Geologic Ages and Accumulation Rates of Basalt-Flow Groups and Sedimentary Interbeds in Selected Wells at the Idaho National Engineering Laboratory, Idaho

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By S.R. Anderson, Michael J. Liszewski, and L. DeWayne Cecil

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
foot (ft)	0.3048	meter
mile (mi)	1.6094	kilometer
square mile (mi^2)	2.590	square kilometer

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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Abstract

Geologic ages and accumulation rates, estimated from regressions, were used to evaluate measured ages and interpreted stratigraphic and structural relations of basalt and sediment in the unsaturated zone and the Snake River Plain aquifer at the Idaho National Engineering Laboratory (INEL) in eastern Idaho. Geologic ages and accumulation rates were estimated from standard linear regressions of 21 mean potassium-argon (K-Ar) ages, selected mean paleomagnetic ages, and cumulative depths of a composite stratigraphic section composed of complete intervals of basalt and sediment that were deposited in areas of past maximum subsidence. Accumulation rates also were estimated from regressions of stratigraphic intervals in three wells in and adjacent to an area of interpreted uplift at and near the Idaho Chemical Processing Plant (ICPP) and the Test Reactor Area (TRA) to allow a comparison of rates in areas of past uplift and subsidence.

Estimated geologic ages range from about 200 thousand to 1.8 million years before present and are reasonable approximations for the interval of basalt and sediment above the effective base of the aquifer, based on reported uncertainties of corresponding measured ages. Estimated ages between 200 and 800 thousand years are within the range of reported uncertainties for all 15 K-Ar ages used in regressions and two out of three argon-argon (^{40}Ar/^{39}Ar) ages of duplicate samples. Two sets of estimated ages between 800 thousand and 1.8 million years are within the range of reported uncertainties for all seven K-Ar ages used in regressions, which include one shared age of about 800 thousand years. Two sets of ages were estimated for this interval because

K-Ar ages make up two populations that agree with previous (1979) and revised (1995) ages of three paleomagnetic subchrons. The youngest set of ages is consistent with a K-Ar age from the effective base of the aquifer that agrees with previous (1979) ages of the Olduvai Normal-Polarity Subchron. The oldest set of ages is consistent with an ^{40}Ar/^{39}Ar age of the same basalt flow that agrees with revised (1995) ages of the Olduvai Subchron. Regressions indicate that measured ages and stratigraphic interpretations are reasonable for basalt and sediment between the ages of 200 and 800 thousand years, the youngest deposits that could be evaluated using regressions. Regressions indicate potential errors in measured ages or stratigraphic interpretations for basalt and sediment between the ages of 800 thousand to 1.8 million years, the oldest deposits in the aquifer. Ages of older basalt flows in the aquifer are difficult to measure because many flows are altered. Stratigraphic relations of older basalt and sediment in the aquifer are difficult to determine because there are few cored intervals of this age.

Accumulation rates, estimated from regressions of stratigraphic intervals younger than 640 thousand years in three wells in and adjacent to an area of interpreted uplift at and near the ICPP and TRA, range from 59 to 282 feet/100,000 years and average 163 feet/100,000 years, a rate that is nearly identical to a previous (1994) estimate of the subsidence rate between the INEL and the Yellowstone Plateau during the past 4 million years, about 164 feet/100,000 years. Accumulation rates estimated from regressions of the composite stratigraphic section, which is made up of stratigraphic intervals deposited in many areas of past subsidence for periods ranging from 200 to 700 thousand years during the past 1.8 million

years, range from 171 to 270 feet/100,000 years and average 218 feet/100,000 years, a rate that is 33 percent greater than the previous (1994) estimated subsidence rate. Although average accumulation rates in wells at and near the ICPP and TRA agree with the previous (1994) estimated subsidence rate, these rates include two apparent rates that are a relative measure of the difference between past rates of contemporaneous subsidence and uplift, based on deep drill-hole data. The best estimates of past subsidence rates range from about 160 to 280 feet/100,000 years and average about 220 feet/100,000 years, based on the previous (1994) estimated subsidence rate and accumulation rates unaffected by differential subsidence or uplift. Estimated subsidence rates averaged about 192 feet/100,000 years and were much greater than accumulation rates during the past 200 thousand years, a period of greatly reduced volcanism. This interruption in basalt accumulation, which is unlike that of earlier periods and continues to the present day, includes most areas of the INEL.

INTRODUCTION

The Idaho National Engineering Laboratory (INEL) is operated by the U.S. Department of Energy (DOE) and covers about 890 mi^2 of the eastern Snake River Plain in eastern Idaho (fig. 1). Facilities at the INEL are used in the development of peacetime atomic-energy applications, nuclear-safety research, defense programs, and advanced energy concepts. Liquid radionuclide and chemical wastes generated at these facilities have been discharged to onsite infiltration ponds and disposal wells since 1952. Liquid-waste disposal has resulted in detectable concentrations of several waste constituents in water from the Snake River Plain aquifer underlying the INEL (Bartholomay and others, 1995).

Concern about the potential for migration of radioactive and chemical wastes in the unsaturated zone and aquifer has resulted in numerous studies of the subsurface at the INEL. In 1988, the U.S. Geological Survey (USGS) in cooperation with the DOE, began a site-wide study of the stratigraphy of basalt and sediment underlying the INEL to determine stratigraphic relations that

might affect the movement of wastes. Three earlier reports, Anderson and Lewis (1989), Anderson (1991), and Anderson and Bowers (1995), describe stratigraphic relations and their implications regarding the movement of waste at the Radioactive Waste Management Complex (RWMC), the Idaho Chemical Processing Plant (ICPP), the Test Reactor Area (TRA), and Test Area North (TAN) (fig. 1). A fourth report, Anderson and others (1996a), describes stratigraphic relations in 333 wells at and near the INEL that include revised relations for the RWMC, ICPP, TRA, and TAN. Each of these reports describes measured and estimated ages of selected basalt-flow groups and sedimentary interbeds in the unsaturated zone and aquifer. Estimated ages reported by Anderson and others (1996a) were determined from linear accumulation rates in selected wells, and were used to evaluate measured geologic ages with respect to their position in a composite stratigraphic section.

Measured ages must be evaluated with respect to estimated stratigraphic ages because ages have been measured for relatively few stratigraphic units, many of them have large associated uncertainties, and some do not agree with ages suggested or required by paleomagnetic, petrographic, chemical, or geophysical-log data. Comparisons of measured ages to ages estimated from accumulation rates are useful because they allow an integrated evaluation of ages and stratigraphy. These comparisons also allow an evaluation of structural interpretations, which at the INEL include subsidence (Anderson and Bowers, 1995; Smith and others, 1994) and uplift (Anderson and Bowers, 1995; Anderson, 1991).

Purpose and Scope

This report describes a range of estimated geologic ages and accumulation rates that are used to evaluate reported measured geologic ages and interpreted stratigraphic and structural relations of basalt and sediment in the unsaturated zone and the Snake River Plain aquifer at the INEL. Ages and maximum accumulation rates are estimated from standard linear regressions of selected mean potassium-argon (K-Ar) ages, selected mean paleomagnetic ages, and cumulative depths of a
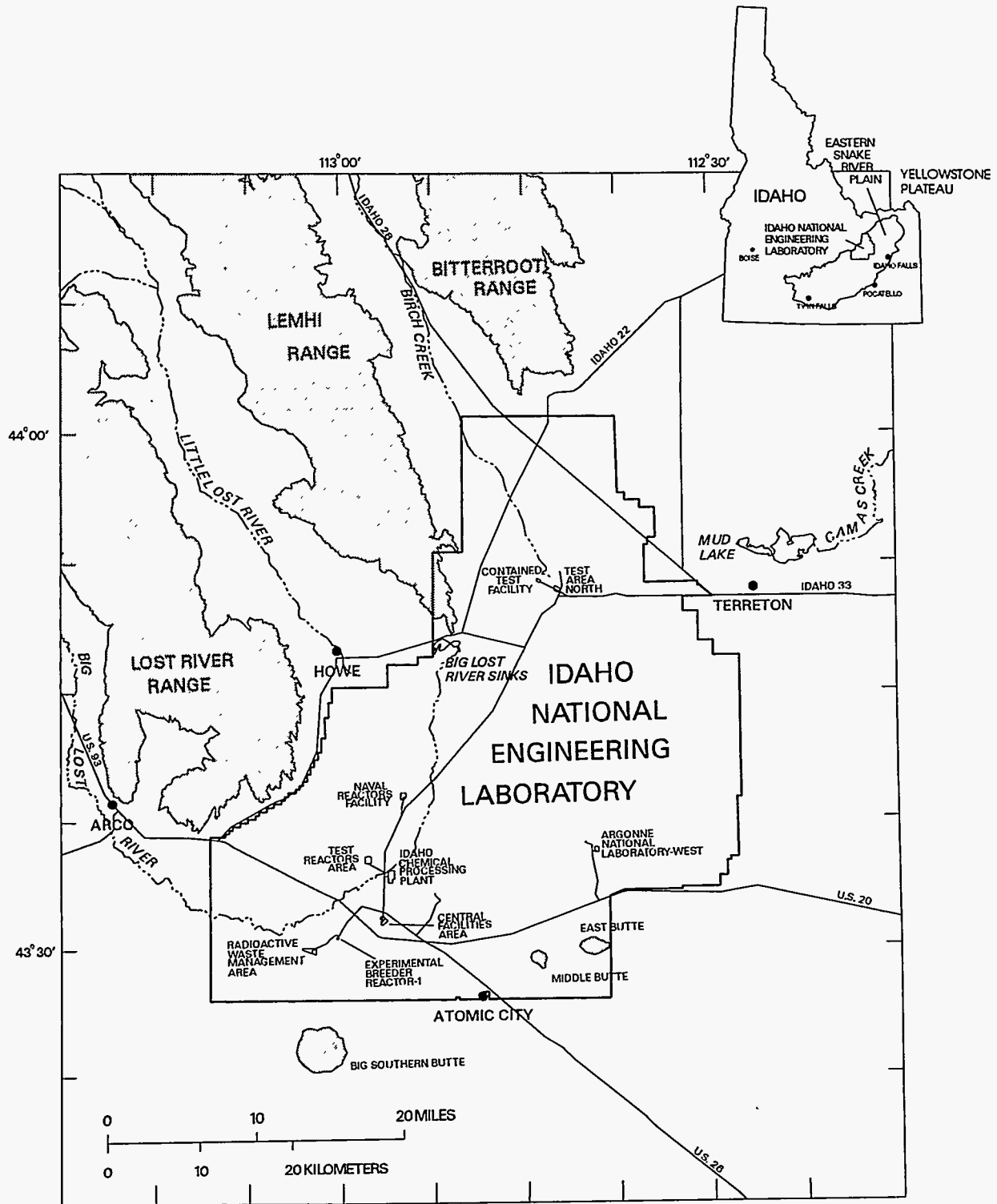
Figure 1. Location of the Idaho National Engineering Laboratory and selected facilities.

composite stratigraphic section composed of complete intervals of basalt and sediment that were deposited in areas of past maximum subsidence. K-Ar ages and their associated uncertainties were obtained from the sources of data listed in table 1 (back of report) and from Kuntz and others (1994); ages generally range from about 200 thousand to 1.8 million years before present and include ages determined for basalt outcrops and cores. Paleomagnetic ages, which are referred to as previous (1979) and revised (1995), were obtained from Mankinen and Dalrymple (1979) and Berggren and others (1995); ages also include the age of an important paleomagnetic reversal identified only at the INEL (Champion and others, 1988). The composite stratigraphic section was constructed from the stratigraphic data presented by Anderson and others (1996a). Ages estimated from regressions of the composite stratigraphic section are compared to measured ages and stratigraphy to evaluate the agreement between K-Ar ages and stratigraphic interpretations. Maximum accumulation rates estimated from regressions of the composite stratigraphic section are compared to accumulation rates estimated from regressions in three wells in and adjacent to an area of interpreted uplift at and near the ICPP and TRA and to the estimated rate of subsidence between the INEL and the Yellowstone Plateau (Smith and others, 1994), hereafter referred to as the previous (1994) estimated subsidence rate, to evaluate interpretations of past subsidence and uplift at the INEL.

Selected K-Ar ages are used in regressions because reported ages for some stratigraphic units are from areas where stratigraphic relations are uncertain or disputed (Anderson and others, 1996a; Anderson and Bowers, 1995). Ages are estimated for 50 of the 230 stratigraphic units described by Anderson and others (1996a). Estimated ages are slightly to significantly different than and supersede those reported by Anderson and others (1996a) because revised (1995) paleomagnetic ages are considered. Estimated ages are provided to supplement measured ages until additional measured ages are obtained. Because the geologic setting of the INEL is complex, some interpretations of geologic ages, accumulation rates, stratigraphy, and structure in this report may change as additional data are obtained.

Acknowledgments

Technical assistance and data from numerous geologic investigations were obtained from Duane E. Champion, Marvin A. Lanphere, and Mel A. Kuntz, USGS, Geologic Division. Scott S. Hughes, Idaho State University, and Mary M. Donato, USGS, Water Resources Division, reviewed the report and provided many helpful suggestions concerning its content and organization.

GEOLOGIC SETTING

The INEL is located on the west-central part of the eastern Snake River Plain, a northeast-trending structural basin about 200 mi long and 50 to 70 mi wide (fig. 1). The INEL is underlain by a sequence of Tertiary and Quaternary volcanic rocks and sedimentary interbeds that is more than 10,000 ft thick (Doherty and others, 1979; Whitehead, 1992; Smith and others, 1994; Hackett and others, 1994). The volcanic rocks consist mainly of basaltic lava flows, ash, and cinders in the upper part of the sequence and rhyolitic ash flows and tuffs of past caldera eruptions in the lower part. Basalt and sediment, which generally range in age from about 200 thousand to 4 million years before present, underlie the plain to depths ranging from about 2,200 to 3,800 ft below land surface in the southwestern part of the INEL. Ages of basalt and sediment in the unsaturated zone and the Snake River Plain aquifer generally range from about 200 thousand to 1.8 million years. Depth to the effective base of the aquifer ranges from about 800 to 1,700 ft below land surface in the western half of the INEL (table 2, back of report).

Stratigraphic units identified in 333 wells completed in the unsaturated zone and aquifer include 121 basalt-flow groups and 102 sedimentary interbeds (Anderson and others, 1996a). Each basalt-flow group consists of one or more distinct basalt flows deposited during a single, brief eruptive event (Kuntz and others, 1980); many older basalt

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flows in and below the aquifer are altered (Fromm and others, 1994). Sedimentary interbeds, which consist of well to poorly sorted deposits of clay, silt, sand, and gravel, accumulated on the ancestral land surface for hundreds to hun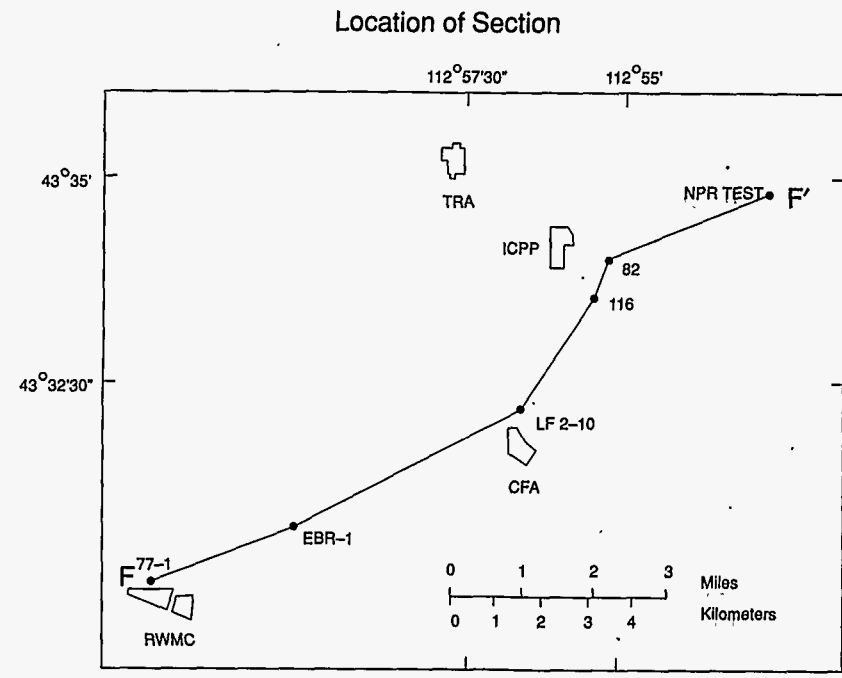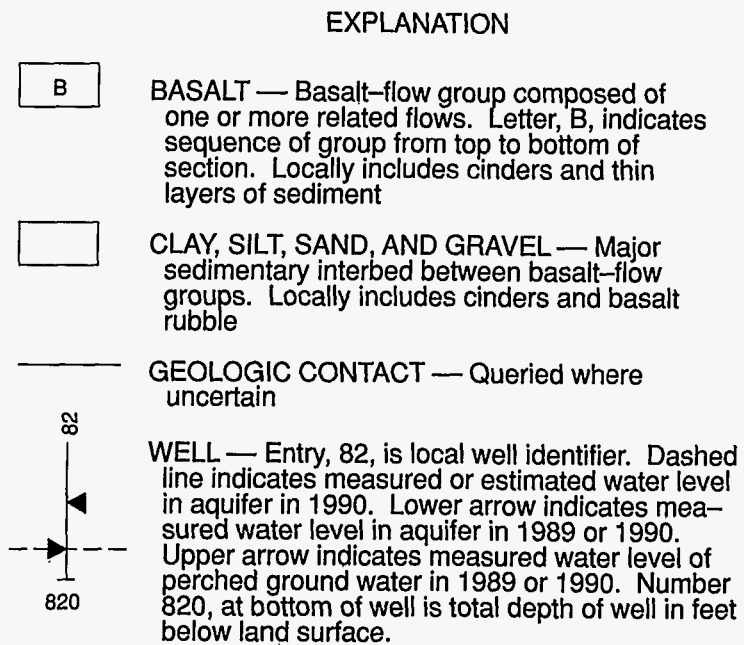dreds of thousands of years during periods of volcanic quiescence. Stratigraphic units are referred to as Al(1) through S5(1) (Anderson and others, 1996a). Basalt-flow groups and sedimentary interbeds AB(1) through L(2) range in age from about 200 to 800 thousand years, are widespread, and make up the unsaturated zone and uppermost part of the aquifer in most areas of the INEL. Basalt-flow groups and sedimentary interbeds LM(1) through S5(1), which range in age from about 800 thousand to 1.8 million years, make up the unsaturated zone and aquifer at TAN (fig. 1) and the lowermost part of the aquifer elsewhere at the INEL (Anderson and Bowers, 1995).

Most wells in the southern and eastern parts of the INEL are completed in basalt and sediment that informally are referred to as basalt-flow groups AB through I and related sediment (Anderson, 1991). Flow groups AB through I and related sediment range in age from about 200 to 640 thousand years and make up a stratigraphic section that is characterized by horizontal to inclined layers (fig. 2). Each basalt-flow group in the section was deposited during an eruption that lasted no longer than a few hundred years (Kuntz and others, 1980). The average length of time between these eruptions was about 10 to 20 thousand years, sufficiently long to accumulate thick layers of sediment in many areas. In places, such as the ICPP, TRA, and RWMC (fig. 2), the section is characterized by missing intervals of basalt and sediment. These interruptions in accumulation, which are referred to as hiatuses, generally lasted no more than a few tens of thousands of years at any one place. However, prolonged hiatuses, which are defined as missing intervals of basalt representing periods of at least 200 thousand years (table 3, back of report), cover the land surface in most areas of the INEL above basalt-flow group AB (fig. 2) and occur within the stratigraphic section at and near the ICPP, TRA, RWMC, and TAN (fig. 1).

The prolonged hiatus at the land surface resulted from significantly reduced volcanism during the past 200 thousand years; for millions of years until this time, the frequency and volume of eruptions were much greater (Kuntz and others, 1994; Anderson and Bowers, 1995). Prolonged hiatuses at and near the ICPP, TRA, RWMC, and TAN are attributed to differential subsidence and uplift during the past 1.8 million years (fig. 3). Volcanism, subsidence, and uplift resulted from the passage of the Yellowstone hot spot and subsequent intrusion of mafic material into the upper crustal layer of the eastern Snake River Plain about 4 to 6 million years ago (Pierce and Morgan, 1992; Sparlin and others, 1982). Subsidence began about 4 million years ago (Smith and others, 1994) and probably resulted from the cumulative effects of several mechanisms that may have included crustal extension, thermal contraction, withdrawal of basaltic magmas, isostatic adjustments, and compaction of sediment and caldera deposits. Uplift, which last occurred about 460 to 800 thousand years ago (fig. 3), probably resulted from the emplacement of laccoliths and domes within or beneath the subsiding stratigraphic section; alternatively, some areas of interpreted uplift may be the result of past differential subsidence or faulting. Regardless of how they formed, areas of interpreted uplift shown in figure 3 are now concealed by younger horizontal stratigraphic intervals and include only those areas that could be delineated using closely spaced wells and the stratigraphic relations of basalt-flow groups AB through I and related sediment (fig. 2); other similar areas probably occur elsewhere in the stratigraphic section underlying the INEL.

Accumulation rates estimated for intervals of basalt and sediment in selected wells provide a method to evaluate areas of past subsidence and uplift at the INEL (figs. 2-6). These rates, which are estimated using the geologic age and depth to the top of each basalt-flow group in areas of representative stratigraphy, must be averaged over hundreds of thousands of years to account for the long average time between basalt eruptions. Accumulation rates also must account for hiatuses related to vent constructs, periods of decreased volcanism, differential subsidence, and uplift; rates affected by hiatuses of more than a few tens

EXPLANATION

Location of Section

B — BASALT — Basalt–flow group composed of one or more related flows. Letter, B, indicates sequence of group from top to bottom of section. Locally includes cinders and thin layers of sediment

CLAY, SILT, SAND, AND GRAVEL — Major sedimentary interbed between basalt–flow groups. Locally includes cinders and basalt rubble

GEOLOGIC CONTACT — Queried where uncertain

WELL — Entry, 82, is local well identifier. Dashed line indicates measured or estimated water level in aquifer in 1990. Lower arrow indicates mea-sured water level in aquifer in 1989 or 1990. Upper arrow indicates measured water level of perched ground water in 1989 or 1990. Number 820, at bottom of well is total depth of well in feet below land surface.

Figure 2. Geologic section F-F' through the Radioactive Waste Management Complex, the Idaho Chemical Processing Plant, and Well NPR TEST (from Anderson, 1991).

Figure 2. Geologic section F-F' through the Radioactive Waste Management Complex, the Idaho Chemical Processing Plant, and Well NPR TEST (from Anderson, 1991)—continued

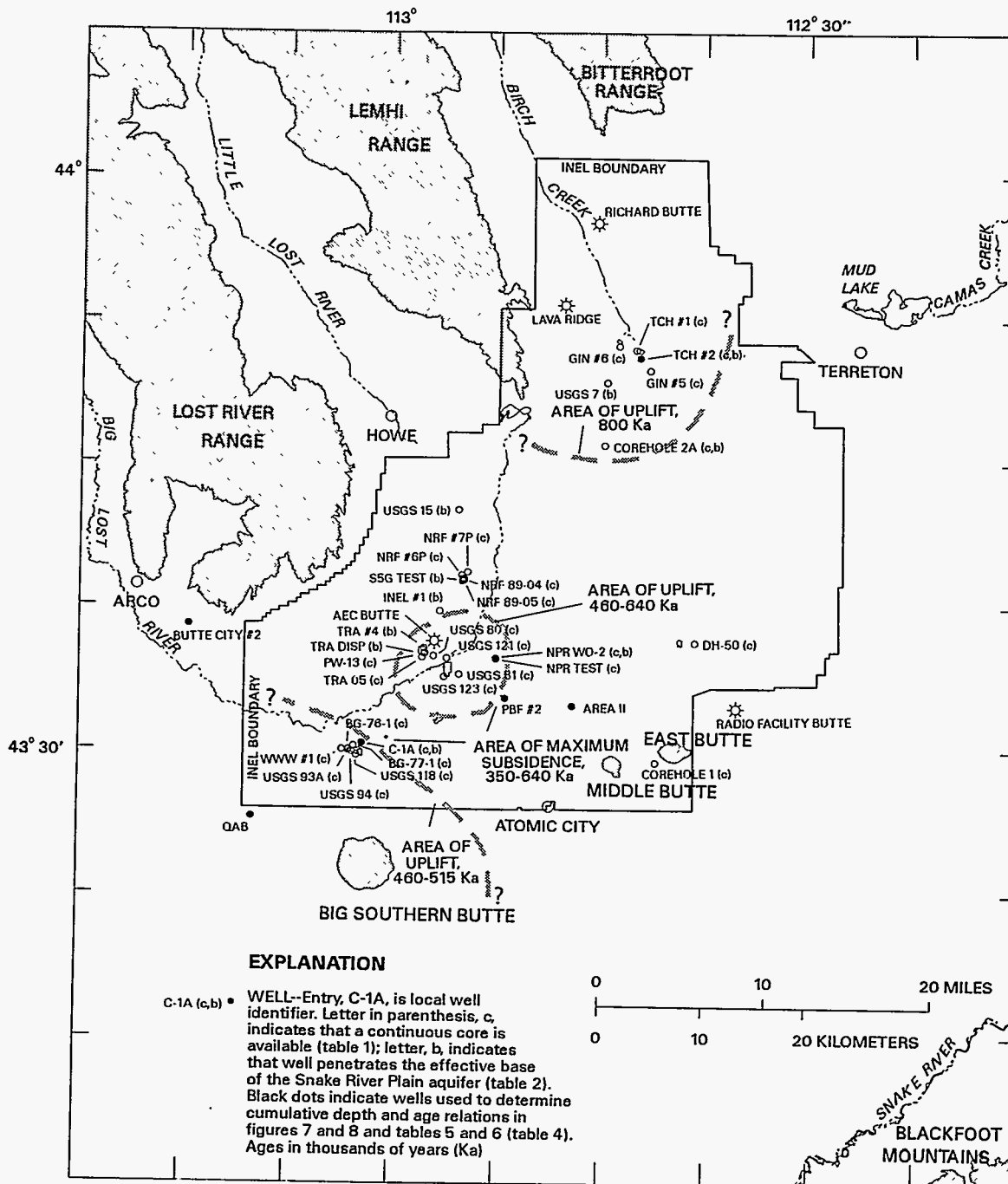**Figure 3.** Locations of selected wells and cores used to evaluate geologic ages, accumulation rates, stratigraphy, and structure of basalt-flow groups and sedimentary interbeds in the unsaturated zone and the Snake River Plain aquifer at the Idaho National Engineering Laboratory.

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of thousands of years are referred to as apparent rates. Accumulation rates in wells USGS 80 and NPR TEST (figs. 4 and 5), which are apparent rates affected only by hiatuses and prolonged hiatuses attributed to past uplift at and near the ICPP and TRA (figs. 2 and 3), range from 59 to 149 ft/100,000 years for stratigraphic intervals younger than 640 thousand years. By contrast, accumulation rates in well PBF #2 (fig. 6), which is in an area of past maximum subsidence adjacent to uplift where stratigraphic intervals of this age generally are thicker and free of hiatuses (figs. 2 and 3), are as great as 282 ft/100,000 years. The average of these rates, 163 ft/100,000 years, is nearly identical to the previous (1994) estimated rate of subsidence between the INEL and the Yellowstone Plateau during the past 4 million years, about 164 ft/100,000 years. The similarity of these rates suggest, as do interpreted stratigraphic relations (fig. 2), that accumulation rates are reasonable approximations of past subsidence rates and apparent subsidence rates for a given location and time at the INEL. However, without deep drill-hole data, apparent subsidence rates can be misleading. Apparent rates are a reasonable approximation of past subsidence rates if they represent motion with respect to a stable datum; however, some rates may violate this condition and, thus, may be a relative measure of the difference between two higher rates of subsidence or a rate of uplift superimposed on a rate of subsidence higher than that indicated by the apparent rate. All accumulation rates, if averaged over long enough periods of time, are apparent rates because all areas of the INEL, based on data from deep wells and cores (tables 1 and 2), are underlain by one or more prolonged hiatuses (table 3) caused by past differential subsidence or uplift. The youngest known hiatuses in the subsurface are attributed to uplift during the past 460 to 800 thousand years and underlie the areas at and near the ICPP, TRA, RWMC, and TAN (figs. 2 and 3). The best estimates of past subsidence rates at the INEL are obtained from linear accumulation rates that account for these hiatuses.

COMPOSITE STRATIGRAPHIC SECTION

A composite stratigraphic section was constructed to estimate ages and maximum accumulation rates of basalt and sediment in the unsaturated zone and the Snake River Plain aquifer at the INEL. The section, except for the uppermost part, was constructed using stratigraphic intervals in selected wells, such as the interval from 323 to 800 ft in well PBF #2 (fig. 3; table 4, back of report), that are in areas of past maximum subsidence and do not contain prolonged hiatuses, based on the stratigraphic data reported by Anderson and others (1996a). Sites D through I, which include wells AREA II, PBF #2, QAB, NPR WO-2, C-1A, and TCH #2 (fig. 3; table 4), were selected because each well contains a representative interval of basalt and sediment of a given age that meet these criteria. Site J, well NPR WO-2, was selected to evaluate the youngest known interval of basalt and sediment below the effective base of the aquifer. Sites A, B, and C were selected to evaluate a period of subsidence and greatly reduced basalt accumulation throughout most areas of the INEL during the past 200 thousand years. Sites A and C, wells Butte City #2 and NPR TEST (fig. 3), are referred to as the subsidence and accumulation datums, respectively (table 4). Site C subsided 380 ft with respect to site A during the past 200 thousand years (Anderson and Bowers, 1995). This difference, which for illustrative purposes is referred to as site B (table 4), represents the hypothetical approximate thickness of basalt that might have accumulated, given past accumulation/subsidence relations, were it not for a significant reduction in volcanism during the past 200 thousand years.

The composite stratigraphic section was constructed using depth and cumulative depth intervals from sites A through J (table 4). Geologic ages of deposits younger than about 800 thousand years generally agree with reported ages of paleomagnetic chrons and subchrons interpreted in this interval (Mankinen and Dalrymple, 1979; Champion and others, 1988; Berggren and others, 1995). Geologic ages of deposits older than about 800 thousand years generally range between previous (1979) and revised (1995) ages of three

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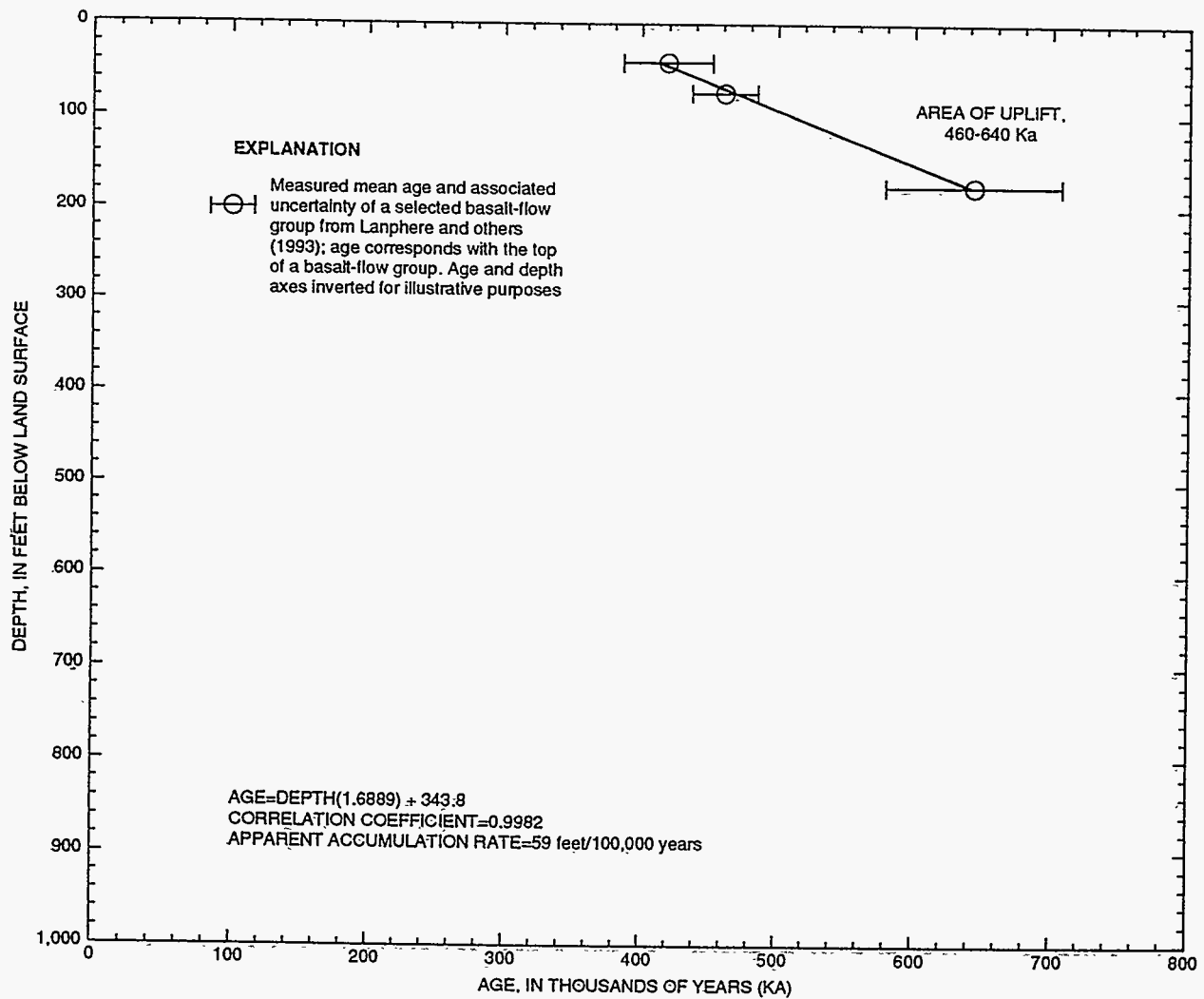
Figure 4. Relation between depths and measured geologic ages of basalt-flow groups DE4-5 through I in well USGS 80 (fig. 3) at the Idaho National Engineering Laboratory.
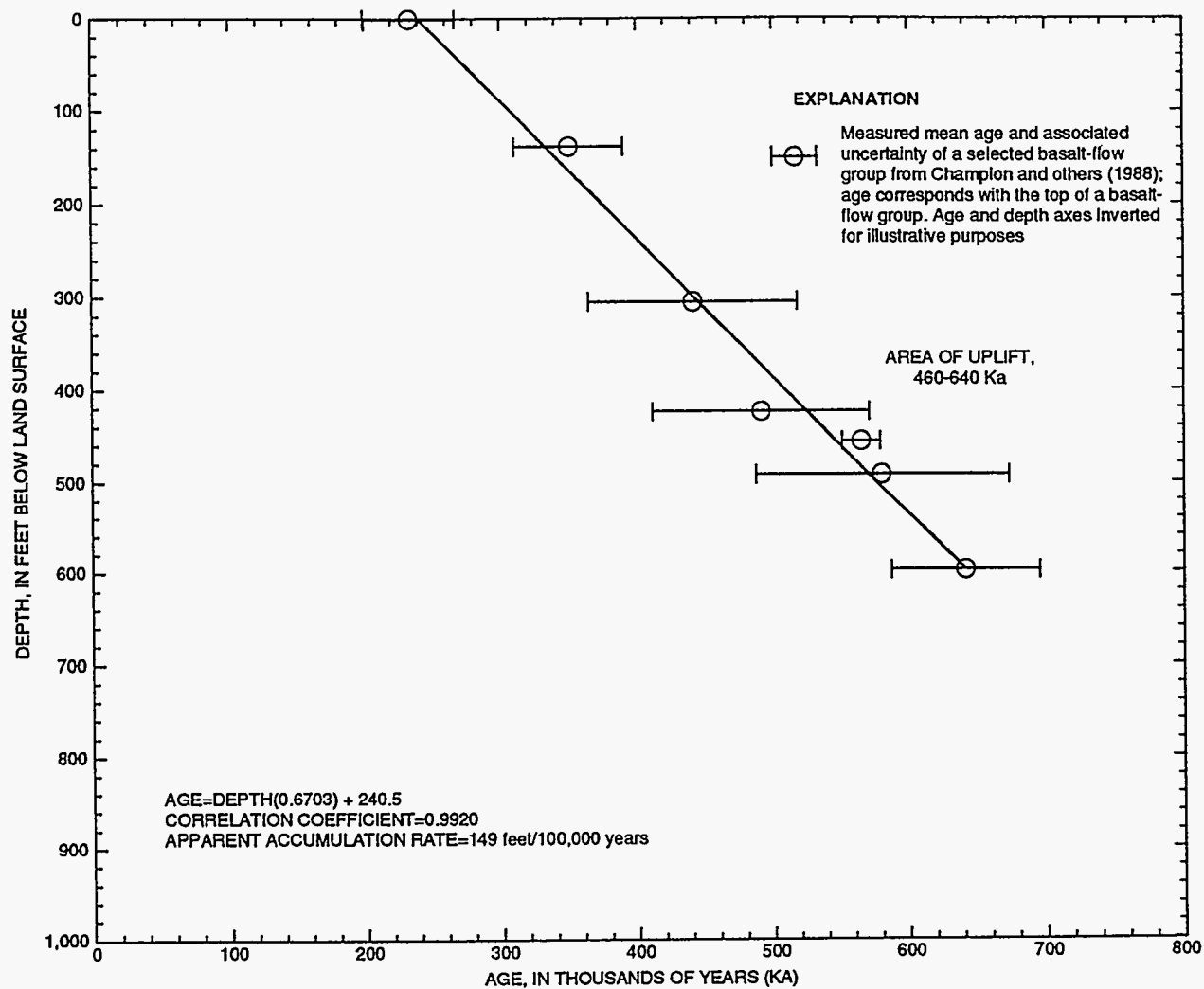
Figure 5. Relation between depths and measured geologic ages of basalt-flow groups AB through I in well NPR TEST (fig. 3) at the Idaho National Engineering Laboratory.

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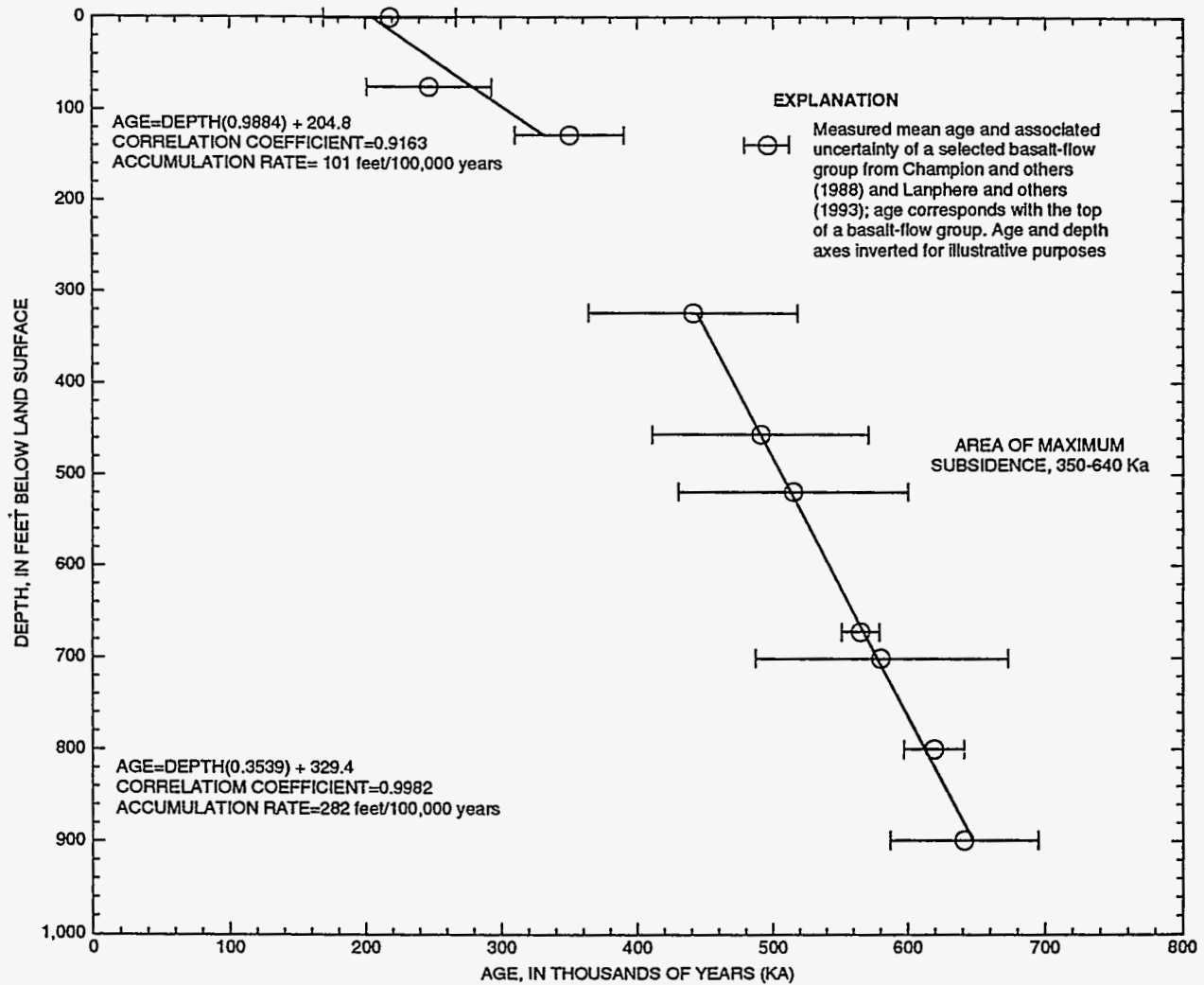
Figure 6. Relation between depths and measured geologic ages of basalt-flow groups AB through I in well PBF #2 (fig. 3) at the Idaho National Engineering Laboratory.

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paleomagnetic subchrons interpreted in this interval. The composite stratigraphic section includes 50 of the 230 stratigraphic units identified by Anderson and others (1996a) and does not contain prolonged hiatuses in deposits older than about 200 thousand years. The remaining 180 units excluded from the section were deposited at other sites at and near the INEL and have ages similar to those of units included in the section. Thickness of the composite stratigraphic section is about twice that of measured sections of a similar age in wells C-1A and NPR WO-2 (fig. 3; table 2). Reduced thicknesses in these and other wells are attributed, in part, to structural movements and their related hiatuses (table 3).

REGRESSION ANALYSIS

Measured geologic ages and interpreted stratigraphic and structural relations of basalt-flow groups and sedimentary interbeds underlying the INEL were evaluated using ages and maximum accumulation rates estimated from standard linear regressions (Iman and Conover, 1983) of 21 mean K-Ar ages, selected mean paleomagnetic ages, and cumulative depths of units in the composite stratigraphic section (figs. 7 and 8; tables 5 and 6, back of report). Each K-Ar age is identified as a primary or a secondary age (figs. 7 and 8) depending on whether it was determined for a basalt-flow group in the composite stratigraphic section or for a group of similar stratigraphic position not in the composite section. Paleomagnetic ages (figs. 7 and 8; table 6) include previous (1979) and revised (1995) ages of the boundary between the Brunhes Normal-Polarity Chron and the Matuyama Reversed-Polarity Chron and the interpreted boundaries of the Jaramillo, Cobb Mountain, and Olduvai Normal-Polarity Subchrons (Mankinen and Dalrymple, 1979; Berggren and others, 1995); ages also include the top of the Big Lost Reversed-Polarity Subchron (Champion and others, 1988). All ages were determined from basalt outcrops and cores distributed throughout the INEL and were correlated with the composite section using stratigraphic methods (Anderson and Bartholomay, 1995; Anderson and others, 1996a).

Primary and secondary K-Ar ages (figs. 7 and 8; table 6) are weighted mean ages reported by Champion and others (1988), Lanphere and others (1993), Lanphere and others (1994), and Kuntz and others (1994). Associated uncertainties of these ages are reported as one standard deviation; associated uncertainties of paleomagnetic ages were not reported. Additional published and unpublished K-Ar and argon-argon ($^{40}Ar/^{39}Ar$) ages for units in the composite stratigraphic section, identified in tables 1 and 6, were used to evaluate regressions but were not included in regressions. Some K-Ar ages reported by Lanphere and others (1993), Lanphere and others (1994), and Kuntz and others (1994) were not included in regressions because they were determined for units of uncertain or disputed stratigraphic position (Anderson and others, 1996a; Anderson and Bowers, 1995). Primary, secondary, and paleomagnetic ages were given equal weight in regressions; however, ages and accumulation rates estimated from regressions are greatly influenced by the large number and range of reported ages of basalt cores from well NPR TEST for units younger than about 800 thousand years and by ages of paleomagnetic subchrons interpreted in basalt and sediment cores from wells C-1A, Corehole 2A, and NPR WO-2 (fig. 3) for units older than about 800 thousand years (figs. 7 and 8; tables 5 and 6). Linear rather than nonlinear regressions of mean ages and cumulative depths were used to estimate ages and accumulation rates of stratigraphic units because measured ages and stratigraphic relations are not yet known with sufficient precision to justify more rigorous methods. Although other regressions are possible (table 5), those used to construct accumulation graphs of the composite stratigraphic section (figs. 7 and 8) provide the most reasonable estimates of ages and accumulation rates based on available age and stratigraphic control and geologic reasoning.

Accumulation graphs showing the relations between geologic ages and depths of units in the composite stratigraphic section (figs. 7 and 8) were constructed using seven principal line segments, 1a, 1b, 1c, 2a, 2b, 3a, and 3b, that were determined from regressions (1a), ($1b_2$), (1c), (2a), (2b), (3a), and (3b) on table 5. Because the

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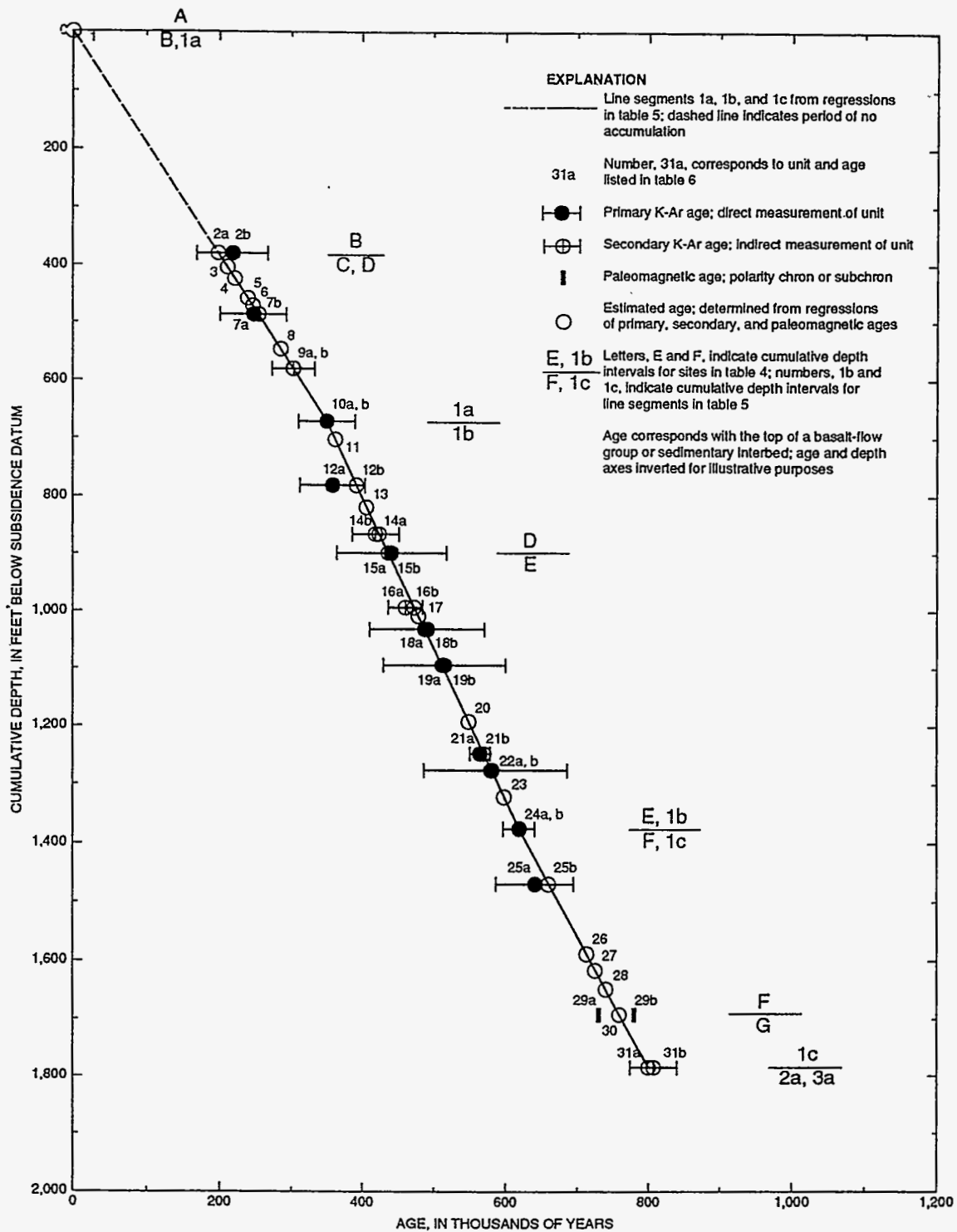
Figure 7. Relation between cumulative depths and geologic ages of selected basalt-flow groups and sedimentary interbeds in a composite stratigraphic section of the unsaturated zone and the Snake River Plain aquifer at the Idaho National Engineering Laboratory— present to about 800 thousand years before present. [Subsidence datum is the land surface at well Butte City #2 (table 4)]
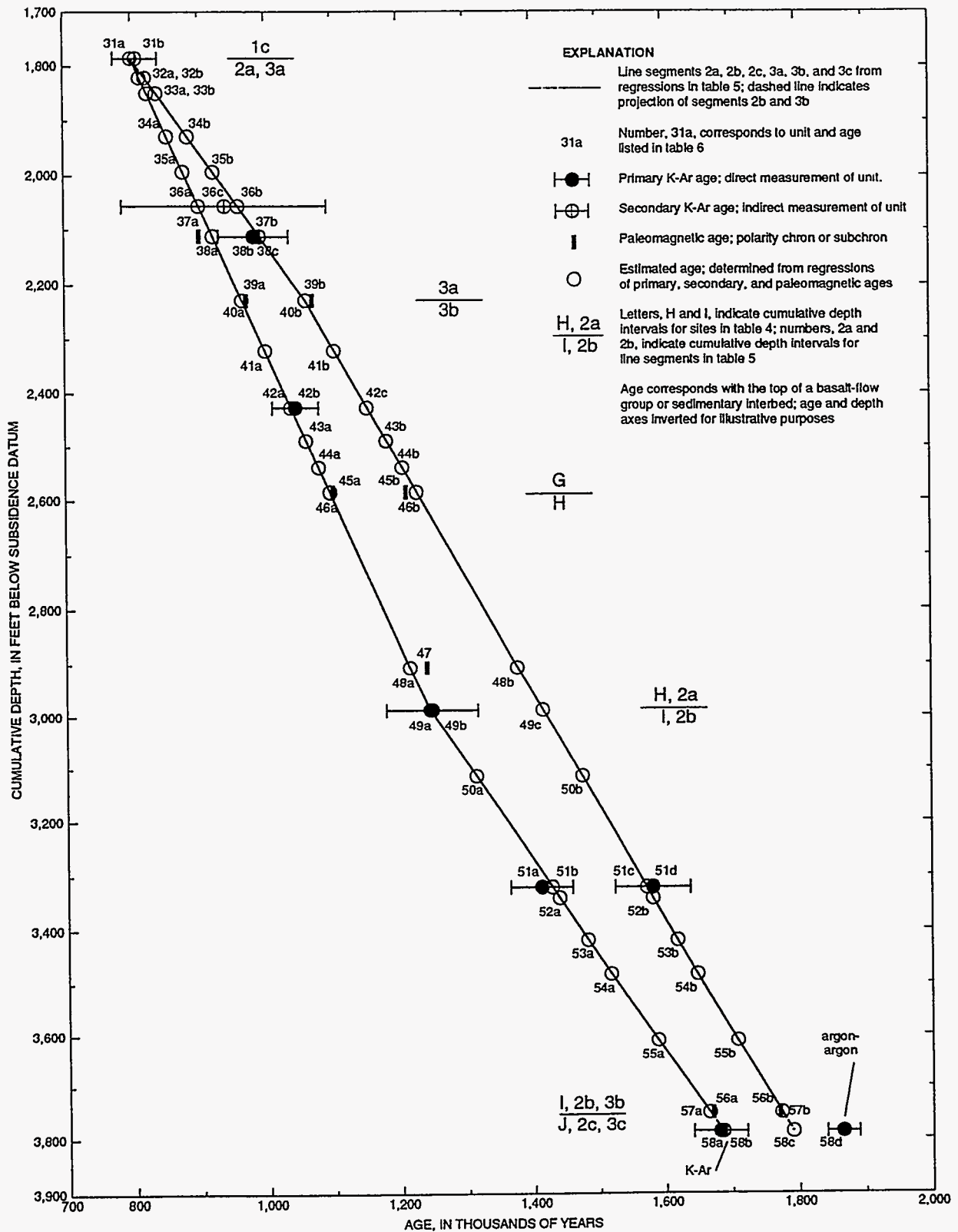
Figure 8. Relation between cumulative depths and geologic ages of selected basalt-flow groups and sedimentary interbeds in a composite stratigraphic section of the unsaturated zone and the Snake River Plain aquifer at the Idaho National Engineering Laboratory—about 800 to 1,800 thousand years before present. [Subsidence datum is the land surface at well Butte City #2 (table 4)]

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end points of adjacent regressions differ by 3 to 12 thousand years (table 5), each line segment, except the top of 1a and the bottoms of 2b and 3b, was determined using average or selected end points from two or more regressions. The top of line segment 1a was forced through zero age and depth without significantly changing regression (1a); the bottom ages and depths of line segments 2b and 3b are the same as those of regressions (2b) and (3b). Line segment 1b was determined using regression (1b$_2$), which excluded one control point, number 12a in figure 7 and on table 5; regression (1b$_1$) includes this control point (table 5). Paleomagnetic ages, control points 29a and 29b (fig. 7), which are previous (1979) and revised (1995) ages for the beginning of the Brunhes Normal-Polarity Chron, were not used for determining line segment 1c because they would have biased results. Previous (1979) paleomagnetic ages were used to supplement a small number of measured ages for determining line segments 2a and 2b. Revised (1995) paleomagnetic ages were used to supplement a small number of measured ages for determining line segments 3a and 3b. Although they biased results, previous (1979) and revised (1995) paleomagnetic ages were used to provide sufficient age control for regressions and to bracket the range of measured ages of basalt and sediment older than about 800 thousand years above the effective base of the aquifer. Line segments 2c and 3c below the effective base of the aquifer were not determined using regressions because age and stratigraphic data for this interval are insufficient; segments 2c and 3c are projections of segments 2b and 3b and are shown by dashed lines in figure 8. Additional regressions, (1a, 1b, 1c), (2a, 2b), (3a, 3b), and (1a, 1b, 1c, 2a, 2b, 3a, 3b) (table 5) represent averaged data used to estimate average rates of accumulation in the composite stratigraphic section for the age interval shown. These regressions, which represent long intervals of time and disregard most age control, are not shown in figures 7 and 8.

GEOLOGIC AGES AND ACCUMULATION RATES

Geologic ages estimated from regressions (table 6) agree with measured ages and interpreted stratigraphic relations, within the range of reported uncertainties of K-Ar ages, for basalt-flow groups and sedimentary interbeds younger than about 800 thousand years (fig. 7). The range of ages estimated for flow groups and interbeds older than about 800 thousand years (fig. 8) indicate potential errors in measured ages or stratigraphic interpretations for this interval. Estimated ages for all intervals are constrained by previous (1979) and revised (1995) paleomagnetic ages, but do not agree precisely with either interpretation. Estimated geologic ages are reasonable approximations of ages for basalt and sediment younger than about 800 thousand years, based on the regression analysis; geologic ages of deposits older than about 800 thousand years probably range between the ages estimated from duplicate regressions (table 6). Accumulation rates estimated from regressions (table 5) are reasonable approximations of maximum accumulation and subsidence rates during the past 1.8 million years for a given site and time, based on the stratigraphic data reported by Anderson and others (1996a).

Geologic Ages

Geologic ages were estimated for 50 stratigraphic units that include 47 basalt-flow groups and 3 sedimentary interbeds. Mean estimated ages range from 198 thousand to 1.790 million years before present and are reasonable approximations of the geologic ages of selected basalt-flow groups and sedimentary interbeds in the unsaturated zone and the Snake River Plain aquifer at the INEL. Agreement between measured and estimated ages is greatest for ages ranging from about 200 to 800 thousand years, line segments 1a, 1b, and 1c (fig. 7; table 6), and is least for ages ranging from about 800 thousand to 1.8 million years, line segments 2a, 2b, 2c, 3a, 3b, and 3c (fig. 8; table 6). Ages of basalt and sediment younger than about 200 thousand years could not be evaluated using this method and are described by Forman and others (1993), Forman and others (1994), and Kuntz and others (1994).

Ages estimated from line segments 1a, 1b, and 1c, about 200 to 800 thousand years, are based on 14 K-Ar ages. Agreement between measured and estimated ages among line segments 1a, 1b, and

1c is greatest for ages ranging from about 350 to 620 thousand years, line segment 1b, and least for ages ranging from about 620 to 800 thousand years, line segment 1c. Agreement between K-Ar, $^{40}Ar/^{39}Ar$, and estimated ages for control points 21 and 24 and between K-Ar and estimated ages for control points 2, 7, 9, 10, 12, 14, 15, 16, 18, 19, 22, 25, and 31 in line segments 1a and 1b indicate that K-Ar ages can reasonably measure geologic ages of young basalt flows at the INEL (fig. 7; table 6). However, estimated ages determined from line segment 1c do not agree with an $^{40}Ar/^{39}Ar$ age for control point 25 and the revised (1995) age for the beginning of the Brunhes Normal-Polarity Chron, control point 29b (fig. 7; table 6). These discrepancies may be related to potential errors in the geochronology, stratigraphy, or regression analysis.

Ages estimated from line segments 2a, 2b, and 2c, about 800 thousand to 1.685 million years, are based on four K-Ar ages, control points 31b, 42b, 49b, and 51a (fig. 8; tables 5 and 6), that generally agree with previous (1979) paleomagnetic ages. A K-Ar age, control point 58a in line segment 2c (fig. 8; table 6), determined from basalt that cooled during the Olduvai Normal-Polarity Subchron agrees with these ages but is considered unreliable by the laboratory (M.A. Lanphere, USGS, written commun., 1992). Ages estimated from line segments 3a, 3b, and 3c, about 800 thousand to 1.790 million years, are based on four K-Ar ages, control points 31b, 36c, 38b, and 51d (fig. 8; tables 5 and 6), that generally agree with revised (1995) paleomagnetic ages. An $^{40}Ar/^{39}Ar$ age, control point 58d in line segment 3c (fig. 8; table 6), although older than the estimated age predicted from line segment 3b, agrees with revised ages for the Olduvai Normal-Polarity Subchron (M.A. Lanphere, USGS, written commun., 1995); because of this age, estimated ages determined from line segments 3a, 3b, and 3c are more likely than those of segments 2a, 2b, and 2c to approximate geologic ages of older stratigraphic units. Neither set of estimated ages agrees with K-Ar ages corresponding to points 52, 53, 54, and 55 in table 6, ages that were considered too old by Anderson and Bowers (1995) based on stratigraphic arguments. Each set of estimated ages is based, in part, on different K-Ar ages, control

points 51a and 51d in line segments 2b and 3b (fig. 8), determined from the same interval of basalt in adjacent cores at TAN (fig. 1) that may (Anderson and Bowers, 1995) or may not (Lanphere and others, 1994) be the same stratigraphic unit. These discrepancies may be related to potential errors in the geochronology, stratigraphy, or regression analysis. Ages of older basalt flows in the aquifer are difficult to measure because many flows are altered. Stratigraphic relations of older basalt and sediment in the aquifer are difficult to determine because there are few cored intervals of this age (table 2).

The associated uncertainties for the estimated ages in table 6 are calculated standard errors and are a measure of the scatter about a given regression line. These errors were calculated using a modification of the following equation from Spiegel (1975) and Davis (1986):

$$S\sqrt{\frac{\Sigma\left(y-y_{est}\right)^2}{n}} \qquad (1)$$

where,

S is the standard error of the estimated geologic age,

Σ is the summation,

y is a measured geologic age used in the linear regression,

y_{est} is the estimated geologic age for a given depth, and

n is the number of observations; n equals 2 for these calculations.

For this analysis, one measured geologic age was used with one corresponding estimated geologic age for the error calculations. Therefore, the sum symbol, Σ, was dropped from equation 1 and n was set equal to 2. Because there are more estimated ages than corresponding measured ages in table 6, two successive measured ages were averaged and the resultant age was used as a guide for selecting the corresponding estimated ages to be used in equation 1. For example, for regression line segment 1a in table 6, the first two measured ages, 218,000 and 247,000 years, have an average of 232,500 years. All estimated ages for line seg-

ment 1a less than 232,500 years were used with the measured age of 218,000 years in equation 1 to calculate an associated standard error. All estimated ages between 232,500 and 275,000 years, the average of the next two successive measured ages, 247,000 and 303,000 years, were used with the measured age of 247,000 years in equation 1 to calculate an associated standard error. This procedure was repeated for all estimated ages in table 6.

These standard errors are an estimate of the precision of the estimated ages in relation to measured ages used for each linear regression (table 6). Therefore, as the cumulative depth for an estimated age approaches the corresponding cumulative depth for a measured age, a control point for a given regression line, the calculated uncertainty for the estimated age becomes smaller. Because the true uncertainties of estimated ages are probably larger than those of measured ages, the standard errors in table 6 should only be used as a guide to evaluate the precision of each estimated age with respect to its associated measured age.

Accumulation Rates

Accumulation rates estimated from regressions of selected stratigraphic intervals in wells AREA II, PBF #2, QAB, NPR WO-2, C-1A, and TCH #2 (table 4) range from 171 to 270 ft/100,000 years (table 5) and are representative of rates that occurred in areas of maximum subsidence for periods ranging from about 200 to 700 thousand years during the past 1.8 million years. Maximum accumulation rates for basalt and sediment younger than about 800 thousand years, line segments 1a, 1b, and 1c (fig. 7; table 5), range from 192 to 262 ft/thousand years. Maximum rates for basalt and sediment older than about 800 thousand years range from 182 to 270 ft/100,000 years using line segments 2a and 2b and from 171 to 213 ft/100,000 years using line segments 3a and 3b (fig. 8; table 5).

Maximum accumulation rates estimated from regressions of the composite stratigraphic section, 171 to 270 ft/100,000 years (table 5), are about 15 to 358 percent greater than the apparent rates of 59 to 149 ft/100,000 years in wells USGS 80 and

NPR TEST (figs. 4 and 5) attributed to uplift at and near the ICPP and TRA during the past 640 thousand years (figs. 2 and 3). Maximum rates for line segments 1b and 2a, 262 and 270 ft/100,000 years (table 5), are about 4 to 7 percent less than the maximum rate of 282 ft/100,000 years in well PBF #2 (fig. 6) in the area adjacent to uplift (figs. 2 and 3). If the apparent rates in wells USGS 80 and NPR TEST are an approximate measure of past subsidence rates, these rates ranged from 59 to 282 ft/100,000 years and averaged 163 ft/ 100,000 years during the past 640 thousand years at and near the ICPP and TRA. However, if the apparent rates in wells USGS 80 and NPR TEST are, instead, a relative measure of the difference between past rates of contemporaneous subsidence and uplift, a relation that is suggested by stratigraphic data from the deepest continuously-cored well at the INEL, well NPR WO-2 (fig. 3; table 1), subsidence rates in this area ranged from more than 149 to 282 ft/100,000 years. On the basis of the previous (1994) estimated subsidence rate between the INEL and the Yellowstone Plateau, 164 ft/100,000 years, the maximum accumulation rate in well PBF #2, 282 ft/100,000 years (fig 6), and the maximum accumulation rates estimated for the composite stratigraphic section, 171 to 270 ft/100,000 years (table 5), subsidence rates at and near the ICPP and TRA and elsewhere at the INEL probably ranged from about 160 to 280 ft/100,000 years and averaged about 220 ft/100,000 years during the past 1.8 million years. Although accumulation rates were similar to subsidence rates for periods ranging from about 200 to 700 thousand years (table 5), overall apparent accumulation rates must have been less than these rates to account for prolonged hiatuses in the stratigraphic section (table 3). Prolonged hiatuses, which are attributed to differential subsidence and uplift until the past 200 thousand years, averaged about 600 thousand years and 38 percent of the total possible accumulation time during the period from 200 thousand to 1.8 million years in seven representative wells at the INEL (table 3). On the basis of this relation, apparent accumulation rates probably ranged from about 99 to 174 ft/100,000 years and averaged about 136 ft/100,000 years, 38 percent less than the probable subsidence rates during the past 1.8 million years. These rates disregard the prolonged

hiatus during the past 200 thousand years above basalt-flow group AB(10) in well NPR TEST (table 3) because the hiatus is above the accumulation datum of the composite stratigraphic section (fig. 7, line segment 1a; table 4) and is not representative of other past accumulation rates and apparent accumulation rates at the INEL.

STRATIGRAPHIC AND STRUCTURAL IMPLICATIONS

The stratigraphic section underlying the INEL is made up of overlapping intervals of basalt and sediment that accumulated in areas of past volcanism and subsidence (Anderson and Bowers, 1995; Anderson, 1991). These areas covered hundreds of square miles, were active for periods ranging from 200 to 700 thousand years, shifted across a 1,000 mi^2 area during the past 1.8 million years, and were preceded and followed by periods of reduced accumulation. Periods of maximum accumulation in each area were accompanied by an approximate volumetric equilibrium between basaltic volcanism, accumulation, and subsidence. Periods of reduced accumulation in each area were accompanied by differential subsidence or uplift. As a result, the stratigraphic section is characterized by a succession of widespread stratigraphic intervals bounded by local offsets and hiatuses and differences in overall thickness as great as 100 percent. The section also is characterized by maximum long-term apparent accumulation rates that are about 38 percent less than past subsidence rates in areas of greatest thickness, a difference identical to that between the approximate average land-surface altitudes of the INEL and the Yellowstone Plateau, about 5,000 and 8,000 ft above sea level, respectively. As used in this report, offsets refer to abrupt changes in dip of stratigraphic intervals that probably resulted from past differential subsidence or uplift. Although possible in some areas, past faulting is not required to explain these offsets.

The complexity of the stratigraphic section at any one place can be demonstrated by a 3,800-ft thick section of basalt and sediment that overlies rhyolite in nested cores obtained from wells NPR WO-2 and NPR TEST (table 1) in the area of interpreted uplift at and near the ICPP and TRA

(fig. 3). Thickness of the section, which ranges in age from about 200 thousand to 4 million years (Smith and others, 1994), is only about 13 percent greater than the composite stratigraphic section below the accumulation datum (figs. 7 and 8; table 4), a representation of the composite thickness of all intervals deposited in areas of maximum subsidence during the past 1.8 million years. Thickness of the equivalent interval above the effective base of the aquifer in wells NPR WO-2 and NPR TEST, 1,660 ft (table 2), is about 51 percent less than the composite stratigraphic section below the accumulation datum, a difference that is attributed to hiatuses in the interval (table 3). Estimated accumulation/subsidence rates for this interval, which contains several short hiatuses near its top and a prolonged hiatus of about 600 thousand years near its base (table 3), range from 149 to 226 ft/100,000 years disregarding the prolonged hiatus (fig. 5; table 5, line segments 1c, 3a, and 3b). The average accumulation/ subsidence rate for the interval, disregarding the prolonged hiatus and using top and bottom ages of about 200 thousand and 1.2 million years, respectively (table 3), is 166 ft/100,000 years, a rate that is nearly identical to the previous (1994) estimated subsidence rate between the INEL and the Yellowstone Plateau during the past 4 million years. The average apparent accumulation rate for this interval using top and bottom ages that encompass the prolonged hiatus, about 200 thousand and 1.8 million years, respectively (table 3), is about 104 ft/100,000 years, a rate that is 36 percent less than the previous (1994) estimated subsidence rate, 37 percent less than the rate above the hiatus, and nearly identical to an apparent rate estimated from the 38 percent difference between the average prolonged hiatus and total accumulation time during the past 1.8 million years at the INEL. These rates, which probably are similar to those of the interval below the effective base of the aquifer based on its thickness (2,100 ft) and age difference (2.2 million years), suggest a mechanism of continuous long-term subsidence accompanied by periodic uplift at this location. Hiatuses attributed to uplift, which last occurred in this area 460 to 640 thousand years ago (fig. 3), make up about 38 percent of the total possible accumulation time for the period from 200 thousand to 1.8 million years. The average accumulation/

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subsidence rate for the period from 200 thousand to 1.2 million years, 166 ft/100,000 years, is about 24 percent less than the average estimated maximum rate at the INEL for the past 1.8 million years, 220 ft/100,000 years. The average apparent accumulation rate for the period from 200 thousand to 1.8 million years, 104 ft/100,000 years, is about 53 percent less than the average maximum accumulation rate. The interval above the effective base of the aquifer in well NPR WO-2 is about the same thickness as that in well C-1A in the area of interpreted uplift at and near the RWMC (fig. 3; table 2). This relation suggests that areas at and near the ICPP, TRA, and RWMC shared a similar history of subsidence accompanied by periodic uplift during the past 1.8 million years.

Although the layering of the stratigraphic section is relatively horizontal beneath most areas of the INEL, the layers of some stratigraphic intervals older than about 500 thousand years are offset by hundreds of feet as a result of past differential subsidence and uplift. Past uplift near the ICPP, TRA, RWMC, and TAN (fig. 3) produced offsets ranging from about 300 to 800 ft during the past 800 thousand years (Anderson and Bowers, 1995; Anderson, 1991). Past differential subsidence in the area beneath the present-day Big Lost River (fig. 3) produced offsets ranging from about 700 to 1,500 ft in stratigraphic intervals older than about 800 thousand years. The greatest offset attributed to uplift is about 270 ft/ mi in intervals older than about 500 thousand years between wells C-1A and EBR-1 just north of the RWMC (figs. 2 and 3). The greatest offset beneath the Big Lost River is about 330 ft/mi in rhyolite older than about 4 million years in wells NPR WO-2 and INEL #1 that are east and west of the river, respectively (fig. 3). This offset is attributed to past differential subsidence because the thicknesses of basalt and sediment intervals above and below the effective base of the aquifer in well NPR WO-2 are each about 74 percent greater than those of respective intervals in well INEL #1. Furthermore, the cumulative difference in thickness of these intervals, 1,600 ft, is about the same as the difference between the altitudes of the underlying rhyolite in each well, about 1,200 and 2,700 ft above sea level, respectively. There-

fore, the difference in altitudes of rhyolite in wells NPR WO-2 and INEL #1 probably resulted from past differential subsidence beneath the Big Lost River (Anderson and Bowers, 1995) rather than from original topographic relief as suggested by Smith and others (1994). The river overlies an area of interpreted uplift (fig. 3), attributed to a concealed laccolith or dome (Anderson, 1991), that is younger than the offset attributed to differential subsidence in this area. Possible faulting related to past differential subsidence in this area might explain the position and origin of this uplift as well as the offset in older stratigraphic intervals between wells NPR WO-2 and INEL #1.

The total thickness of the basalt and sediment section above the effective base of the aquifer is not known in many areas but can be evaluated using estimated accumulation and subsidence rates and the thickness of the composite stratigraphic section below the accumulation datum, 3,371 ft (figs. 7 and 8; tables 4 and 5). The thickness of the section in five wells mountainward of the Big Lost River, wells USGS 15, S5G TEST, INEL #1, TRA #4, and TRA DISP (fig. 3), averages about 900 ft (table 2) and includes only basalt and sediment younger than about 800 thousand years (fig. 7). The thickness of the section in three wells in the area of interpreted uplift at and near TAN, wells TCH #2, USGS #7, and Corehole 2A (fig. 3), averages about 875 ft (table 2) and includes only basalt and sediment older than about 800 thousand years (fig. 8). Thickness of the section in two wells in the areas of interpreted uplift at and near the ICPP, TRA, and RWMC, wells NPR WO-2 and C-1A (fig. 3), averages about 1,685 ft (table 2) and includes basalt and sediment that are younger and older than 800 thousand years (figs. 7 and 8). The average thickness of the section mountainward of the Big Lost River and at and near TAN is about 73 percent less than that of the composite stratigraphic section below the accumulation datum. The average thickness of combined sections older and younger than 800 thousand years, in these areas, 1,775 ft, is about 47 percent less than that of the composite stratigraphic section below the accumulation datum and about 5 percent greater than that of the average section in wells NPR WO-2 and C-1A, the thickest known section above the

effective base of the aquifer at the INEL. These relations suggest that differential subsidence and uplift reduced the apparent accumulation rates and thicknesses of the stratigraphic section, compared to those of the composite stratigraphic section, by about 50 to 75 percent in the western half of the INEL. The thickness of the stratigraphic section in some areas between and east of the ICPP, RWMC, and TAN may be greater than that of the section in wells NPR WO-2 and C-1A, based on interpreted stratigraphic relations and estimates of maximum accumulation/subsidence rates (figs. 2-6; table 5) However, the maximum thickness of the section must be less than that of the composite stratigraphic section below the accumulation datum because maximum rates occurred for relatively short periods of time, shifted across the INEL during the past 1.8 million years, and were preceded and followed by periods of reduced accumulation and hiatuses.

Given the range of estimated maximum accumulation/subsidence rates and the thickness of the composite stratigraphic section (figs. 7 and 8; table 5), hiatuses and apparent accumulation rates related to differential subsidence and uplift are required to explain the stratigraphic data reported by Anderson and others (1996a) and the known thicknesses of basalt and sediment younger than about 1.8 million years at the INEL. Hiatuses and apparent accumulation rates, such as those in well NPR WO-2, also are required to explain why, given that maximum accumulation and subsidence rates were similar during the past 1.8 million years, the altitude of the land surface at the INEL, about 5,000 ft, is about 3,000 ft below that of the Yellowstone Plateau. The difference in altitude between these areas, about 38 percent, is nearly identical to the difference between the apparent accumulation rate of 104 ft/100,000 years and the average subsidence rate of 166 ft/ 100,000 years in well NPR WO-2. The lowest rate, which disregards the prolonged hiatus attributed to uplift near the effective base of the aquifer in this well (table 3), is about 36 percent less than the previous (1994) estimated subsidence rate between the INEL and the Yellowstone Plateau; the highest rate, which accounts for the hiatus, is nearly identical to this rate.

The previous (1994) estimated subsidence rate is based on the assumption that differences between the average altitudes of rhyolite in wells NPR WO-2 and INEL #1 at the INEL (fig. 3) and at the land surface on the Yellowstone Plateau are the result of subsidence during the past 4 million years (Smith and others, 1994). This assumption and the estimated rate, about 164 ft/100,000 years, appear reasonable on the basis of the younger subsidence rate of 166 ft/100,000 years estimated from accumulation rates in well NPR WO-2, the difference of 37 to 38 percent between apparent accumulation rates and subsidence rates estimated for young stratigraphic intervals at the INEL, and the difference of 38 percent between the average land-surface altitudes of the INEL and the Yellowstone Plateau. However, the previous (1994) estimated subsidence rate, which depends on geologic data from wells NPR WO-2 and INEL #1 located in areas of reduced stratigraphic thickness related to past differential subsidence and uplift (figs. 2 and 3), is about 25 to 41 percent less than the average and maximum subsidence rates estimated for the INEL during the past 1.8 million years, about 220 to 280 ft/100,000 years. If these higher rates were sustained anywhere at the INEL for the entire period, the resulting thickness of the stratigraphic section might be about 31 to 68 percent greater than that of 1,660 ft in well NPR WO-2. This estimate is based on an accumulation time of 1.6 million years, the period of time represented by basalt-flow groups AB(10) and TU(1) (table 6), and apparent accumulation rates of 136 to 174 ft/100,000 years that are 38 percent less than the average and maximum estimated subsidence rates. The greatest possible thickness of the stratigraphic section, estimated from the maximum apparent rate, is about 17 percent less than the thickness of the composite stratigraphic section below the accumulation datum, 3,371 ft (figs. 7 and 8; table 4).

A slight reduction in the rate of subsidence during the past 350 thousand years was accompanied by an equal reduction of volcanism from about 200 to 350 thousand years ago and a near cessation of volcanism during the past 200 thousand years (fig. 7, line segment 1a). Basalt flows ranging in age from about 5 to 165 thousand years cover parts of the INEL and adjacent areas (Kuntz

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and others, 1994), but accumulation rates of these young rocks at the INEL were much less than the subsidence rate of about 192 ft/100,000 years estimated for this period. Surficial deposits at the INEL mainly include young sediment (Anderson and others, 1996b) and basalt flows that were deposited more than 200 thousand years ago (Kuntz and others, 1994). As a result, most of the land surface at the INEL is part of a prolonged hiatus of large areal extent (table 3) that is related to a significant reduction in volcanism rather than structural processes. Similar volcanic hiatuses of such large areal extent and duration are not known to exist in older intervals of basalt and sediment at the INEL.

On the basis of accumulation rates, as much as 62 percent of the cumulative subsidence volume during the past 1.8 million years may have resulted from the mechanisms that controlled the withdrawal of basaltic magmas. This estimate is based on the short-term similarity of accumulation and subsidence rates in many areas of past volcanism and the long-term difference between these rates and maximum apparent accumulation rates at the INEL. At least 38 percent of the cumulative subsidence volume, now represented by the difference between the land-surface altitudes of the INEL and the Yellowstone Plateau, must have resulted from other mechanisms. Most of this volume probably resulted from isostatic adjustments related to the high-density mafic intrusion in the upper crust (Sparlin and others, 1982) and the added weight of accumulated basalt and sediment.

SUMMARY

Geologic ages and accumulation rates, estimated from regressions, were used to evaluate measured ages and interpreted stratigraphic and structural relations of basalt and sediment in the unsaturated zone and the Snake River Plain aquifer at the INEL in eastern Idaho. Geologic ages and accumulation rates were estimated from standard linear regressions of 21 mean K-Ar ages, selected mean paleomagnetic ages, and cumulative depths of a composite stratigraphic section composed of complete intervals of basalt and sediment that were deposited in areas of past

maximum subsidence. Accumulation rates also were estimated from regressions of stratigraphic intervals in wells USGS 80, NPR TEST, and PBF #2 in and adjacent to an area of interpreted uplift at and near the ICPP and the TRA to allow a comparison of rates in areas of past uplift and subsidence.

Estimated geologic ages range from about 200 thousand to 1.8 million years before present and are reasonable approximations for the interval of basalt and sediment above the effective base of the aquifer, based on reported uncertainties of corresponding measured ages. Estimated ages between 200 and 800 thousand years are within the range of reported uncertainties for all 15 K-Ar ages used in regressions and two out of three $^{40}Ar/^{39}Ar$ ages of duplicate samples. Two sets of estimated ages between 800 thousand and 1.8 million years are within the range of reported uncertainties for all seven K-Ar ages used in regressions, which include one shared age of about 800 thousand years. Two sets of ages were estimated for this interval because K-Ar ages make up two populations that agree with previous (1979) and revised (1995) ages of three paleomagnetic subchrons. The youngest set of ages is consistent with a K-Ar age from the effective base of the aquifer that agrees with previous (1979) ages of the Olduvai Normal-Polarity Subchron. The oldest set of ages is consistent with an $^{40}Ar/^{39}Ar$ age of the same basalt flow that agrees with revised (1995) ages of the Olduvai Subchron. Regressions indicate that measured ages and stratigraphic interpretations are reasonable for basalt and sediment between the ages of 200 and 800 thousand years, the youngest deposits that could be evaluated using regressions. Regressions indicate potential errors in measured ages or stratigraphic interpretations for basalt and sediment between the ages of 800 thousand to 1.8 million years, the oldest deposits in the aquifer. Ages of older basalt flows in the aquifer are difficult to measure because many flows are altered. Stratigraphic relations of older basalt and sediment in the aquifer are difficult to determine because there are few cored intervals of this age.

The stratigraphic section underlying the INEL is made up of overlapping intervals of basalt and

sediment that accumulated in areas of past vol-
canism and subsidence. These areas covered
hundreds of square miles, were active for periods
ranging from 200 to 700 thousand years, shifted
across a 1,000 mi² area during the past 1.8 million
years, and were preceded and followed by periods
of reduced accumulation. Periods of maximum
accumulation in each area were accompanied by
an approximate volumetric equilibrium between
basaltic volcanism, accumulation, and subsidence.
Periods of reduced accumulation in each area
were accompanied by differential subsidence or
uplift. As a result, the stratigraphic section is
characterized by a succession of widespread strati-
graphic intervals bounded by local offsets and
hiatuses and differences in overall thickness as
great as 100 percent. The section also is character-
ized by maximum long-term apparent accumula-
tion rates that are about 38 percent less than past
subsidence rates in areas of greatest thickness, a
difference identical to that between the approxi-
mate average land-surface altitudes of the INEL
and the Yellowstone Plateau, about 5,000 and
8,000 ft above sea level, respectively.

Accumulation rates, estimated from regres-
sions of stratigraphic intervals younger than 640
thousand years in wells USGS 80, NPR TEST,
and PBF #2 in and adjacent to the area of interpre-
ted uplift at and near the ICPP and TRA, range
from 59 to 282 ft/100,000 years and average 163
ft/100,000 years, a rate that is nearly identical to
the previous (1994) estimated subsidence rate
between the INEL and the Yellowstone Plateau
during the past 4 million years, about 164 ft/
100,000 years. Accumulation rates estimated from
regressions of the composite stratigraphic section,
which is made up of stratigraphic intervals de-
posited in many areas of past subsidence for
periods ranging from 200 to 700 thousand years
during the past 1.8 million years, range from 171
to 270 ft/100,000 years and average 218 ft/
100,000 years, a rate that is 33 percent greater
than the previous (1994) estimated subsidence
rate. Although average accumulation rates in
wells USGS 80, NPR TEST, and PBF #2 agree
with the previous (1994) estimated subsidence
rate, the rates in wells USGS 80 and NPR TEST
are apparent rates that are a relative measure of
the difference between past rates of contemporan-

eous subsidence and uplift, based on deep drill-
hole data. The best estimates of past subsidence
rates range from about 160 to 280 ft/100,000
years and average about 220 ft/100,000 years,
based on the previous (1994) estimated subsi-
dence rate and accumulation rates unaffected by
differential subsidence or uplift. Estimated subsi-
dence rates averaged about 192 ft/100,000 years
and were much greater than accumulation rates
during the past 200 thousand years, a period of
greatly reduced volcanism. This interruption in
basalt accumulation, which is unlike that of
earlier periods and continues to the present day,
includes most areas of the INEL.

On the basis of accumulation rates, subsidence
probably resulted from the cumulative effects of
several mechanisms that may have included crust-
al extension, thermal contraction, withdrawal of
basaltic magmas, isostatic adjustments, and com-
paction of sediment and caldera deposits. Uplift
proably resulted from the emplacement of laco-
liths and domes within or beneath the subsiding
stratigraphic section. As much as 62 percent of
the cumulative subsidence volume during the past
1.8 million years may have resulted from the
mechanisms that controlled the withdrawal of
basaltic magmas. This estimate is based on the
short-term similarity of accumulation and subsi-
dence rates in many areas of past volcanism and
the long-term difference between these rates and
maximum apparent accumulation rates at the
INEL. At least 38 percent of the cumulative sub-
sidence volume, now represented by the differ-
ence between the land-surface altitudes of the
INEL and the Yellowstone Plateau, must have
resulted from other mechanisms. Most of this
volume probably resulted from isostatic adjust-
ments related to the high-density mafic intrusion
in the upper crust and the added weight of
accumulated basalt and sediment.

REFERENCES CITED

Anderson, S.R., 1991, Stratigraphy of the unsaturated
    zone and uppermost part of the Snake River Plain
    aquifer at the Idaho Chemical Processing Plant and
    Test Reactors Area, Idaho National Engineering
    Laboratory, Idaho: U.S. Geological Survey Water-

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Resources Investigations Report 91-4010 (DOE/ID-22095), 71 p.

Anderson, S.R., Ackerman, D.J., Liszewski, M.J., and Freiburger, R.M., 1996a, Stratigraphic data for wells at and near the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 96-248, (DOE/ID-22127), 27 p., 1 diskette

Anderson, S.R., Liszewski, M.J., and Ackerman, D.J., 1996b, Thickness of surficial sediment at and near the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 96-330, (DOE/ID-22128), 16 p.

Anderson, S.R., and Bartholomay, R.C., 1995, Use of natural-gamma logs and cores for determining stratigraphic relations of basalt and sediment at the Radioactive Waste Management Complex, Idaho National Engineering Laboratory, Idaho: Journal of the Idaho Academy of Science, v. 31, no. 1, p. 1-10.

Anderson, S.R., and Bowers, Beverly, 1995, Stratigraphy of the unsaturated zone and uppermost part of the Snake River Plain aquifer at Test Area North, Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 95-4130, (DOE/ID-22122) 47 p.

Anderson, S.R. and Lewis, B.D., 1989, Stratigraphy of the unsaturated zone at the Radioactive Waste Management Complex, Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 89-4065 (DOE/ID-22080), 54 p.

Bartholomay, R.C., Orr, B.R., Liszewski, M.J., and Jensen, R.G., 1995, Hydrologic conditions and distribution of selected radiochemical and chemical constituents in water, Snake River Plain aquifer, Idaho National Engineering Laboratory, Idaho, 1989 through 1991: U.S. Geological Survey Water-Resources Investigations Report 95-4175 (DOE/ID-22123), 47 p.

Berggren, W.A., Hilgen, F.J., Langereis, C.G., Kent, D.V., Obradovich, J.D., Raffi, I., Raymo, M.E., Shackleton, N.J., 1995, Late Neogene chronology: New perspectives in high-resolution stratigraphy: Geological Society of America Bulletin, v. 107, no. 11, p. 1,272-1,287.

Champion, D.E., Lanphere, M.A., and Kuntz, M.A., 1988, Evidence for a new geomagnetic reversal from lava flows in Idaho—discussion of short polarity reversals in the Brunhes and Late Matuyama Polarity Chrons: Journal of Geophysical Research, v. 93, no. B10, p. 11,677-11,680.

Davis, J.C., 1986, Statistics and data analysis in Geology, 2nd. ed.: John Wiley and Sons, New York, 646 p.

Doherty, D.J., McBroome, L.A., and Kuntz, M.A., 1979, Preliminary geological interpretation and lithologic log of the exploratory geothermal test well (INEL-1), Idaho National Engineering Laboratory, Eastern Snake River Plain, Idaho: U.S. Geological Survey Open-File Report 79-1248, 7 p.

Forman, S.L., Pierson, J., Smith, R.P., Hackett, W.R., and Valentine, G., 1994, Assessing the accuracy of thermoluminescence for dating baked sediments beneath late Quaternary lava flows, Snake River Plain, Idaho: Journal of Geophysical Research, v. 99, no. B8, p. 15,569-15,576.

Forman, S.L., Smith, R.P., Hackett, W.R., Tullis, J.A., and McDaniel, P.A., 1993, Timing of late Quaternary glaciations in the western United States based on the age of loess on the Eastern Snake River Plain, Idaho: Journal of Quaternary Research, v. 40, p. 30-37.

Fromm, J.M., Hackett, W.R., and Stephens, J.D., 1994, Primary mineralogy and alteration of basalts and sediments in drillcores from the Idaho National Engineering Laboratory, eastern Snake River Plain [Abs.]: International Symposium on the Observation of the Continental Crust Through Drilling, VIIth, Santa Fe, N. Mex., April 25-30, 1994, [Abstracts] unpaginated.

Hackett, W.R., Anders, M., and Walter, R.C., 1994, Preliminary stratigraphic framework of rhyolites from corehole WO-2, Idaho National Engineering Laboratory: Caldera-related, late-Tertiary silicic volcanism of the eastern Snake River Plain [Abs.]: International Symposium on the Observation of the Continental Crust Through Drilling, VIIth, Santa Fe, N. Mex., April 25-30, 1994, [Abstracts] unpaginated.

Iman, R.L., and Conover, W.J., 1983, A modern approach to statistics: John Wiley and sons, Inc, New York, 497 p.

Knobel, L.L., Cecil, L.D., and Wood, T.R., 1995, Chemical composition of selected core samples, Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Open-File Report 95-748, 59 p.

Kuntz, M.A., Dalrymple, G.B., Champion, D.E., and Doherty, D.J., 1980, Petrography, age, and paleomagnetism of volcanic rocks at the Radioactive Waste Management Complex, Idaho National Engineering Laboratory, Idaho, with an evaluation of potential volcanic hazards: U.S. Geological Survey Open-File Report 80-388, 63 p.

Kuntz, M.A., Skipp, Betty, Lanphere, M.A., Scott, W.E., Pierce, K.L., Dalrymple, G.B., Champion, D.E., Embree, G.F., Page, W.R., Morgan, L.A., Smith, R.P., Hackett, W.R., and Rodgers, D.W., 1994, Geologic map of the Idaho National Engineering Laboratory and adjoining areas, eastern Idaho: U.S. Geological Survey Miscellaneous Investigations Map I-2330, scale 1:100,000.

Lanphere, M.A., Champion, D.E., and Kuntz, M.A., 1993, Petrography, age, and paleomagnetism of basalt lava flows in coreholes Well 80, NRF 89-04, NRF 89-05, and ICPP 123, Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Open-File Report 93-327, 40 p.

Lanphere, M.A., Kuntz, M.A., and Champion, D.E., 1994, Petrography, age, and paleomagnetism of basaltic lava flows in coreholes at Test Area North (TAN), Idaho National Engineering Laboratory: U.S. Geological Survey Open-File Report 94-686, 49 p.

Lawrence, R.F., and Hackett, W.R., 1994, Petrography and lithology of Tertiary rhyolites in WO-2 drillcore, Idaho National Engineering Laboratory (INEL), eastern Snake River Plain [Abs.]: International Symposium on the Observation of the Continental Crust Through Drilling, VIIth, Santa Fe, N. Mex., April 25-30, 1994, [Abstracts] unpaginated.

Mankinen, E.A., and Dalrymple, G.B., 1979, Revised geomagnetic polarity time scale for the interval 0.5 m.y. B.P.: Journal of Geophysical Research, v. 84, p. 615-626.

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

Reed, M.F., Bartholomay, R.C., and Hughes, S.S., 1996, Geochemistry and stratigraphic correlation of basalt lavas beneath the Idaho Chemical Processing Plant, Idaho National Engineering Laboratory, Idaho: Environmental Geology, in press.

Shervais, John, Vetter, Scott, and Hackett, William, 1994, Chemical stratigraphy of basalts in coreholes NPR-E and WO-2, Idaho National Engineering Laboratory, Idaho—implications for plume dynamics in the Snake River Plain: International Symposium on the Observation of the Continental Crust Through Drilling, VIIth, Santa Fe, N. Mex., April 25-30, 1994, Proceedings, p. 93-96.

Smith, R.P., Hackett, W.R., Josten, N.E., Knutson, C.F., Jackson, S.M., Barton, C.A., Moos, D., Blackwell, D.D., and Kelley, S., 1994, Synthesis of deep drill hole information at the Idaho National Engineering Laboratory (INEL)—upper crustal environment in the continental track of a mantle hotspot: International Symposium on the Observation of the Continental Crust Through Drilling, VIIth, Santa Fe, N. Mex., April 25-30, 1994, Proceedings, p. 89-92.

Sparlin, M.A., Braile, L.W., and Smith, R.B., 1982, Crustal structure of the eastern Snake River Plain determined from ray-trace modeling of seismic refraction data: Journal of Geophysical Research, v. 87, p. 2,619-2,633.

Spiegel, M.R., 1975, Probability and Statistics: McGraw-Hill Book Company, New York, 372 p.

Whitehead, R.L., 1992, Geohydrologic framework of the Snake River Plain regional aquifer system, Idaho and eastern Oregon: U.S. Geological Survey Professional Paper 1408-B, 32 p., 6 pls. in pocket.

Table 1. Selected cores and sources of data used to evaluate stratigraphic units underlying the Idaho National Engineering Laboratory

[Well is one from which continuous core was obtained (fig. 3). Depth is total depth of well and approximate total depth of core, in feet below land surface. Data include paleomagnetic inclination and polarity, K-Ar (potassium-argon) and ^{40}Ar/^{39}Ar (argon-argon) ages, petrographic descriptions, and major-oxide and trace element chemistry. Symbol: -- indicates no data. Numbers in columns 3-6 indicate the following data references: 1 = Kuntz and others (1980); 2 = Champion and others (1988); 3 = Lanphere and others (1993); 4 = Lanphere and others (1994); 5 = Knobel and others (1995); 6 = Reed and others (1996); 7 = Duane E. Champion, USGS, written commun., 1989-95; 8 = Marvin A. Lanphere, USGS, written commun., 1989-95; 9 = Mel A. Kuntz, USGS, written commun., 1989-95; and 10 = Roy C. Bartholomay, written commun., 1989-95. Additional data for deposits in and underlying the Snake River Plain aquifer are indicated by the following references: 11 = Shervais and others, 1994; 12 = Lawrence and Hackett, 1994; and 13 = Hackett and others, 1994]

Well and core identifier	Depth (feet)	Source of paleomagnetic data	Source of geochronologic data	Source of petrographic data	Source of chemical data
BG-76-1	228	1	1	1	--
BG-77-1	600	1	1, 2	1	10
C-1A	1,805	7	8	--	--
Corehole 1	2,002	7	--	--	--
Corehole 2A	3,000	7	8	--	--
DH-50	250	7	---	--	--
GIN #5	430	4	--	--	--
GIN #6	200	4	--	--	--
NPR TEST	609	2	2	--	5, 10, 11
NPR WO-2	5,000	7, 13	8, 13	12	11
NRF #6P	500	7	--	--	--
NRF #7P	500	7	8	--	--
NRF 89-04	248	3	3	--	--
NRF 89-05	242	3	3	3	--
PW-13	148	7	--	--	--
TCH #1	600	4	4	4	5
TCH #2	1,114	4	4	4	5
TRA 05	297	7	8	--	5
USGS 80	204	3	3	3	--
USGS 81	108	7	--	--	--
USGS 93A	233	--	--	1	--
USGS 94	302	1	1	1	--
USGS 118	570	7	--	--	10
USGS 121	746	7	8	9	6
USGS 123	744	3	3	3	6
WWW #1	265	7	--	--	--

Table 2. Wells that penetrate the effective base of the Snake River Plain aquifer at the Idaho National Engineering Laboratory

[Depth is total depth of well, in feet below land surface. Base is the depth to the effective base of the Snake River Plain aquifer, in feet below land surface. Lithology indicates the relative abundance of basalt (B) and sediment (S) below the base of the aquifer to a depth of 500 feet; greatest abundance is listed first. Core indicates the availability of continuous core; see table 1]

Well identifier	Depth (feet)	Base (feet)	Lithology	Core
C-1A	1,805	1,710	B, S	Yes
Corehole 2A	3,000	846	S, B	Yes
INEL #1	10,365	965	S, B	No
NPR WO-2	5,000	1,660	B, S	Yes
S5G TEST	1,276	884	B, S	No
TCH #2	1,114	883	B, S	Yes
TRA #4	970	909	B, S	No
TRA DISP	1,275	907	B, S	No
USGS 7	1,200	895	B, S	No
USGS 15	1,497	815	S, B	No

Table 3. Prolonged hiatuses between basalt flows above the effective base of the Snake River Plain aquifer in selected wells at the Idaho National Engineering Laboratory

[Well, C-1A, is a well that penetrates one or more hiatuses of at least 200 thousand years duration (fig. 3; table 1). Unit, D(1), is a basalt-flow group described by Anderson and others (1996a); single entry indicates that unit crops out or is overlain by sediment near the land surface. Depth, 41 (single entry), is the depth, in feet below land surface, to the youngest basalt-flow group in a well; depths, 279 and 287 (double entry), are depths to the base and top, respectively, of two basalt-flow groups that differ in age by more than 200 thousand years. Measured age, 218, is the mean age of a unit, in thousands of years before present from table 6; age in brackets, [230], is mean age or pooled mean age reported by Kuntz and others (1980). Estimated age, 198, is mean age that was estimated for a unit in the composite stratigraphic section (figs. 7 and 8; table 6); age in brackets, [290], is mean age that was estimated for a unit not in the composite section. Line segments, 1a through 3c, correspond to line segments in figures 7 and 8 and table 5. Hiatus, 198, is the length of elapsed time, in thousands of years, since the last basalt flow or between two basalt flows in a well; time determined from [measured] and estimated mean ages. Symbol, --, indicates no data]

Well identifier	Unit	Depth (feet)	Measured age (thousands of years)	Estimated age (thousands of years)	Line segment	Hiatus (thousands of years)	Core
NPR TEST	AB(10)	0	218	198	1a	[218], 198	Yes
QAB	C(1)	194	[211]	[270]	1a		No
	DE 6-7(1)	194	--	[476]	1b	206	
BG-77-1	D(1)	279	[230]	[290]	1a		Yes
	E(1)	287	515	512	1b	[285], 212	
C-1A	Q(2)	1,710	--	[1,480]	3b		Yes
	T(2)	1,710	--	1,773	3b	293	
USGS 80	DE4-5(3)	41	419	[430]	1b	[419], 430	Yes
C-1A	H(1)	698	619	619	1c		Yes
	LM(8)	703	--	1,060	3a	441	
NPR WO-2	N(4)	1,660	--	1,205	3b		Yes
	TU(1)	1,696	1,865	1,790	3c	585	
TRA DISP	LM1(1)	897	--	800	3a		No
	TU(1)	907	1,865	1,790	3c	990	
TCH #2	M(1)	40	--	[1,080]	3b	1,080	Yes

Table 4. Sites used to construct a composite stratigraphic section of selected basalt-flow groups and sedimentary interbeds in the unsaturated zone and the Snake River Plain aquifer at the Idaho National Engineering Laboratory

[Sites, A through J, indicate wells and datums used to construct line segments 1a through 3c in figures 7 and 8. Wells include selected wells from the stratigraphic data base described by Anderson and others (1996a). Altitude is the land surface altitude at each well, in feet above sea level. Depth indicates the depth or depth interval of a site, in feet below land surface. Cumulative depth indicates the depth or depth interval of a site, in feet below the subsidence datum; interval for site B (fig. 7, line segment 1a) indicates the difference in land-surface altitude, 380 feet, between the subsidence datum, site A, and the accumulation datum, site C. Units, AB(10) through TU(1), are selected basalt-flow groups and sedimentary interbeds from Anderson and others (1996a). Altitude, depth, and cumulative depth are rounded to the nearest foot and are accurate ±2 feet]

Site	Well identifier	Altitude (feet)	Depth (feet)	Cumulative depth (feet)	Core	Datums and units
A	Butte City #2	5,315	0	0	No	Subsidence datum
B				0-380		No accumulation
C	NPR TEST	4,935	0	380	Yes	Accumulation datum
D	AREA II	5,130	6-524	380-898	No	AB(10) through DE5(1)
E	PBF #2	4,924	323-800	898-1,375	No	DE5(1) through H(1)
F	QAB	5,190	770-1,087	1,375-1,692	No	H(1) through L(1)
G	NPR WO-2	4,930	767-1,660	1,692-2,585	Yes	L(1) through NO(1)
H	C-1A	5,029	1,074-1,477	2,585-2,988	Yes	NO(1) through P(3)
I	TCH #2	4,792	120-883	2,988-3,751	Yes	P(1) through S5(1)
J	NPR WO-2	4,930	1,660-1,696	3,751-3,787	Yes	T(2) through TU(1), effective base of aquifer

Table 5. Line segments and regressions used to estimate geologic ages and maximum accumulation/subsidence rates of selected basalt-flow groups and sedimentary interbeds in the unsaturated zone and the Snake River Plain aquifer at the Idaho National Engineering Laboratory

[Line segments, 1a through 3c, correspond to line segments in figures 7 and 8 and table 6. Age, in thousands of years before present, is the dependent variable in each regression equation for the age interval shown. Cumulative depth, in feet below the subsidence datum (table 4), is the independent variable in each regression equation for the depth interval shown. Correlation coefficient of 1.0000 indicates that regression equation is based on average or selected end points; coefficient of less than 1.0000 indicates that equation is based on selected measured ages. Regression equation indicates that age equals the cumulative depth multiplied by the computed slope plus or minus the computed intercept. Rate of accumulation/subsidence indicates the average rate of accumulation and subsidence at sites in table 4 for the age intervals shown, in feet per hundred thousand years (ft/100 Ky); rates in brackets indicate that accumulation did not occur at sites during the past 200 thousand years. Age and depth control, numbers 1 through 57b, correspond to numbered ages and cumulative depths in figures 7 and 8 and table 6; numbers indicate the ages and cumulative depths used in each regression. Cumulative depths are rounded to the nearest foot and are accurate to ±2 feet]

Line segment (regression)	Age (thousands of years)	Cumulative depth (feet)	Correlation coefficient	Regression equation	Rate of accumulation/ subsidence	Age and depth control
1a	0-350	0-671	1.0000	Age = Depth (0.5216)	[192 ft/100 Ky]	1, 10a
(1a)	5-352	0-671	0.9973	Age = Depth (0.5172)+4.6	[193 ft/100 Ky]	1, 2b, 7a, 9b, 10a
1b	350-619	671-1,375	1.0000	Age = Depth (0.3821)+93.6	262ft/100 Ky	10a, 24b
(1b$_1$)	340-620	671-1,375	0.9930	Age = Depth (0.3986)+72.1	251ft/100Ky	10a, 12a,14b, 15b, 16a, 18b, 19b, 21a, 22a, 24b
(1b$_2$)	349-618	671-1,375	0.9981	Age = Depth (0.3816)+92.8	262ft/100Ky	10a, 14b, 15b, 16a, 18b, 19b, 21a, 22a, 24b
1c	619-800	1,375-1,785	1.0000	Age = Depth (0.4415)+12.0	226ft/100Ky	24b, 31a
(1c)	609-804	1,375-1,785	0.9717	Age = Depth (0.4755)-44.6	210ft/100Ky	24b, 25a, 31b
(1a, 1b, 1c)	0-800	0-1,785	1.0000	Age = Depth (0.4482)	223ft/100Ky	1, 31a
2a	800-1,245	1,785-2,988	1.0000	Age = Depth (0.3699)+139.7	270ft/100Ky	31a, 49a
(2a)	798-1,249	1,785-2,988	0.9976	Age = Depth (0.3742)+130.5	267ft/100Ky	31b, 37a, 39a, 42b, 45a, 49b
2b	1,245-1,665	2,988-3,751	1.0000	Age = Depth (0.5504)-399.8	182ft/100Ky	49a, 57a

Table 5. Line segments and regressions used to estimate geologic ages and maximum accumulation/subsidence rates of selected basalt-flow groups and sedimentary interbeds in the unsaturated zone and the Snake River Plain aquifer at the Idaho National Engineering Laboratory—Continued

Line segment (regression)	Age (thousands of years)	Cumulative depth (feet)	Correlation coefficient	Regression equation	Rate of accumulation/ subsidence	Age and depth control
(2b)	1,240-1,664	2,988-3,751	0.9985	Age = Depth (0.5553)-418.8	180ft/100Ky	49b, 51a, 56a
(2a, 2b)	800-1,665	1,785-3,751	1.0000	Age = Depth (0.4400)+14.6	227ft/100Ky	31a, 57a
2c		3,751-3,787		not calculated		
3a	800-1,060	1,785-2,229	1.0000	Age = Depth (0.5856)-245.3	171ft/100Ky	31a, 40b
(3a)	800-1,058	1,785-2,229	0.9927	Age = Depth (0.5828)-240.6	172ft/100Ky	31b, 36c, 37b, 39b
3b	1,060-1,773	2,229-3,751	1.0000	Age = Depth (0.4685)+15.8	213ft/100Ky	40b, 57b
(3b)	1,060-1,773	2,229-3,751	0.9992	Age = Depth (0.4685)+15.7	213ft/100Ky	39b, 45b, 51d, 56b
(3a, 3b)	800-1,773	1,785-3,751	1.0000	Age = Depth (0.4949)-83.4	202ft/100Ky	31a, 57b
3c		3,751-3,787		not calculated		
(1a, 1b, 1c, 2a, 2b, 3a, 3b)	0-1,719	0-3,751	1.0000	Age = Depth (0.4583)	218ft/100Ky	1, average of 57a and 57b

Table 6. Measured and estimated geologic ages of selected basalt-flow groups and sedimentary interbeds in the unsaturated zone and the Snake River Plain aquifer at the Idaho National Engineering Laboratory

[Numbers, 1 through 58d, correspond to ages and cumulative depths shown in figures 7 and 8. Units, AB(10) through TU(1), are selected basalt-flow groups and sedimentary interbeds from Anderson and others (1996a). Information in brackets between units indicates the following paleomagnetic chrons and subchrons described by Mankinen and Dalrymple (1979), Champion and others (1988), and Berggren and others (1995): BL = Big Lost; B/M = Brunhes/Matuyama boundary; J(T) = top of the Jaramillo; J(B) = bottom of the Jaramillo; C(T) = top of the Cobb Mtn.; C(M) = middle of the Cobb Mtn.; C(B) = bottom of the Cobb Mtn.; and O(T) = top of the Olduvai. Measured ages, 218±49 to <1,865±24>, include the following categories of ages, in thousands of years before present: 218±49 = K-Ar age reported by Champion and others (1988), Lanphere and others (1993), Lanphere and others (1994), or Kuntz and others (1994); 1,210 = age of paleomagnetic chron or subchron; [982±53] = unpublished K-Ar age that disagrees with revised (1995) ages of paleomagnetic subcron (M.A. Lanphere, USGS, written commun., 1992); and <619±22> = unpublished $^{40}Ar/^{39}Ar$ age that agrees with previous K-Ar age or revised (1995) ages of paleomagnetic subchron (M.A. Lanphere, USGS, written commun., 1994-95). Ages followed by (Y) were used for regressions; ages followed by (N) were not used for regressions (table 5). Estimated ages interpolated from line segments 1a, 1b, 1c, 2a, 2b, 3a, and 3b in figures 7 and 8 and table 5; ages in parentheses are estimated mean ages of paleomagnetic chron or subchron. Paleomagnetic polarity is indicated by the following symbols: N = normal; R = reversed; N/R = older unit(s) reversed; R/N = older unit(s) normal; N or R = polarity of basalt core or outcrop; (N) or (R) = probable polarity of basalt in well that was not cored; [N] or [R] = probable polarity of sediment; and <N> = basalt that cooled during an R/N reversal. Site indicates well, core, or outcrop where ages of units were measured or estimated (figure 3; table 4). Depth indicates the depth, in feet below land surface, to the top of a unit in a well for which ages were estimated. Depth also indicates the depth or depth interval of a core sample for which ages were measured; S, indicates surficial samples. Cumulative depth (table 4) corresponds to the top of a unit or units in figures 7 and 8. Line segment corresponds to a line segment in figures 7 and 8 and table 5. Depth and cumulative depth are rounded to the nearest foot and are accurate to ±2 feet. Age uncertainties are reported standard deviations of measured ages and calculated standard errors of estimated ages; uncertainties of paleomagnetic ages not reported or estimated. Large differences between measured and estimated ages, such as for numbers 52, 53, 54, and 55, indicate areas that need additional study.]

Number	Unit	Measured age and uncertainty (thousands of years)	Estimated age and uncertainty (thousands of years)	Polarity	Site	Depth (feet)	Cumulative depth (feet)	Line segment
1	Land surface		0	[N]	Butte City #2	0	0	1a
2a	Land surface		198±14	N	NPR Test	0	380	1a
2a	AB(10)		198±14	N	NPR Test	0	380	1a
2a	AB(10)		198±14	(N)	AREA II	6	380	1a
2b	AB(10)	218±49(Y)		N	NPR Test	23	380	1a
3	AB(11)		211±5	(N)	AREA II	30	404	1a
4	B(1)		221±2	(N)	AREA II	50	424	1a
5	B-BC(3)		239±6	(N)	AREA II	84	458	1a
6	B-BC(4)		246±1	(N)	AREA II	97	471	1a
7a	BC(1)	247±46(Y)		N	NPR Test	81	486	1a
7b	BC(1)		254±5	(N)	AREA II	112	486	1a

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Table 6. Measured and estimated geologic ages of selected basalt-flow groups and sedimentary interbeds in the unsaturated zone and the Snake River Plain aquifer at the Idaho National Engineering Laboratory—Continued

Number	Unit	Measured age and uncertainty (thousands of years)	Estimated age and uncertainty (thousands of years)	Polarity	Site	Depth (feet)	Cumulative depth (feet)	Line segment
8	CD(1)		285±13	(N)	AREA II	172	546	1a
9a	D(4)		302±1	(N)	AREA II	206	580	1a
9b	DE1(2)	303±30(Y)		N	NRF 89-05	79	580	1a
10a	DE2(1)	350±40(Y)		N	NPR Test	157	671	1a, b
10b	DE2(1)		350±0	(N)	AREA II	297	671	1a, b
11	DE3(1)		362±3	(N)	AREA II	328	702	1b
12a	DE3-4(1)	358±46(N)		N	Radio Facility Butte	S	781	1b
12b	DE3-4(1)		392±19	(N)	AREA II	407	781	1b
13	DE3-4(3)		406±9	(N)	AREA II	445	819	1b
14a	DE4(1)		424±4	(N)	AREA II	491	865	1b
14b	DE4-5(3)	419±33(Y)		N	USGS 80	51 to 55	865	1b
15a	DE5(1)		437±3	(N)	AREA II	524	898	1b
15a	DE5(1)		437±3	(N)	PBF #2	323	898	1b
15b	DE5(1)	441±77(Y)		N	NPR Test	352	898	1b
16a	DE5-6(1)	461±24(Y)		N	USGS 80	99 to 127	993	1b
16b	DE6(1)		473±8	(N)	PBF #2	418	993	1b
17	DE7(1)		479±8	(N)	PBF #2	433	1,008	1b
18a	DE8(1)		488±2	(N)	PBF #2	456	1,031	1b
18b	DE8(1)	491±80(Y)		N	NPR Test	444	1,031	1b
19a	E(1)		512±2	(N)	PBF #2	519	1,094	1b
19b	E(1)	515±85(Y)		N	BG-77-1	300 to 329	1,094	1b

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Table 6. Measured and estimated geologic ages of selected basalt-flow groups and sedimentary interbeds in the unsaturated zone and the Snake River Plain aquifer at the Idaho National Engineering Laboratory—Continued

Number	Unit	Measured age and uncertainty (thousands of years)	Estimated age and uncertainty (thousands of years)	Polarity	Site	Depth (feet)	Cumulative depth (feet)	Line segment
20	EF(1)		549±11	(N)	PBF #2	617	1,192	1b
21a	F(1) [BL, 1988]	565±14(Y)	(570)	R	BG-77-1	426 to 544	1,247	1b
	F(1)	<567±6>(N)		R	BG-77-1	473	1,247	
21b	F(1)		570±4	(R)	PBF #2	672	1,247	1b
22a	FG(1)	580±93(Y)		N	NPR Test	508	1,276	1b
22b	FG(1)		581±1	(N)	PBF #2	701	1,276	1b
23	G(1)		598±13	(N)	PBF #2	746	1,321	1b
24a	H(1)		619±0	(N)	PBF #2	800	1,375	1b, c
24a	H(1)		619±0	(N)	QAB	770	1,375	1b, c
24b	H(1)	619±22(Y)		N	USGS 123	540	1,375	1b, c
	H(1)	<619±9>(N)		N	USGS 123	540	1,375	
	I(1)	<596±18>(N)		N	AEC Butte	S	1,469	
	I(1)	626±67(N)		N	AEC Butte	S	1,469	
25a	I(1)	641±54(Y)		N	NPR Test	606	1,469	1c
	I(1)	643±64(N)		N	USGS 80	198	1,469	
25b	I(1)		660±15	(N)	QAB	864	1,469	1c
26	J(1)		713±51	(N)	QAB	983	1,588	1c
27	K(1)		725±58	(N)	QAB	1,011	1,616	1c
28	KL(1)		740±47	(N)	QAB	1,043	1,648	1c
29a	[B/M, 1979]	730(N)	(759)	N/R			1,692	1c
29b	[B/M, 1995]	780(N)	(759)	N/R			1,692	1c
30	L(1)		759±34	(R)	QAB	1,087	1,692	1c

Table 6. Measured and estimated geologic ages of selected basalt-flow groups and sedimentary interbeds in the unsaturated zone and the Snake River Plain aquifer at the Idaho National Engineering Laboratory—Continued

Number	Unit	Measured age and uncertainty (thousands of years)	Estimated age and uncertainty (thousands of years)	Polarity	Site	Depth (feet)	Cumulative depth (feet)	Line segment
30	L(1)		759±34	R	NPR WO-2	767	1,692	1c
31a	LM1(1)		800±5	[R]	NPR WO-2	860	1,785	1c, 2a, 3a
31b	LM1(4)	807±33(Y)		R	Richard Butte	S	1,785	1c, 2a, 3a
31a	LM1(1)		800±5	[R]	NPR WO-2	860	1,785	1c, 2a
31b	LM1(4)	807±33(Y)		R	Richard Butte	S	1,785	1c, 2a
32a	LM2(1)		813±4	R	NPR WO-2	896	1,821	2a
33a	LM3(1)		824±12	R	NPR WO-2	925	1,850	2a
34a	LM4(1)		853±32	R	NPR WO-2	1,003	1,928	2a
35a	LM5(1)		877±16	R	NPR WO-2	1,068	1,993	2a
36a	LM6(1)		900±0	R	NPR WO-2	1,131	2,056	2a
37a	[J(T), 1979]	900(Y)	(921)	R/N			2,112	2a
38a	LM7(1)		921±15	<N>	NPR WO-2	1,187	2,112	2a
39a	[J(B), 1979]	970(Y)	(964)	N/R			2,229	2a
40a	LM8(1)		964±4	R	NPR WO-2	1,304	2,229	2a
41a	M(2)		999±20	R	NPR WO-2	1,397	2,322	2a
42a	N(1)		1,037±5	R	NPR WO-2	1,502	2,427	2a
42b	N(1)	1,044±35(Y)		R	TCH #1	87	2,427	2a
43a	N(3)		1,060±11	R	NPR WO-2	1,564	2,489	2a
44a	N(4)		1,079±15	R	NPR WO-2	1,614	2,539	2a

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Table 6. Measured and estimated geologic ages of selected basalt-flow groups and sedimentary interbeds in the unsaturated zone and the Snake River Plain aquifer at the Idaho National Engineering Laboratory—Continued

Number	Unit	Measured age and uncertainty (thousands of years)	Estimated age and uncertainty (thousands of years)	Polarity	Site	Depth (feet)	Cumulative depth (feet)	Line segment
45a	[C(M), 1979]	1,100(Y)	(1,096)	R/N			2,585	2a
46a	NO(1)		1,096±3	(N)	NPR WO-2	1,660	2,585	2a
46a	NO(1)		1,096±3	N	C-1A	1,074	2,585	2a
48a	O(1)		1,215±23	[R]	C-1A	1,396	2,907	2a
49a	P(3)		1,245±2	R	C-1A	1,477	2,988	2a, b
49a	P(1)		1,245±2	R	TCH #2	120	2,988	2a, b
49b	P(1)	1,248±69(Y)		R	TCH #1	175	2,988	2a, b
50a	Q(1)		1,314±47	R	TCH #2	246	3,114	2b
51a	R1(1)	1,412±47(Y)		R	TCH #2	467	3,321	2b
51b	R1(1)		1,428±11	R	TCH #2	453	3,321	2b
52a	R2(1)		1,439±19	R	TCH #2	473	3,341	2b
	R2(1)	2,053±79(N)		R	TCH #2	534	3,341	2b
53a	S1(1)		1,482±49	R	TCH #2	551	3,419	2b
	S1(1)	1,936±83(N)		R	TCH #1	523	3,419	2b
54a	S2(1)		1,517±74	R	TCH #2	615	3,483	2b
	S2(1)	2,115±46(N)		R	TCH #2	637	3,483	
55a	S5(1)		1,588±58	R	TCH #2	743	3,611	2b
	S5(1)	2,556±35(N)		R	TCH #2	785	3,611	2b
Effective base of aquifer				R	TCH #2	883	3,751	2b, c
Effective base of aquifer				R	NPR WO-2	1,660	3,751	2b, c
56a	[O(T), 1979]	1,670(Y)	(1,665)	R/N			3,751	2b, c
57a	T(2)		1,665±11	[N]	NPR WO-2	1,660	3,751	2b, c
58a	TU(1)	[1,681±40](N)		N	NPR WO-2	1,708	3,787	2c

Table 6. Measured and estimated geologic ages of selected basalt-flow groups and sedimentary interbeds in the unsaturated zone and the Snake River Plain aquifer at the Idaho National Engineering Laboratory—Continued

Number	Unit	Measured age and uncertainty (thousands of years)	Estimated age and uncertainty (thousands of years)	Polarity	Site	Depth (feet)	Cumulative depth (feet)	Line segment
58b	TU(1)		1,685±4	N	NPR WO-2	1,696	3,787	2c
31a	LM1(1)		800±5	[R]	NPR WO-2	860	1,785	1c, 3a
31b	LM1(4)	807±33(Y)		R	Richard Butte	S	1,785	1c, 3a
32b	LM2(1)		821±10	R	NPR WO-2	896	1,821	3a
33b	LM3(1)		838±22	R	NPR WO-2	925	1,850	3a
34b	LM4(1)		884±39	R	NPR WO-2	1,003	1,928	3a
35b	LM5(1)		922±12	R	NPR WO-2	1,068	1,993	3a
36b	LM6(1)		959±14	R	NPR WO-2	1,131	2,056	3a
36c	LM6(3)	939±154(Y)		R	Lava Ridge	S	2,056	3a
37b	[J(T), 1995]	990(Y)	(991)	R/N			2,112	3a
38b	LM7(1)	[982±53](Y)		<N>	NPR WO-2	1,259	2,112	3a
38c	LM7(1)		991±1	N	NPR WO-2	1,187	2,112	3a
39b	[J(B), 1995]	1,070(Y)	(1,060)	N/R			2,229	3a
40b	LM8(1)		1,060±7	R	NPR WO-2	1,304	2,229	3a, b
41b	M(2)		1,103±23	R	NPR WO-2	1,397	2,322	3b
42c	N(1)		1,152±41	R	NPR WO-2	1,502	2,427	3b
43b	N(3)		1,181±20	R	NPR WO-2	1,564	2,489	3b
44b	N(4)		1,205±4	R	NPR WO-2	1,614	2,539	3b
45b	[C(T), 1995]	1,210(Y)	(1,226)	R/N			2,585	3b

Table 6. Measured and estimated geologic ages of selected basalt-flow groups and sedimentary interbeds in the unsaturated zone and the Snake River Plain aquifer at the Idaho National Engineering Laboratory—Continued

Number	Unit	Measured age and uncertainty (thousands of years)	Estimated age and uncertainty (thousands of years)	Polarity	Site	Depth (feet)	Cumulative depth (feet)	Line segment
46b	NO(1)		1,226±11	(N)	NPR WO-2	1,660	2,585	3b
46b	NO(1)		1,226±11	N	C-1A	1,074	2,585	3b
47	[C(B), 1995]	1,240(N)	--	N/R			--	3b
48b	O(1)		1,377±118	[R]	C-1A	1,396	2,907	3b
49c	P(3)		1,415±117	R	C-1A	1,477	2,988	3b
49c	P(1)		1,415±117	R	TCH #2	120	2,988	3b
50b	Q(1)		1,475±75	R	TCH #2	246	3,114	3b
51c	R1(1)		1,572±6	R	TCH #2	453	3,321	3b
51d	R1(1)	1,581±57(Y)		R	TCH #1	413	3,321	3b
52b	R2(1)		1,581±0	R	TCH #2	473	3,341	3b
	R2(1)	2,053±79(N)		R	TCH #2	534	3,341	
53b	S1(1)		1,618±26	R	TCH #2	551	3,419	3b
	S1(1)	1,936±83(N)		R	TCH #1	523	3,419	
54b	S2(1)		1,648±47	R	TCH #2	615	3,483	3b
	S2(1)	2,115±46(N)		R	TCH #2	637	3,483	
55b	S5(1)		1,708±44	R	TCH #2	743	3,611	3b
	S5(1)	2,556±35(N)		R	TCH #2	785	3,611	
	Effective base of aquifer			R	TCH #2	883	3,751	3b, c
	Effective base of aquifer			R	NPR WO-2	1,660	3,751	3b, c
56b	[O(T), 1995]	1,770(Y)	(1,773)	R/N			3,751	3b, c
57b	T(2)		1,773±2	[N]	NPR WO-2	1,660	3,751	3b, c

Table 6. Measured and estimated geologic ages of selected basalt-flow groups and sedimentary interbeds in the unsaturated zone and the Snake River Plain aquifer at the Idaho National Engineering Laboratory—Continued

Number	Unit	Measured age and uncertainty (thousands of years)	Estimated age and uncertainty (thousands of years)	Polarity	Site	Depth (feet)	Cumulative depth (feet)	Line segment
58c	TU(1)		1,790±14	N	NPR WO-2	1,696	3,787	3c
58d	TU(1)	<1,865±24>(N)		N	NPR WO-2	1,708	3,787	3c