder terrace.

The Whitney terrace is an extensive, well-preserved surface. It is younger than the Sunrise and Gowen terraces (less than about 572 ka) and probably is somewhat older than the basalt of Mores Creek (100 ka). Based on the lack of erosion of its surface and the degree of soil development, its age is late middle Pleistocene (Figure 8).

Field relationships demonstrate that the Whitney terrace existed before the Bonneville Flood, but the relationship of the Boise terrace to the Bonneville Flood is less clear. Field investigations show that, like the Whitney terrace, the Boise terrace may have been scoured by late Bonneville Flood waters near the course of the Snake River. Clear evidence of the laminated silts and fine sands that characterize the slack-water sediments overlying the Whitney and Wilder terraces is lacking in exposures of the Boise terrace surface sediments. A clay deposit, however, which may be a slack-water deposit, extends upstream in the Boise Valley to Caldwell. Because soil developed to a greater degree on the Boise terrace and neither the clay nor the laminated silt and fine sand deposits occur on the current flood plain, the Boise terrace was probably the active level of the Boise River at the onset of the Bonneville Flood. If so, then the Boise terrace represents the level of the Boise River during the late Wisconsin glaciation (Figure 8).

Pierce and Scott (1982) suggested that the climate during the Holocene may have been too moderate to greatly modify Pleistocene alluvial fans. An analogous situation may exist for the Boise River valley in that during the last 10,000 years the Boise River has modified its valley very little when compared to the evidence of downcutting and gravel deposition represented by the terraces. Moreover, at times of similar nonglacial climate in the past, the Boise River would likely have accomplished little modification of its valley. If downcutting and gravel deposition depend on glacial climates, then the Boise Valley terraces probably correlate with times of glaciation in the central mountains of Idaho — the source area of the Boise River.

POSSIBLE CORRELATIONS WITH GLACIAL EVENTS

In areas where terraces can be traced upstream to moraines, the one may be easily correlated with the other. Unfortunately, remnants of terraces typically are scarce where rivers follow canyons in mountains. Terraces of the Boise Valley have not been traced upstream from Lucky Peak Lake. Nonetheless, a case can be made for correlating gravel deposits and terraces in the western Snake River Plain to glacial episodes in the headwater areas.

Three characteristics suggest the Boise Valley terraces formed in response to changes in climate rather than changes in base level. First, there is an apparent periodicity to the terrace sequence. Second, an erosive event is paired with a depositional event in the construction of each alluvial surface represented by a terrace. And third, each terrace is composed of crude beds of coarse sandy gravel with lenses and tongues of coarse sand. These observations suggest that each terrace represents a replay in the Boise River's changes in discharge and load. A straightforward explanation for the sequence of terraces in the Boise Valley would seem to be related to the known pattern of glacial and interglacial cycles during the Quaternary (Figure 8). Each terrace may have formed in response to factors induced by glacial climates coupled with an adjustment of the base level which was controlled by episodic incision in Hells Canyon.

PROBLEMS WITH CORRELATING FLUVIAL AND GLACIAL STRATIGRAPHY

Baker (1983) reviewed the problems in analyzing late Pleistocene fluvial systems. During the last full glacial event in the United States, apparently an erratic pattern of wetter and drier conditions existed, even though the pattern of decreasing temperature was consistent (Peterson and others, 1979). This pattern of climate was in part due to the complex ways fluvial systems can respond to external change (Schumm, 1977). Flint (1976) questioned fluvial evidence for climatic change, because of the possibility of tectonic complications. The larger the river system, the more difficult it is to "pinpoint a climatic versus a tectonic cause of the observational data. . . . A specific hypothesis of climatic causes is justified only where all other influences can be eliminated" (Flint, 1976, p. 527). In addition to climate, base level, and tectonic changes, other conditions that may produce terracing are stream capture (Ritter, 1967) and the removal of outwash and alluvium stored in the upper reaches of valleys (Baker, 1983).

Evidence of stream gradation, including terraces and terrace deposits, has been used by some geologists to infer changes in climate. Yet, scientists disagree about the meaning of the evidence. Some maintain that aggradation implies decreasing runoff, whereas others conclude that Pleistocene aggradation occurred during increased runoff. Furthermore, coarse gravel texture has been cited as evidence for wetter climate, but that conclusion has been criticized by Morrison (1968). Diverse interpretations also exist in the correlation of stream aggradation and erosion in relation to glacial and interglacial cycles. Morrison found little agreement among researchers. He noted (Morrison, 1968, p. 79, Figure 5):

> *Some of the apparent differences in correlations between the various areas are due to varying interpretations as to which horizons in given stratigraphic records mark (or correlate with) the beginning, maximum, and ending of a glaciation or interglaciation; also, some interpretations pertain to a simple glacial-interglacial cycle, others . . . to such a cycle complicated by an interstadial.*

Morrison (1968, p. 37) quoted a more optimistic statement by Butzer (1963):

> [W]*herever tectonic factors can be discounted it is the sediment rather than the erosional form that is more elucidating. . . .* [I]*t is certainly possible to determine whether transporting capacity was greater or smaller than that of today, and very often possible to suggest whether a contemporary stream belongs to the same hydrologic class as it did in the past.*

REGIONAL EVIDENCE FOR CORRELATING FLUVIAL AND GLACIAL STRATIGRAPHY

Pleistocene proglacial fluvial landforms developed along almost all glacial margins. When compared with the interglacial conditions of today, the extensive proglacial fluvial deposits leave little doubt that much more coarse sediment was deposited in the large Pleistocene outwash trains and outwash plains. Examples of well-studied areas showing cause and effect relationships between glaciation and fluvial landforms include the Big Horn Basin (Moss, 1974), Yellowstone National Park (Pierce, 1979), the Madison Range (Schneider, 1990; Ritter and others, 1990), south-central and southeastern Idaho (Scott, 1982; Pierce and Scott, 1982), the Rocky Mountain Trench, southeastern British Columbia (Clague, 1975), the eastern Cascade Mountains (Porter, 1976; Waitt, 1977, 1979), and southwestern British Columbia (Church and Ryder, 1972). East of the Rocky Mountains, the pattern with respect to the Laurentide ice sheet was similar in the development of prominent glaciofluvial terraces (Baker, 1983). The Mississippi River became the proglacial drainage system for the Laurentide ice sheet producing evidence of increased fresh water flow in the sediments of the Gulf of Mexico (Baker, 1983; Kennett and Shackleton, 1975). Cooler climate during full glacial events (CLIMAP Project Members, 1976) also produced changes in alluvial fan deposition, typically from "dry" fans to "wet" fans (Schumm, 1977; Brakenridge, 1978; Pierce and Scott, 1982). The changes in fan deposition can be attributed to an annual cooling of 7°-8°C in the American Southwest (Brakenridge, 1978) and as much as 10°-15°C in southeastern Idaho (Pierce and Scott, 1982).

Rates of higher incision during glacial events were documented by Foley (1980) for a river diverted by a glacial piedmont lobe in west-central Montana. Incision has continued to the present since diversion, but the rate of downcutting was fourteen times greater during Pinedale stades[11] (Wisconsin) than during interstades or at the present time.

Studies of modern proglacial systems also indicate a direct relationship between glacial processes and increased stream power. This is shown by a tendency for braided channels and by the long profiles of proglacial streams, which are steep and concave upward due to persistent aggradation. Stream regimen is governed by early summer flooding; moderate floods are common and glacial outburst floods (jökulhlaups) are always a potentiality (Church and Gilbert, 1975).

Pierce and Scott's (1982) detailed study of alluvial-gravel deposition in southeastern Idaho provides an argument for a direct relationship between lowered average annual temperatures and periods of increased gravel deposition on both alluvial fans and mainstream terraces. Pierce and Scott found increased deposition on alluvial fans similar in both glaciated and unglaci-

[11]In Rocky Mountain glacial terminology, the stades of the Pinedale glaciation correlate with the Wisconsin glaciation, and the Bull Lake glaciation correlates broadly with the Illinoian glaciation (Richmond and Fullerton, 1986).

ated drainages and concluded that "climatic effects other than glaciation itself were of major importance" (Pierce and Scott, 1982, p. 698). The textures, fabrics, and bedding of the gravels suggest deposition by streams with "sustained seasonal flows probably at least ten times larger than discharges of present streams" (Pierce and Scott, 1982, p. 685). Pierce and Scott hypothesized that three factors caused the increased discharges: (1) thicker cold-season snowpacks caused by mean annual temperatures 10°-15°C colder, (2) a later and more vigorous seasonal runoff, and (3) greater surface runoff. In addition to more coarse debris contributed by glaciers, the periglacial conditions of the Pleistocene also produced a greater supply of gravel to streams. The increase in gravel supply was important not only in the high source areas, where glacier accumulation occurred, but also in the intermediate altitudes where snowpacks accumulated to depths greater than in today's climate. Rapidly melting snow in the intermediate altitudes probably caused great floods in June followed in late summer by additional floods of meltwater from the glaciated areas.

Pierce and Scott (1982, p. 699) concluded from the evidence in Idaho

> *that maximum sediment supply and sediment and water discharges* [were] *directly associated with full glacial conditions* . . . [and that] *annual snowmelt, not the effects of deglaciation, was the key ingredient causing higher sediment and water discharges.*

Ritter and others (1990) found direct relationships between glaciation and deposition of gravel on the Cedar Creek alluvial fan in the Madison Valley of southwest Montana. They concluded that stream transport capacity and sediment discharge increased to the maximum during glacial periods because of the increased seasonal meltwater discharge and the availability of glacially eroded debris. They were unable to determine an exact association of aggradation on the fan with advancing, stationary, or retreating ice.

Schneider (1990) studied the Madison River terraces. He concluded the higher terrace deposits formed during periods of glacial aggradation common to the region during the Pleistocene. The periods of incision that created the terraces probably relate to complex variables controlling base level such as tectonic movements, drainage capture, the erosion history of varied lithologies as well as the sediment load and discharge changes associated with glaciation. The highest terrace in the Madison Valley represents a maximum level of fill during the Pleistocene, and it probably formed just before or with the onset of Bull Lake glaciation. Schneider (1990, p.46) further concluded that although the initial Pleistocene base level change for the Madison Valley induced incision and sediment excavation, "the rate of incision was muted by the large influx of sediment associated with the Bull Lake glacial condition." With the decrease in sedimentation following the Bull Lake glaciation, incision resumed until the next major glacial aggradation during Pinedale time.

GLACIAL CLIMATE CORRELATIONS FOR BOISE VALLEY TERRACES

If glacial climates caused alluvial terraces and fans to form in nearby areas, then the Boise River drainage basin probably experienced similar effects. Because it drains both high elevation, glaciated source areas and extensive intermediate elevation mountainous terrain, the Boise River must have been subjected to sustained peak discharges that possibly were at least ten times greater than observed today. In addition, the base level for the western Snake River Plain that further controlled the aggradation and degradation of valleys was lowered episodically. This lowering may be explained by episodic uplift in the Hells Canyon area or by varied rates of downcutting due to a climate-controlled modulation in discharge, or both. Active Quaternary uplift cannot be ruled out in the Hells Canyon area. But if uplift were occurring, why is evidence lacking of Quaternary fine-sediment aggradation just upstream from the uplifted area? By contrast, the Quaternary evidence indicates episodic downcutting followed by temporary coarse-gravel deposition. Evidence of a restricted outlet, possibly due to tectonic causes, including continued subsidence in the western Snake River Plain, is present in the fine-grained sediments of the pre-Quaternary Glenns Ferry Formation. The longitudinal profile of the Snake River indicates the river has yet to adjust its grade. As Wheeler and Cook (1954) suggested, the nick point near the Oxbow of the Snake River could be inherited from the gradients existing at the time of the northward diversion of western Snake River Plain drainage.

It seems reasonable to believe that accelerated downcutting in Hells Canyon varied considerably over time and that the periods of greatest downcutting occurred when sustained peak stream flows were much higher than today. During these periods of high discharge, there would have been a delay in the transport of gravel to the downstream reaches of the Boise River in the western Snake River Plain. The alluvial fans described by Pierce and Scott (1982) probably responded more rapidly to climate change, so that gravel deposition on the fans appears synchronous with the onset of the glacial climate. In the western plain, and especially in Hells Canyon, the sustained early- to mid-summer peak flood flows, perhaps ten times greater than the seasonal flood discharges of today, would have had a synchronous effect, but the movement of sediment from the mountain source areas into the lower Boise River and into the Snake River would have been delayed.

The immediate response of the Boise River (and the Snake River in Hells Canyon) would have been the scouring and downcutting of channels at times of greater discharge. Subsequently, the coarse-gravel bed load from the mountains would have been transported onto the western Snake River Plain, aggrading the valley and steepening the longitudinal profile of the river as the efficiency of braided channels to carry coarse gravel was maintained. Deposition then would have continued until the seasonal flood discharges diminished to lower levels.

In my correlations of Boise Valley terraces with glaciations and oxygen isotope cold stages, I use the time divisions and ages of oxygen isotope stages shown in Figure 8. Absolute age-correlation of any one terrace with any one glaciation, in the absence of precise age control, is impossible. A glacial climate origin for the Boise Valley terraces, however, suggests correlation with glaciations and oxygen isotope cold stages. The terrace record, like the glacial record, almost surely is incomplete. Correlating terraces may involve multiple possible glaciations and oxygen isotope cold stages, and, in some places, terraces may correlate with cold stages for which there is no identified record of glaciations. Figure 33 shows my correlations of Boise Valley terraces to glaciations and oxygen isotope cold stages as described in the following text.

The age of the Tenmile terrace is bracketed by the argon-40/argon-39 date of 1.58 Ma for the valley-rim basalt of Pickles Butte and the age of the "Chalk Hills" section of the Glenns Ferry Formation, which probably is younger than 1.76 Ma. The Tenmile terrace may date to oxygen isotope cold stage 60 or 62 and may correlate with pre-Illinoian glaciation I.

The Amity terrace predates the basalt of Hubbard Reservoir by an unknown amount. It may predate the Kuna City lava flow, which has an argon-40/argon-39 date of about 1.376 Ma. The Deer Flat terrace may correlate with the terrace buried by the basalt of Pickles Butte, dated at about 1.58 Ma. The Deer Flat terrace may correlate with pre-Illinoian glaciation H and oxygen isotope cold stages 50-54.

The basalts of Fivemile Creek and Hubbard Reservoir have normal polarity, and the precision limits of their potassium/argon dates span the Jaramillo Normal Polarity Subchron. The basalt of Slaters Flat, which rests on a surface cut into the Tenmile Gravel at a similar level as the Fivemile Creek surface, also has normal polarity. The precision range of its date also encompasses the Jaramillo Normal Polarity Subchron. These three dates on normal-polarity basalts suggest ages within the Jaramillo Subchron. Soils on the basalt of Fivemile Creek are about as highly developed as those found on Amity terrace, Deer Flat terrace, and Tenmile terrace. This indicates an age much greater, not closer, to that of the Gowen terrace and further argues against an age within the Brunhes Normal Polarity Chron. In addition, the basalt of Fivemile Creek erupted onto an active flood plain. Therefore, the Fivemile Creek surface is between 0.98 and 1.05 Ma. These data correspond to oxygen isotope cold stages 28 and 30, which have no identified glaciation counterparts in the United States.

The Lucky Peak surface is stratigraphically older than the Gowen terrace but must be less than 780 ka because the associated lava flow has normal polarity. The Lucky Peak surface tentatively correlates with either the pre-Illinoian D or the pre-Illinoian E glaciation (oxygen isotope stage 16 or 18).

The potassium/argon date for the basalt of Gowen terrace has a large range in precision (0.575 ± 0.21 Ma). It encompasses the ages of four pre-Illinoian glaciations, B-E, (oxygen isotope cold stages 12-18). I suggest the Gowen terrace is in either the pre-Illinoian B or the pre-Illinoian C glaciation (oxygen isotope stage 12 or 14).

The Sunrise terrace lacks radiometric dates that can help constrain any correlation. The soil characteristics are intermediate in development to the soils on the Whitney terrace and the Gowen terrace. The Sunrise terrace tentatively correlates with either the early Illinoian or the pre-Illinoian A glaciation (oxygen isotope stage 8 or 10).

The Whitney terrace is extensive and has soils with initial duripan development. The alluvial surface of the terrace is everywhere buried by loess except near the Snake River, where it was stripped by the Bonneville Flood. Where the terrace received slack-water sediments of the Bonneville Flood, the buried loess is thick and reveals more than one period of deposition separated by minor soil development. The Whitney terrace is older than the basalt of Mores Creek, which is dated

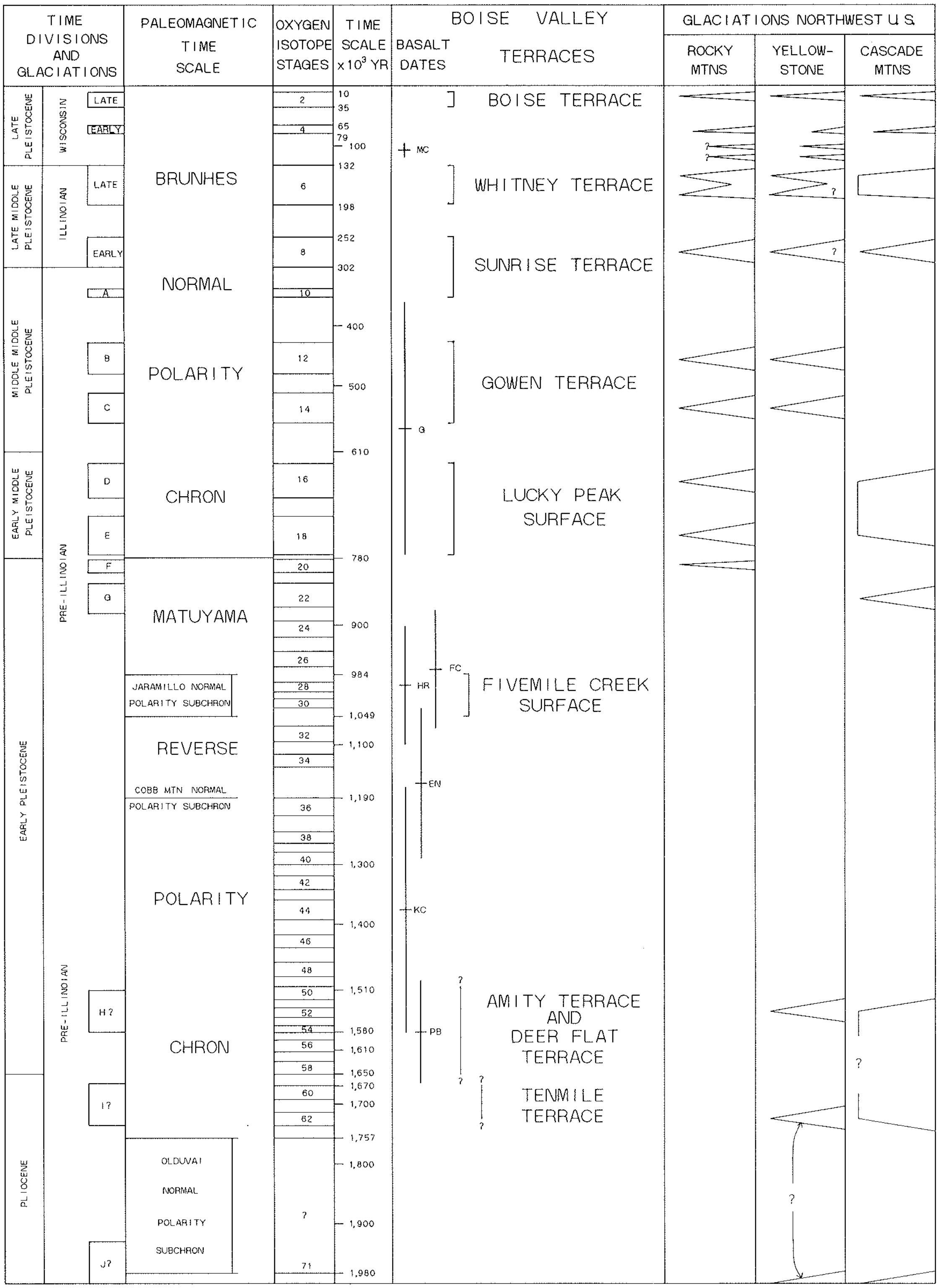

Figure 33. Correlation of Boise Valley terraces with the glaciations of the northwestern United States and the marine oxygen-isotope cold stages as adapted from Richmond and Fullerton (1986, Chart 1), Ruddiman and others (1986), Shackleton and others (1990), and Cande and Kent (1992). Abbreviations for basalt units: MC, Mores Creek; G, Gowen terrace; FC, Fivemile Creek; HR, Hubbard Reservoir; EN, East Nampa; KC, Kuna City; PB, Pickles Butte.

at about 100 ka. For all of these reasons, the Whitney terrace correlates with the late Illinoian glaciation (oxygen isotope stage 6). In Rocky Mountain glacial terminology, the Whitney terrace correlates with the Bull Lake glaciation.

The Boise terrace may correspond with the late Wisconsin glaciation (oxygen isotope stage 2) because of the weak calcic soil development, the scour by the Bonneville Flood near the Snake River, and the presence of Bonneville Flood slack-water sediments on the terrace. In Rocky Mountain glacial terminology, the Boise terrace correlates with the late Pinedale glaciation.

Judging from the character of the flood-plain channel deposits, the Holocene Boise River probably was capable of moving coarse gravel debris. Evidence of the Pleistocene periglacial processes that generated excessive coarse sediment is visible in the source areas in the form of stored colluvium and outwash (Pierce and Scott, 1982; Othberg, 1982a, 1982b, 1982c). These accumulations are prone to removal and transport during rare storm events and unusual snowmelt runoff. In addition, during the Holocene, Neoglacial conditions may have in part mimicked the full glacial climate and produced higher discharges than seen today.

The Bonneville Flood, which occurred during the last glaciation, must have greatly augmented the erosion of Hells Canyon. If the active river was at the level of the Boise terrace at the time of the Bonneville Flood, was there degradation or aggradation in the valley? Being the unique event in the history of the Snake River and its tributaries, the Bonneville Flood left a singular effect on the river system's grade at the end of the last glaciation. The cut surface at the base of the Boise terrace may mark the late Wisconsin, oxygen isotope stage 2 period of rapid downcutting, whereas the cut surface underlying the gravels of the current Boise and Snake River flood plains may mark the period of rapid incision during the time of the Lake Bonneville outlet into the Snake River drainage. If so, then the current flood plain may be filled primarily with post-Bonneville Flood, late-glacial gravels, and the Boise River has altered these deposits only by relatively minor changes in its channel.

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