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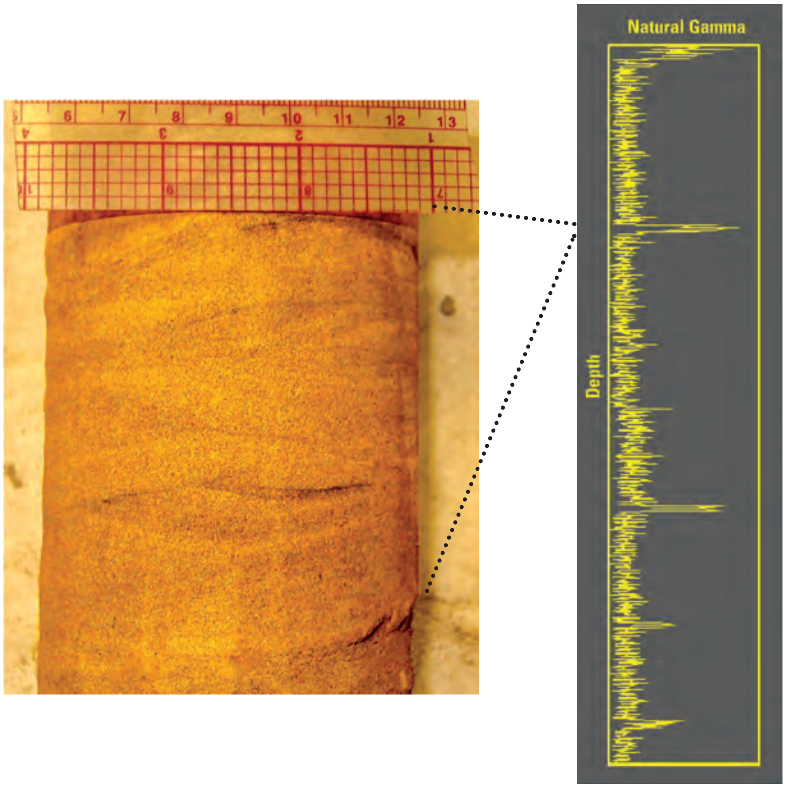
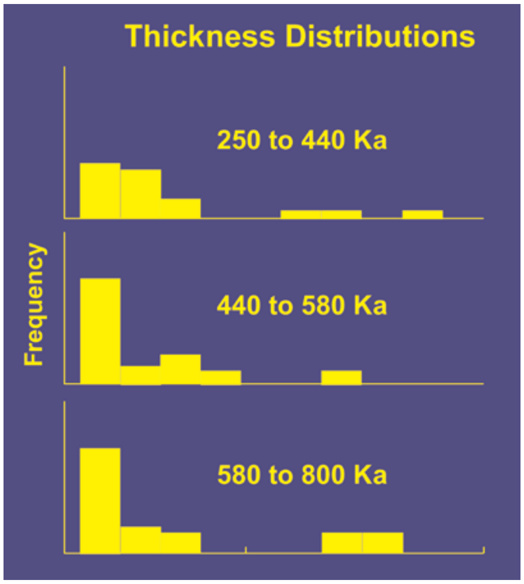
Statistical Stationarity of Sediment Interbed Thicknesses in a Basalt Aquifer, Idaho National Laboratory, Eastern Snake River Plain, Idaho





Scientific Investigations Report 2008-5167

U.S. Department of the Interior
U.S. Geological Survey

Cover: Photograph of sediment core, corresponding natural gamma log, and sediment thickness distributions with time. (Courtesy of John Welhan, Idaho Geological Survey).

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By Caleb N. Stroup, Department of Geosciences, Idaho State University, John A. Welhan, Idaho Geological Survey, and Linda C. Davis, U.S. Geological Survey

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Conversion Factors

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8.$$

Datums

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations and Acronyms

Abbreviation or Acronym	Definition
DOE	U.S. Department of Energy
ESRP	eastern Snake River Plain
INL	Idaho National Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
Ka	Thousand years
K-S	Kolmogorov-Smirnov two sample test of similarity of distribution shape
K-W	Kruskal-Wallis test for similarity of multiple medians
L	Levene’s test of similarity of variances
M-W	Mann-Whitney test for similarity of two medians
PDF	Portable Document Format
RWMC	Radioactive Waste Management Complex
USGS	U.S. Geological Survey

Statistical Stationarity of Sediment Interbed Thicknesses in a Basalt Aquifer, Idaho National Laboratory, Eastern Snake River Plain, Idaho

By Caleb N. Stroup[1], John A. Welhan[2], and Linda C. Davis[3]

Abstract

The statistical stationarity of distributions of sedimentary interbed thicknesses within the southwestern part of the Idaho National Laboratory (INL) was evaluated within the stratigraphic framework of Quaternary sediments and basalts at the INL site, eastern Snake River Plain, Idaho. The thicknesses of 122 sedimentary interbeds observed in 11 coreholes were documented from lithologic logs and independently inferred from natural-gamma logs. Lithologic information was grouped into composite time-stratigraphic units based on correlations with existing composite-unit stratigraphy near these holes. The assignment of lithologic units to an existing chronostratigraphy on the basis of nearby composite stratigraphic units may introduce error where correlations with nearby holes are ambiguous or the distance between holes is great, but we consider this the best technique for grouping stratigraphic information in this geologic environment at this time.

Nonparametric tests of similarity were used to evaluate temporal and spatial stationarity in the distributions of sediment thickness. The following statistical tests were applied to the data: (1) the Kolmogorov-Smirnov (K-S) two-sample test to compare distribution shape, (2) the Mann-Whitney (M-W) test for similarity of two medians, (3) the Kruskal-Wallis (K-W) test for similarity of multiple medians, and (4) Levene's (L) test for the similarity of two variances.

Results of these analyses corroborate previous work that concluded the thickness distributions of Quaternary sedimentary interbeds are locally stationary in space and time. The data set used in this study was relatively small, so the results presented should be considered preliminary, pending incorporation of data from more coreholes.

Statistical tests also demonstrated that natural-gamma logs consistently fail to detect interbeds less than about 2–3 ft thick, although these interbeds are observable in lithologic logs. This should be taken into consideration when modeling aquifer lithology or hydraulic properties based on lithology.

Introduction

The eastern Snake River Plain (ESRP) aquifer, Idaho's largest fresh-water source, lies within the ESRP mafic volcanic province. Pahoehoe basalt and intercalated sediments make up most of the aquifer, with andesite and rhyolite as minor components. Transmissivities and hydraulic conductivities in the aquifer range over six orders of magnitude, and linear ground-water flow velocities are as much as 10 ft/d (Ackerman, 1991; Anderson and others, 1999). Recent ground-water flow modeling has shown that these hydraulic properties are sensitive to the proportion of sediment intercalated within the basalt.

Analysis of sedimentary occurrences by Welhan and others (2006) indicated that the abundance of sediment relative to basalt was statistically stationary: the local medians and variances of sediment abundance do not vary in response to spatial trends, either geographically or time-stratigraphically. Evidence of this was used to justify the application of the kriging interpolation method for modeling sediment abundance in the aquifer. Nonstationary data can be kriged by accounting for a trend, but more importantly, the absence of a trend reveals one of the underlying properties of the geologic system (in this case, a relatively constant sedimentation rate over the entire study area for at least the past 800 thousand years [Ka]).

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Testing for stationarity is relatively straightforward. In this study, as in the work of Welhan and others (2006), nonparametric tests of similarity were applied because the distributions were non-normal and variably skewed. The tests evaluate the degree of statistical similarity between paired and multiple sample populations, in terms of their similarity in shape, medians, and variances.

Numerous well borings, geophysical and lithologic logging records, and drill cores have been collected in the INL region to help define the geohydrologic regime in this part of the ESRP aquifer (fig. 1). Improved understanding of the subsurface stratigraphy has led to increasingly sophisticated conceptual and digital models of the aquifer and of ground-water flow and contaminant transport at various spatial scales. A subregional-scale flow model (approximately 25 by 75 mi; fig. 1) is currently being tested and refined at the U.S. Geological Survey (USGS) INL Project Office. Relative sediment abundances within the aquifer have been shown through model calibration to significantly affect hydraulic conductivity values. A more realistic model of the spatial and stratigraphic variability of sediment may be required to further refine the ground-water flow model.

This study was undertaken by the USGS, in cooperation with the U.S. Department of Energy, to test fundamental assumptions, namely spatial and temporal stationarity, of a geostatistical model of sediment abundance at INL that was developed by Welhan and others (2006). Any future ground-water flow model calibrations will hinge on the accuracy and reliability of such models, and this study was designed to test statistical assumptions in the sediment abundance model. The study also was designed to identify problems or biases in data sets that could affect subsequent studies of a larger scope, such as the subregional scale ground-water flow model being developed by the USGS (Ackerman and others, 2006).

Purpose and Scope

This report describes the results of statistical tests that were used to evaluate the conclusion of Welhan and others (2006) that sedimentary interbeds at INL are distributed in a statistically stationary manner, in a spatial and a temporal sense, using new and more detailed data available subsequent to their study. Welhan and others used stratigraphic data interpreted from geophysical logs of 333 wells to demonstrate that sediment abundances of the stratigraphic units below the water table appear to be statistically invariant in different areas of the INL and through geologic time. The data used in this study are of higher quality than those used by Welhan and others (2006) because detailed lithologic logs of drill cores were available to compliment interpretations based on natural-gamma logs by confirming the existence, position, and thickness of sedimentary interbeds.

The lithologic information used in the previous study of Welhan and others (2006) was based only on natural-gamma log interpretations, so the reliability and quality of the stratigraphic data were unknown; therefore, this study also evaluated the accuracy of the lithologic information that can be obtained solely from natural-gamma logs. High quality stratigraphic data compiled from lithologic logs in this study were compared with stratigraphic inferences based only on geophysical logs to determine if the natural-gamma logs consistently failed to identify interbeds less than about 2–3 feet thick. The relative effort required to interpret geophysical data in conjunction with lithologic logs versus natural-gamma logs alone was also evaluated.

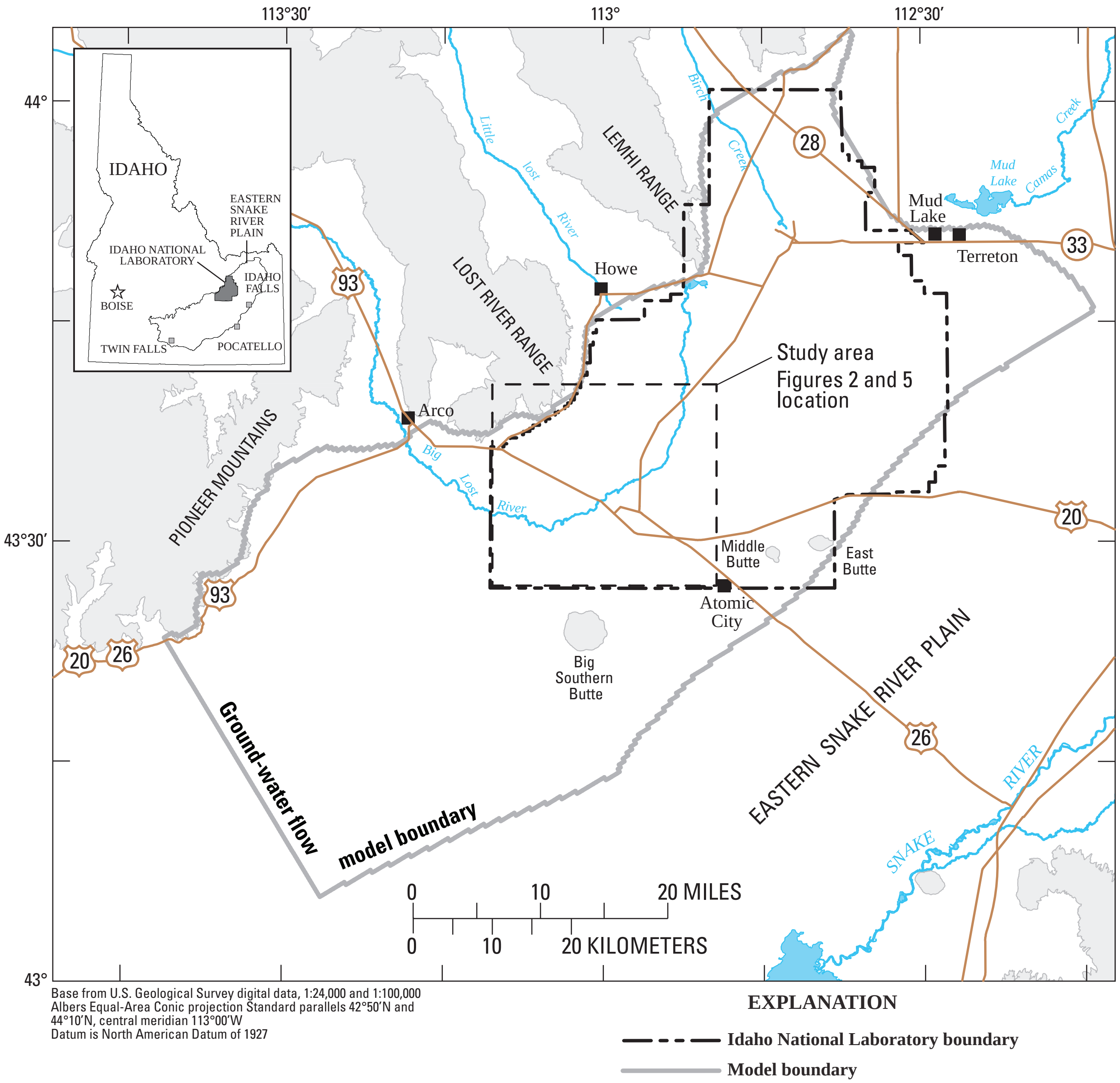
Stratigraphic data, including 122 sedimentary interbeds, from 11 coreholes within the INL boundary were entered into a stratigraphic database. The 11 holes included eight “USGS series” holes and three “Middle series” holes. All new holes are in the southwestern part of the INL. Stratigraphic information was gathered using lithologic, photo, and natural-gamma logs.

Previous Work

Geophysical logging has been the primary method for characterizing lithologies and distinguishing sediment from basalt in the subsurface at the INL (Barraclough and others, 1976; Anderson, 1991; Anderson and Liszewski, 1997). Drill cores have been selectively analyzed for properties such as geochronology, paleomagnetism, and bulk geochemistry (Kuntz and others, 1980; Anderson and others, 1997). Systematic interpretation of these and other data sets has led to the development of a stratigraphic framework and a conceptual model of ground-water flow in the ESRP aquifer (Ackerman and others, 2006). Recent work has focused on characterizing the geostatistical distribution of sediment within the aquifer to aid in future model calibrations (Welhan and others, 2006).

Statistical Analysis

Welhan and others (2006) modeled the distribution of sediment in the aquifer to better understand the variability in hydraulic conductivity within the aquifer and to increase the accuracy of simulation made with the subregional-scale ground-water flow model being developed by the USGS INL Project Office. A main conclusion drawn from their work was that sediment abundance (relative to basalt) in the aquifer is spatially and temporally stationary (statistically invariant). This fundamental assumption allowed Welhan and others (2006) to krige borehole data as two-dimensional spatial data, characterize the geographic distribution of sediment abundance, and parameterize hydraulic conductivity with respect to individual flow model layers (Welhan and others, 2006, p. 13–15).



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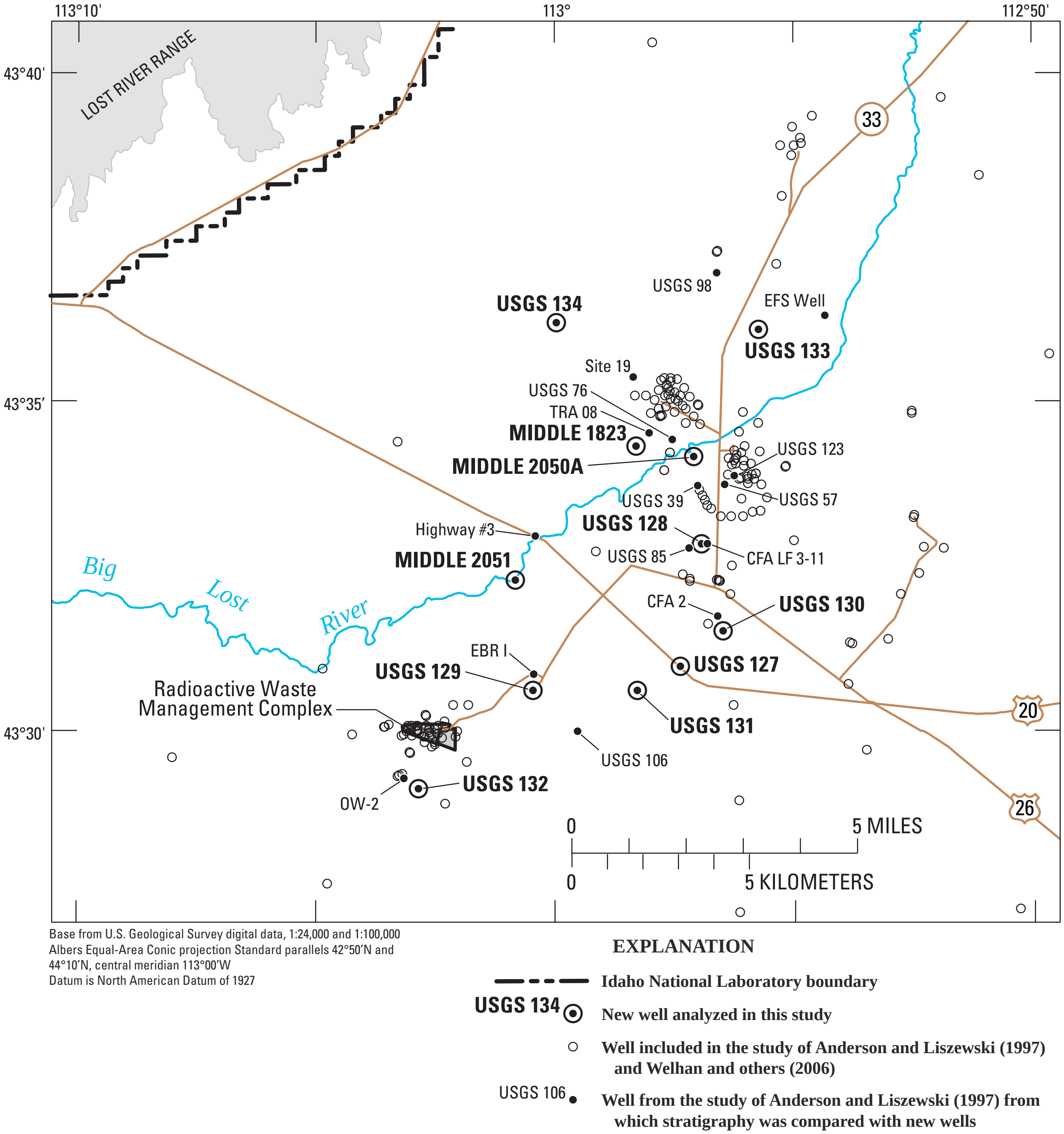
Albers Equal-Area Conic projection Standard parallels 42°50′N and 44°10′N, central meridian 113°00′W
Datum is North American Datum of 1927

Figure 1. Location of the study area, major topographic features, and ground-water flow model boundaries within the Idaho National Laboratory, Idaho.

Interpreted Stratigraphy

Because fewer than 10 percent of all boreholes on the INL have been cored, almost all stratigraphic correlation analyses have relied on geophysical and geochemical indicators. Early subsurface stratigraphic work in the area of the Radioactive Waste Management Complex (RWMC) (Barraclough and others, 1976) used predominantly geophysical logs to characterize sedimentary interbeds and individual basalt-flow groups (defined as packages of flows derived from a single shield volcano). Studies conducted by Anderson and coworkers (Anderson and Lewis, 1989; Anderson, 1991; Anderson and Bowers, 1995; Anderson and Bartholomay, 1990) resulted in the first and most carefully documented stratigraphic framework for the INL subsurface. This work characterized subsurface lithologic variability and offered stratigraphic correlations across the INL on the basis of natural-gamma log records that had been calibrated to available core properties. Interpreted subsurface stratigraphy from 333 boreholes across the INL and vicinity (fig. 2)



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Albers Equal-Area Conic projection Standard parallels 42°50′N and 44°10′N, central meridian 113°00′W
Datum is North American Datum of 1927

Figure 2. Locations of wells included in this study and in the studies of Anderson and Liszewski (1997) and Welhan and others (2006), in the study area, Idaho National Laboratory, Idaho.

were compiled into a database (Anderson and others, 1996; Anderson and Liszewski, 1997). These data were used by Welhan and others (2006) to analyze and geostatistically model sediment abundances in the aquifer beneath the INL.

Composite-Unit Stratigraphy

Anderson and Liszewski (1997) proposed a stratigraphic classification based on groups of units of similar age to show principal subsurface stratigraphic features. They grouped individual basalt and sedimentary units into 14 composite stratigraphic units, each made up of 5 to 90 individual stratigraphic units of similar age (Anderson and Liszewski, 1997, p. 14, table 4).

Composite units recognized in the subsurface of the INL are summarized in table 1. Composite unit 1, the youngest, consists of 78 basalt-flow groups and as many as 12 sedimentary interbeds. Composite unit 14, the oldest, consists of 4 identified basalt-flow groups and 1 sedimentary interbed. The decreasing number of individual units within successively older composite units may be either the result of larger and less-frequent volcanic eruptions or possibly a function of the decreasing availability of borehole data with depth on which to base stratigraphic correlations. Composite units 2–7 are the primary focus of this study because the ESRP aquifer is hosted primarily in these units within the study area. Composite units 8–14 were grouped together and evaluated as a single sample because of the limited number of deep coreholes, resulting in small sample size and the difficulty of making individual composite-unit assignments.

Table 1. Summary of composite stratigraphic units and time spans as defined by Anderson and Liszewski (1997), Idaho National Laboratory, Idaho.

[**Abbreviation:** Ka, thousand years]

Composite stratigraphic unit	Approximate time span of the unit (Ka)
1	5–250
2	250–350
3	350–440
4	440–515
5	515–580
6	580–650
7	650–800
8–14	800–1,800

Data Acquisition and Methods

Stratigraphic data were collected from multiple sources and used to test hypotheses of statistical similarity of the frequency distributions of sediment interbed thickness. Data were collected from several sources and by various methods, and were analyzed by a selected suite of statistical tests.

Data Collection

Subsurface stratigraphic information for boreholes in this study was derived from lithologic data and natural-gamma geophysical logs. Independent stratigraphic interpretations based on only natural-gamma logs and interpretations based on a combination of natural-gamma and lithologic log information were catalogued in a spreadsheet database (appendix A). Unless otherwise specified, “interbed thickness” data in this report refers to what are considered the most accurate inferences of thicknesses derived from a combination of lithologic and natural-gamma log information.

Lithologic logs from “USGS series” holes 127 through 134 were obtained from the USGS INL Project Office in electronic format (table 2). Lithologic information from holes designated Middle 2050a and Middle 2051 was obtained from photographic logs of recovered core. Visual distinction between sediment and basalt in the core-box photographs was fairly straightforward. Lithologic information for hole Middle 1823 was available only from a depth of 500 ft to 1,654 ft (Mazurek, 2005); the first 500 ft of the hole were not cored (table 2). Natural-gamma logs were provided by the USGS INL Project Office for all coreholes in this study and were the only type of geophysical data used in this analysis.

Table 2. Summary of available lithologic, natural-gamma, and photographic log sources and logged intervals from coreholes used in this study, Idaho National Laboratory, Idaho.

[**Abbreviations:** PDF, Portable Document Format; USGS, U.S. Geological Survey; ft, foot]

Corehole	Lithologic log coverage		Natural-gamma log coverage
	Log source	Depth below land surface (ft)	Depth below land surface (ft)
USGS 127	USGS PDF	15–598	4–576
USGS 128	USGS PDF	0–766	7–743
USGS 129	USGS PDF	0–779	3–732
USGS 130	USGS PDF	0–703	0–693
USGS 131	USGS PDF	0–809	3–726
USGS 132	USGS PDF	9–1,235	0–1,220
USGS 133	USGS PDF	0–812	7–746
USGS 134	USGS PDF	0–949	0–921
Middle 1823	Mazurek (2005)	500–1,650	6–1,593
Middle 2050A	USGS photo log	76–1,427	0–1,413
Middle 2051	USGS photo log	127–1,179	0–1,170

Each lithologic unit encountered in a corehole was assigned to a composite stratigraphic unit by correlating the corehole's stratigraphy with that of nearby holes in which a composite-unit stratigraphy had been previously defined by Anderson and Liszewski (1997). Boreholes that were used for this purpose are listed in table 3. Where direct correlation of individual units was difficult or ambiguous, a comparison of depth of interbed and depth of composite units in surrounding holes aided in composite unit assignment.

Five coreholes (USGS 129, USGS 130, USGS 133, USGS 134, and Middle 1823; fig. 2) terminated within a sedimentary interbed, thus providing only a minimum thickness estimate. Such interbeds were excluded from subsequent analysis. Such omission ensures that all thickness data used in this analysis are tied to best estimates of actual thicknesses. Considering the rarity of this occurrence (5 interbeds of 122 observed), omission of these beds does not significantly affect the statistical tests.

Analysis Approach

Welhan and others (2006) concluded that the proportion of sediment relative to basalt in composite unit 1 was larger than that in other composite units. Composite unit 1 also tends to lack thin interbeds (less than about 10 feet) (figs. 3 and 4), which may be the result of relative volcanic quiescence over the past 200 Ka (Anderson and others, 1997; Champion and others, 2002; Welhan and others, 2006).

Welhan and others (2006) tested the frequency distribution of sediment abundance within individual composite units in 333 boreholes across the INL and concluded that these frequency distributions did not vary in a statistically significant manner among composite units 2 through 7 (and less confidently, between composite unit groups 2–7 and 8–14) (Welhan and others, 2006, p. 12 and 16). This study tests the stationarity of the frequency distribution of individual interbed thicknesses within a composite unit rather than the distribution of total sediment thickness in a composite unit. The term distribution will be used hereafter in the statistical sense (that is, synonymous with frequency distribution).

Table 3. List of boreholes with defined composite unit stratigraphy near new coreholes analyzed in this study, Idaho National Laboratory, Idaho.

[Stratigraphy assigned in these holes by Anderson and Liszewski (1997) was used to make composite unit stratigraphic determinations in the new holes. **Abbreviation:** ft, foot]

Corehole	Borehole(s) used to assign composite unit designations	Approximate distance apart (ft)
USGS 127	USGS 130; USGS 106	5,150; 11,200
USGS 128	CFA LF 3-11; USGS 85	95; 1,200
USGS 129	EBR I	1,500
USGS 130	CFA 2	1,450
USGS 131	USGS 106	6,600
USGS 132	OW-2	1,650
USGS 133	EFS Well	6,350
USGS 134	Site 19; USGS 98	8,850; 15,850
Middle 1823	USGS 76; TRA 08	3,500; 1,750
Middle 2050A	USGS 57; USGS 76; USGS 39; USGS 123	3,850; 2,500; 2,750; 4,200
Middle 2051	Highway 3	4,500

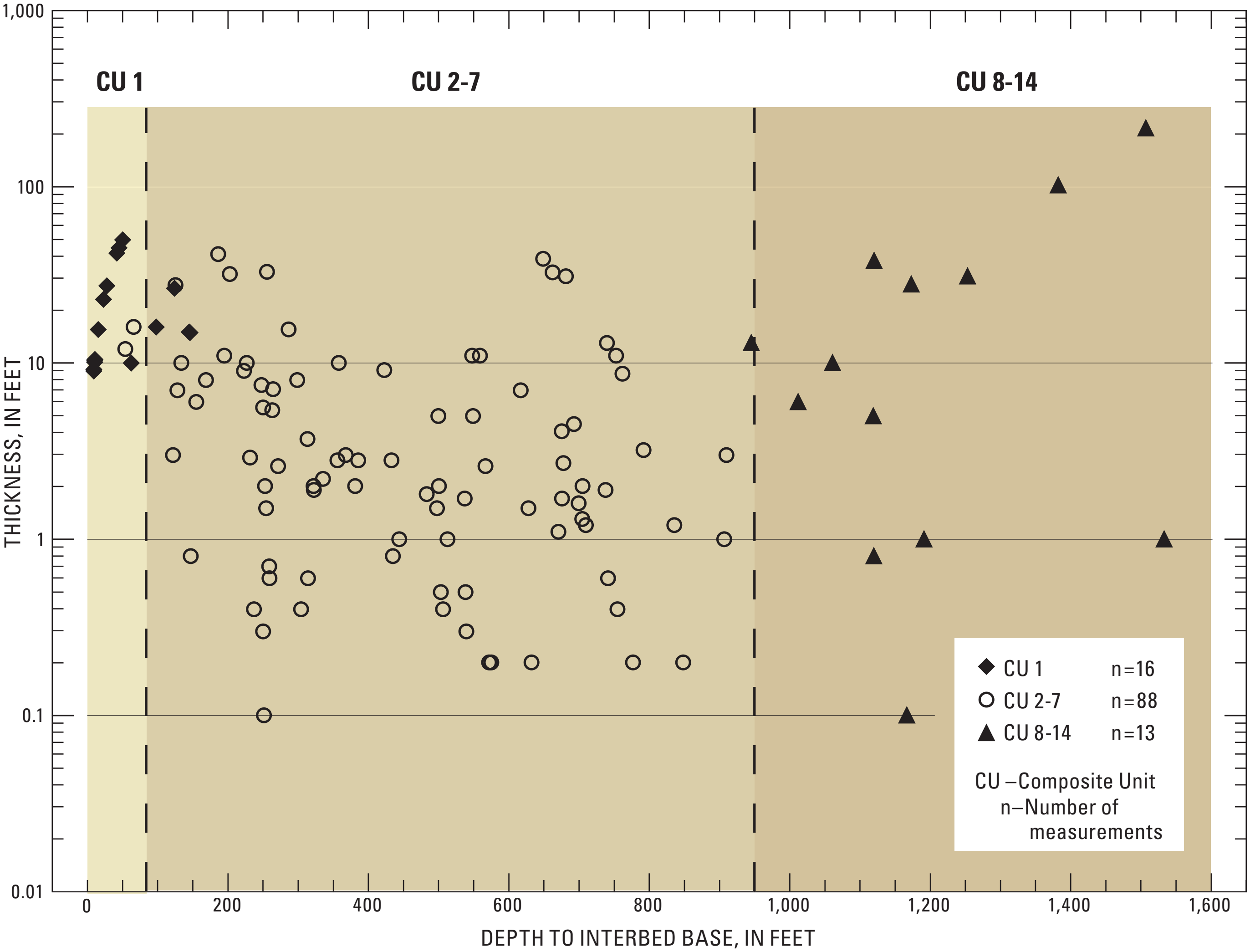

Figure 3. Thickness and depth to the base of all sedimentary interbeds observed in this study, Idaho National Laboratory, Idaho. Shaded areas indicate the average depth to the base of composite-stratigraphic unit 1 and the maximum depth to the base of composite-stratigraphic unit group 2–7.

The analyses conducted here differ from the approach taken by Welhan and others (2006) because of the small sample size of the new corehole data set. The analyses conducted here allow more refined tests of temporal stationarity because they consider more information about the statistics of individual rather than aggregate interbed thicknesses, whereas the approach taken by Welhan and others (2006) is better at testing spatial stationarity across time. The two approaches are equivalent if the relative rates of sedimentation and volcanism that affect sediment thickness distributions have been invariant in time and space.

Nonparametric statistical tests of similarity were performed on distribution shapes, medians, and variances of interbed thicknesses to determine if the different sample populations displayed statistically significant differences or if they were statistically stationary. The Kolmogorov-Smirnov (K-S) two sample test was used to compare distribution shape (form, skewness, peakedness, and degree of tailing) among pairs of sample populations; the Mann-Whitney (M-W) test was used to determine similarity of two medians; the Kruskal-Wallis (K-W) test was used to determine similarity of multiple medians; and Levene's (L) test was used to determine the similarity of two variances.

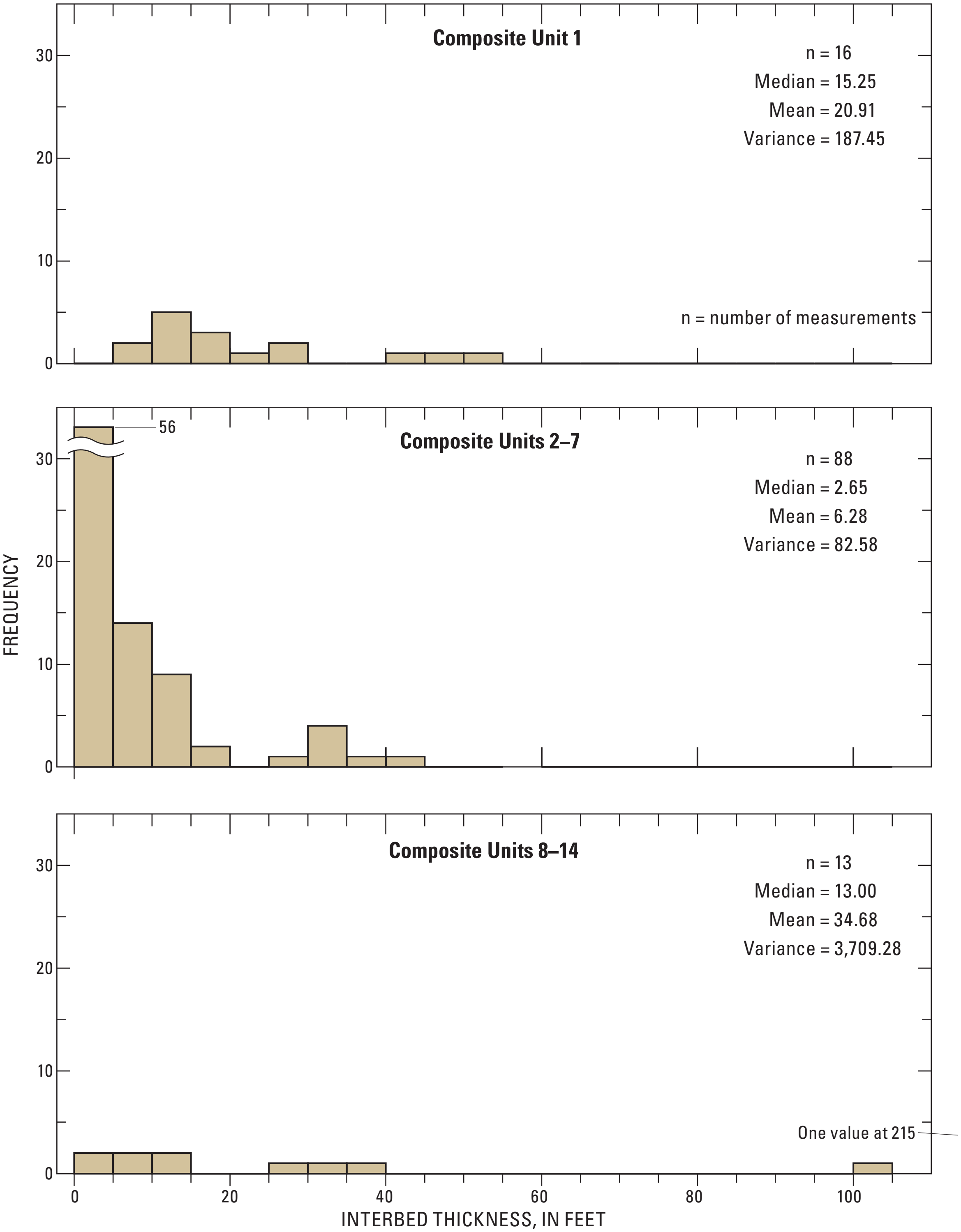

Figure 4. Frequency distribution of individual sedimentary interbed thicknesses among three groups of composite-stratigraphic units, Idaho National Laboratory, Idaho.

Statistical Analysis of Sedimentary Interbed Thickness

Nonparametric statistical tests of spatial and temporal stationarity of sediment interbed thickness distributions were performed and are discussed in the following sections.

Tests of Spatial Stationarity: Composite Units 2–7

To test for spatial stationarity, interbed thickness distributions from two geographically grouped sets of five coreholes were compared (Northeast Hole Group and Southwest Hole Group, fig. 5). Middle 1823 was excluded from this analysis because lithologic information was not available for much of composite units 2–7 in this corehole. All tests of similarity showed no statistically significant difference between these sample groups at the 95 percent confidence level, thereby supporting the hypothesis of spatial stationarity of distributions, medians, and variances of interbed thicknesses (fig. 6; table 4) within the area studied. P-values greater than 0.05 indicate a less than 5 percent probability that the tested populations actually differ in the property being tested and therefore violate the hypothesis of stationarity.

Tests of Temporal Stationarity

The hypothesis of temporal stationarity was tested by comparing sedimentary interbed thickness distributions between groups of composite units. A general grouping scenario using the three groups shown in table 5 (composite unit 1, units 2–7, and units 8–14) was used to test if particular stratigraphic intervals differ from others with respect to interbed thickness distributions (fig. 4, table 5). The K-W test of similarity of multiple medians and the M-W test of similarity of two medians shows thickness distributions of composite units 2–7 are statistically different from composite unit 1 and units 8–14 (table 5). These results corroborate the conclusions of Welhan and others (2006) regarding composite unit 1. They concluded that sediment abundances in composite unit 1 were higher than in other composite units. The data obtained in this study also indicate that interbeds in composite unit 1 tend to be thicker than those in composite units 2–7 (fig. 4, table 5), possibly because of relative volcanic quiescence during the past 200 Ka (Anderson and others, 1997; Champion and others, 2002).

Although the results of this study corroborate the conclusions of Welhan and others (2006) regarding temporal stationarity among composite units 2–7, the new data obtained in this study on interbed thicknesses in composite units 8-14 do not support their conclusion that median sediment content in composite units 2–14 does not statistically vary. The low *p*-values indicate that median interbed thicknesses in composite units 2–7 are statistically different than those in composite units 8–14 (table 5). Sample size, however, is small; more deep stratigraphic data would be needed to confirm this result.

Welhan and others (2006) inferred temporal stationarity among two groupings of composite units 2-7 (composite units 2-5 and 6-7), not among individual composite units. The K-W test was used to analyze the similarity of medians among three grouping scenarios (fig. 7, table 6). Results indicate that the interbed distribution of composite units 2–3 is significantly different at the 95 percent confidence level, whereas the differences among other groups are not statistically significant (table 6). With the exception of composite units 2–3, interbed thicknesses among different groupings support the hypothesis of temporal stationarity across composite units 4–7.

The apparent difference between composite units 2–3 and 4–7 may be due to random variations arising from small sample size (Welhan and others, 2006) or it may reflect a real difference. More data are needed to determine if composite units 2 and 3, like composite unit 1, tend to have significantly thicker interbeds than older units.

Interbed Thicknesses Inferred from Natural-Gamma Logs

Welhan and others (2006) used the data on Quaternary interbed thicknesses that Anderson and Liszewski (1997) interpreted solely from natural-gamma logs. Those data were compared with the interbed thickness data compiled in this study from a combination of lithologic and natural-gamma logs. The statistical distributions of interbed thicknesses in the eight USGS series coreholes (USGS 127 through 134), Middle 2050A, and Middle 2051 (fig. 2) were compared with the statistical distributions of interbed thicknesses in 10 nearby boreholes analyzed by Anderson and Liszewski (1997) (table 7), using the same statistical tests described above (K-S, M-W, and L). Data from only 10 boreholes of Anderson and Liszewski (1997) were used so the number of borings from their analysis was equal to the number of new coreholes studied here. Only composite unit group 1–7 was analyzed because sample size from composite unit group 8–14 was small.

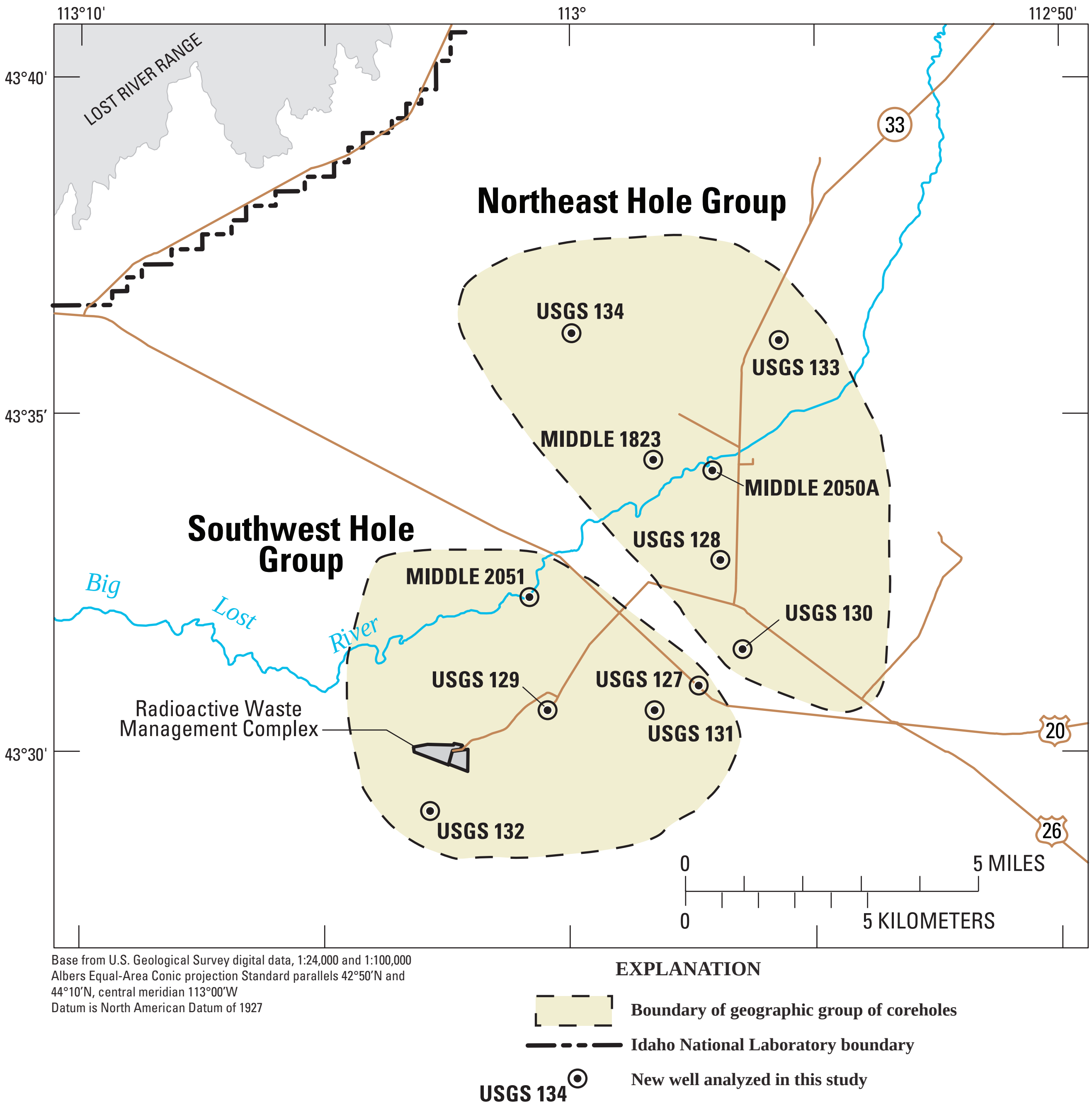

Figure 5. Locations of two geographic groups of coreholes used in tests of spatial stationarity, Idaho National Laboratory, Idaho.

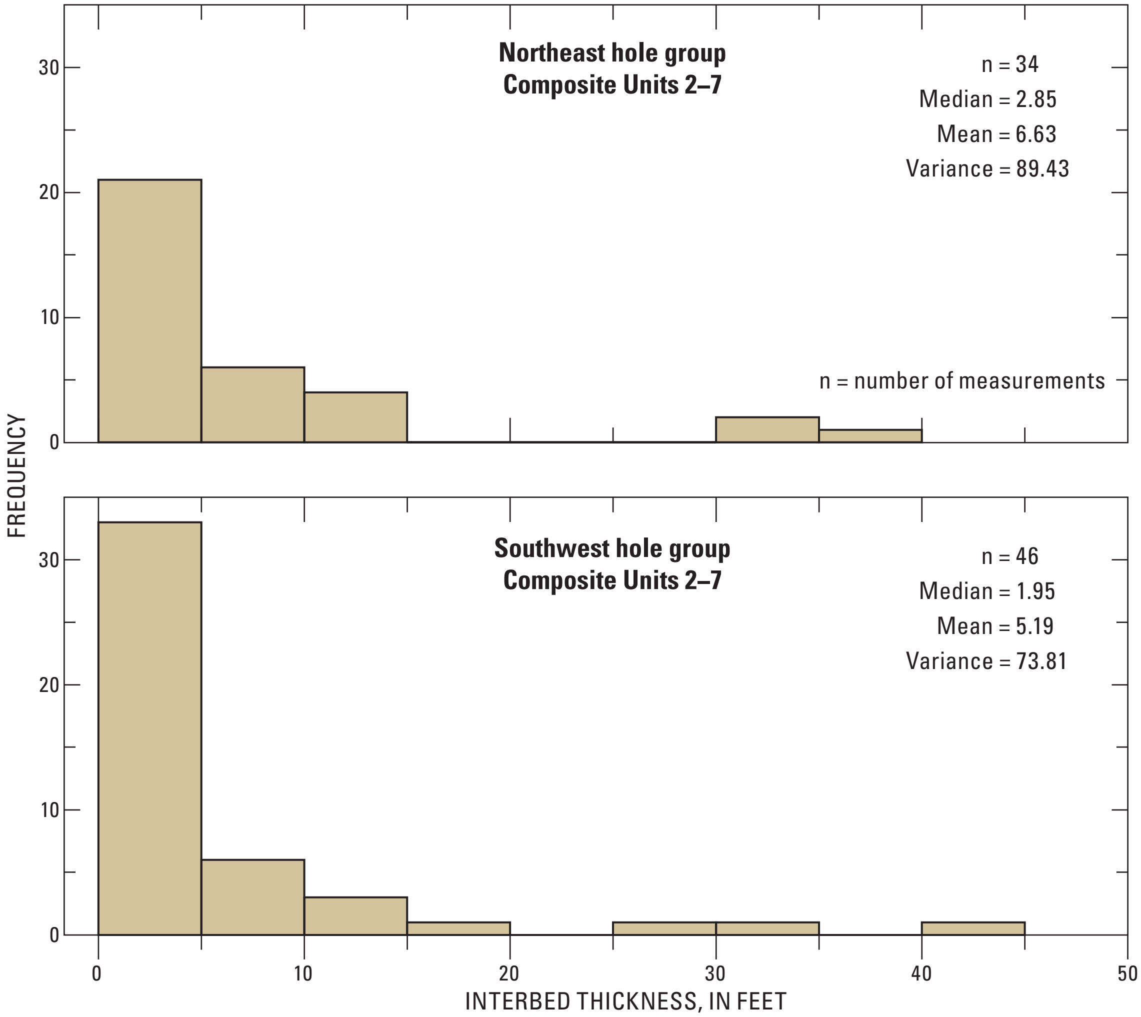

Figure 6. Frequency distributions of individual sedimentary interbed thicknesses within composite stratigraphic units 2–7 from two geographic groups of coreholes, Idaho National Laboratory, Idaho.

Table 4. Results of nonparametric tests of similarity of sediment thickness medians, variances, and distribution shapes between two geographic groups of coreholes, Idaho National Laboratory, Idaho.

[See figure 5 for geographic group locations. **Abbreviations:** M-W, Mann-Whitney test of similarity of medians; L, Levene's test of similarity of variances; K-S, Kolmogorov-Smirnov test of similarity of distribution shape; *p*-value, probability value; vs., versus]

Composite units 2–7 from geographic hole groups			Test	*p*-value	Number of measurements from samples	
1		2			1	2
			M-W	0.182	46	34
Southwest	vs.	Northeast	L	0.219	46	34
			K-S	0.503	46	34

Table 5. Results of nonparametric tests of similarity of median sediment thicknesses between three composite unit groups, Idaho National Laboratory, Idaho.

[**Abbreviations:** K-W, Kruskal-Wallis test for similarity of multiple medians; M-W, Mann-Whitney test of similarity of two medians; *p*-value, probability value; vs., versus]

Groupings of composite units					Test	*p*-value	Number of measurements from samples		
1		2		3			1	2	3
1	vs.	2–7	vs.	8–14	K-W	0.000	16	88	13
1	vs.	2–7			M-W	0.000	16	88	
		2–7	vs.	8–14	M-W	0.005		88	13
1		vs.		8–14	M-W	0.693	16		13

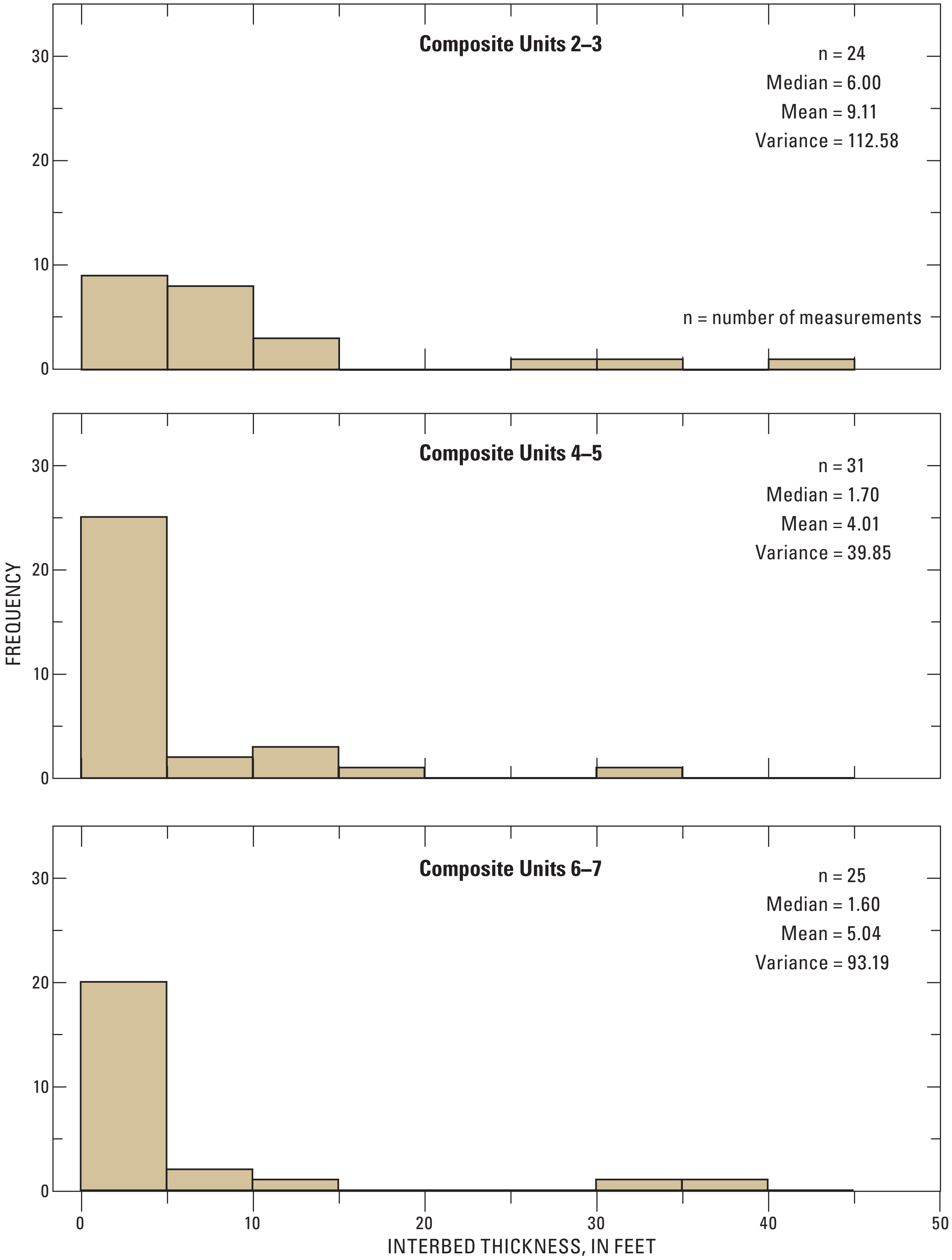

Figure 7. Frequency distributions of individual sedimentary interbed thickness for composite units 2–3, 4–5, and 6–7, Idaho National Laboratory, Idaho.

Table 6. Results of nonparametric tests of similarity of median sediment thicknesses between various composite unit groups within composite units 2–7, Idaho National Laboratory, Idaho.

[**Abbreviations:** K-W, Kruskal-Wallis test for similarity of multiple medians; M-W, Mann-Whitney test of similarity of two medians; *p*-value, probability value; vs., versus]

Groupings of composite units					Test	*p*-value	Number of measurements from samples		
1		2		3			1	2	3
2–3	vs.	4–5	vs.	6–7	K-W	0.001	24	31	25
2–3	vs.	4–5			M-W	0.003	24	31	
		4–5	vs.	6–7	M-W	0.891		31	25
2–3	vs.			6–7	M-W	0.004	24		25
2–4	vs.	5–7			M-W	0.166	47	33	
2–5	vs.	6–7			M-W	0.174	55	25	

Table 7. Boreholes from which stratigraphic information was compiled by Anderson and Liszewski (1997) and compared with information gathered from new coreholes in this study, Idaho National Laboratory, Idaho.

Comparison holes for statistical tests, from Anderson and Liszewski (1997)
USGS 39
USGS 76
USGS 85
USGS 106
CFA LF 3-11
CFA 2
EBR 1
EFS Well
OW-2
Site 19

Distributions of interbed thicknesses from composite units 1-7 were quite different from those of the Anderson and Liszewski (1997) database, consistently showing a statistically significant difference in both the medians (M-W test) and the shapes (K-S test) of the distributions (fig. 8; table 8). These differences are due to the presence of relatively thin (~1-3 ft) interbeds that were distinguished in the new data set from lithologic logs, but not in the Anderson and Liszewski (1997) data set, and probably reflects the difference in data collection methods used in the two studies. Because both the medians and distribution shapes are statistically distinguishable, the similarity of variances demonstrated by the L test has no relevance to the overall similarity of these two samples.

By using lithologic logs in conjunction with geophysical logs to quantify interbed thicknesses, many more thin interbeds could be identified than could be inferred from natural-gamma signatures alone. The physical sensing limitation of natural-gamma sonde censors small features such as thin beds (Keys, 1997). Because the Anderson and Liszewski (1997) lithologic data were compiled using only natural-gamma logs, it is likely that their data are censored of these thin interbeds.

To test the hypothesis that the Anderson and Liszewski (1997) lithologic data are censored of thin interbeds, the interbed thickness data obtained in this study were artificially censored to varying degrees and compared to the data of Anderson and Liszewski (1997) (table 9). By excluding interbeds of thicknesses less than 2 ft, the statistical similarities between the two datasets increased such that they were not statistically different (table 9). By evaluating a range of censoring thresholds, it is possible to conclude that the thickness data of Anderson and Liszewski (1997) are censored at a threshold of between 1 and 2 feet with a 95 percent confidence level, and therefore are not representative of the statistical distribution of all interbed thicknesses.

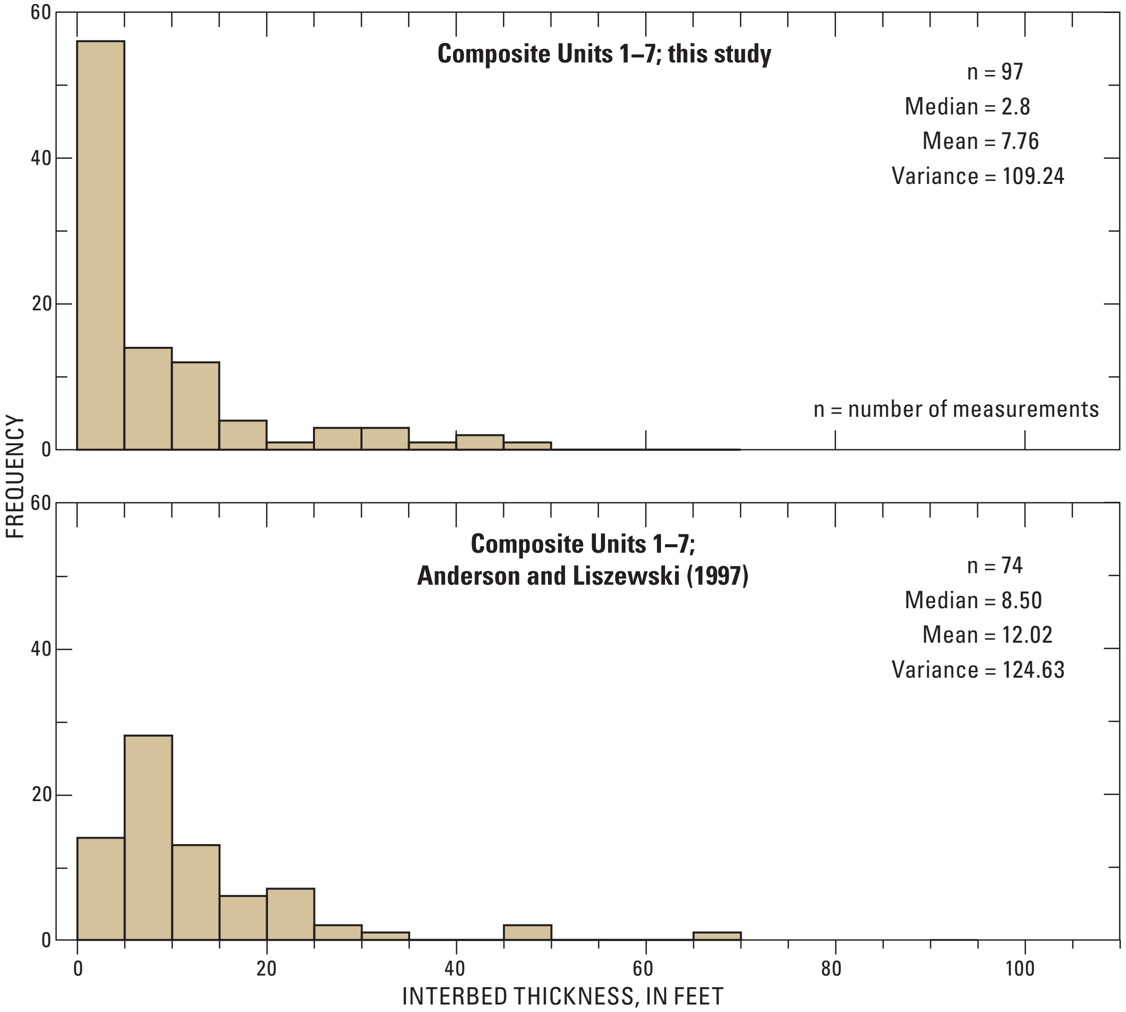

Figure 8. Frequency distributions of individual sedimentary interbed thicknesses among two groups of interbeds from nearby boreholes, from this study and from the study of Anderson and Liszewski (1997), Idaho National Laboratory, Idaho.

Table 8. Results of nonparametric tests of similarity of sediment thickness medians, variances, and distribution shapes between two independent data sets, Idaho National Laboratory, Idaho.

[Selected data from Anderson and Liszewski (1997) interpreted from natural-gamma logs and data from this study gathered using both lithologic logs and natural-gamma logs. **Abbreviations:** M-W, Mann-Whitney test of similarity of medians; L, Levene's test of similarity of variances; K-S, Kolmogorov-Smirnov test of similarity of distribution shape; *p*-value, probability value; vs., versus]

Sedimentary interbed thicknesses of composite units 1–7			Test	*p*-value	Number of measurements from samples	
1		2			1	2
Anderson and Liszewski (1997)	vs.	This data set	M-W	0.000	74	97
			L	0.861	74	97
			K-S	0.000	74	97

Table 9. Results of nonparametric tests of similarity of sediment thickness medians, variances, and frequency distribution shapes, Idaho National Laboratory, Idaho.

[Selected data from Anderson and Liszewski (1997) and data gathered in this study, with various degrees of artificial censoring. **Abbreviations:** M-W, Mann-Whitney test of similarity of medians; L, Levene's test of similarity of variances; K-S, Kolmogorov-Smirnov test of similarity of distribution shape; *p*-value, probability value; vs., versus; >, greater than]

Sedimentary interbed thicknesses of composite units 1–7			Test	*p*-value	Number of measurements from samples	
1		2			1	2
Anderson and Liszewski (1997)	vs.	This data set	M-W L K-S	0.000 0.861 0.000	74 74 74	97 97 97
Anderson and Liszewski (1997)	vs.	This data set (> 1 foot)	M-W L K-S	0.014 0.687 0.000	74 74 74	73 73 73
Anderson and Liszewski (1997)	vs.	This data set (> 2 feet)	M-W L K-S	0.991 0.617 0.386	74 74 74	56 56 56
Anderson and Liszewski (1997)	vs.	This data set (> 3 feet)	M-W L K-S	0.050 0.603 0.103	74 74 74	46 46 46

Conversely, statistical comparisons of the new corehole data based solely on natural-gamma logs showed no statistically significant difference with the Anderson and Liszewski (1997) data (fig. 9; table 10). A few relatively thin (2–3 ft) interbeds were still observed with the new geophysical data, indicating that an unintentional bias may have been introduced because of pre-existing knowledge of the lithologic log information.

The analyses conducted here document the censoring effect of natural-gamma logs and indicate that detailed lithologic logs are essential for accurately interpreting subsurface interbed occurrences. Lithologic logs do not require significantly more effort to interpret than geophysical logs, and in fact may entail less effort overall. Drawbacks include potentially poor knowledge of the actual sediment recovery when coreholes are logged, together with the expense and infrastructural overhead involved with coring, logging, and core storage.

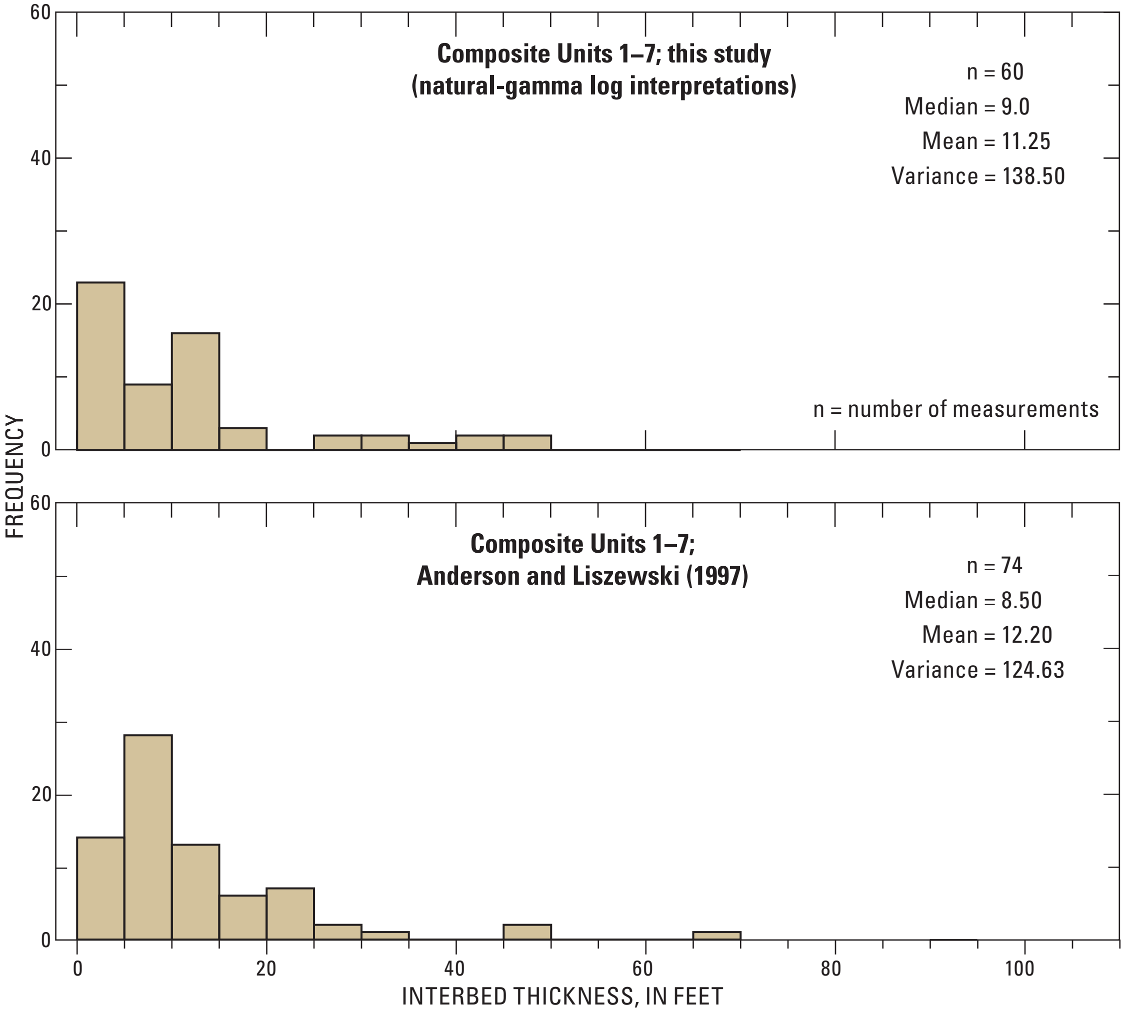

Figure 9. Frequency distributions of individual sedimentary interbed thicknesses among two groups of interbeds, from this study based only on natural-gamma logs and from the study of Anderson and Liszewski (1997), Idaho National Laboratory, Idaho.

Table 10. Results of nonparametric tests of similarity of sediment thickness medians, variances, and distribution shapes between two independent data sets interpreted from natural-gamma logs, Idaho National Laboratory, Idaho.

[Selected data from Anderson and Liszewski (1997) and data gathered in this study. **Abbreviations:** M-W, Mann-Whitney test of similarity of medians; L, Levene's test of similarity of variances; K-S, Kolmogorov-Smirnov test of similarity of distribution shape; *p*-value, probability value; vs., versus]

Sedimentary interbed thicknesses of composite units 1–7			Test	*p*-value	Number of measurements from samples	
1		2			1	2
Anderson and Liszewski (1997)	vs.	This data set (interpreted from natural-gamma logs)	M-W	0.120	74	60
			L	0.548	74	60
			K-S	0.052	74	60

Summary and Conclusions

The stratigraphy of sedimentary interbeds from 11 coreholes at the Idaho National Laboratory, Idaho, was interpreted using the best available lithologic and natural-gamma log information. This information was used to test hypotheses posed by earlier investigators regarding the spatial and temporal stationarity of aggregate interbed thickness distributions in the Quaternary basalt-dominated eastern Snake River Plain (ESRP) aquifer. A total of 122 sedimentary interbeds were observed in 11 subsurface borings using natural-gamma geophysical logs and lithologic core logs to identify the occurrence and thickness of interbeds beneath the southwestern part of the Idaho National Laboratory.

The statistical analyses conducted in this study tested the stationarity of individual interbed thickness distributions rather than aggregate thicknesses as conducted by earlier investigators. The following statistical tests were applied to the data (1) the Kolmogorov-Smirnov (K-S) two-sample test to compare distribution shape, (2) the Mann-Whitney (M-W) test for similarity of two medians, (3) the Kruskal-Wallis (K-W) test for similarity of multiple medians, and (4) Levene's (L) test for the similarity of two variances. The results generally support the hypothesis that the frequency distribution of sedimentary interbed thicknesses in composite stratigraphic units designated 2 through 7 is temporally and spatially stationary (invariant). However, because sample size was small, the results should be considered preliminary until more high-quality corehole information becomes available. For example, the new data indicate that interbeds in composite units 2 and 3 may be thicker than those in units 4–7. The approach taken in this study (testing individual interbed thickness distributions) also might be applied to a data set developed for the INL by earlier investigators to explore more subtle aspects of statistical variability in a stratigraphic context, such as possible trends in the proportion of sediment relative to basalt in the uppermost part of the stratigraphic section.

The composite unit stratigraphy developed for the Idaho National Laboratory in an earlier study provides a useful framework for grouping stratigraphic intervals and correlating stratigraphy in new boreholes with that of nearby existing holes. However, unique, laterally persistent marker horizons are rare and it can be difficult to correlate stratigraphic intervals and assign composite unit stratigraphy when holes are separated spatially.

High quality lithologic logs greatly improve the ability to identify sedimentary interbeds in the ESRP aquifer, especially those that are relatively thin (less than 2–3 ft. thick). A combination of high-quality lithologic logs and natural-gamma logs provide a more confident characterization of aquifer lithology and stratigraphy. However, good quality stratigraphic data still can be obtained from geophysical logs alone when the presence of thin interbeds is not critical to the scope of the stratigraphic analysis.

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Appendix A. Development of Database

Stratigraphic information interpreted from geophysical and lithologic logs was entered into a Microsoft Excel™ spreadsheet. The spreadsheet was set up with Excel's AutoFilter capability, which allowed data in each field to be easily queried, sorted, or filtered. The spreadsheet can be imported into Microsoft Access™. Stratigraphic data were entered into 14 individual fields. A field list with a brief description of each field is given in table A1.

Data flags were used if information was irrelevant or unavailable. An -888 flag was entered if no data were available. A -999 flag was used if an entry was irrelevant; for example, -999 was entered under the Thickness_Geophys field for all basalt units, because geophysical logs were not used to quantify basalt thicknesses.

Locations of each well (Albers coordinates) and elevations to the top of the wells were obtained from a USGS-INL shapefile of borings on the INL. The depth of the well log was entered as the deepest log recording from either lithologic or geophysical logs. For lithologies logged by USGS personnel, a flag value of 2 was entered in the Source_Flag field, and for coreholes logged by non-USGS personnel, a 1 was entered. The general lithology (sediment or basalt) of each identified unit was entered under the StratUnit_type field.

Sediment interbeds were generally represented by higher natural-gamma signatures. A sedimentary interbed was interpreted to exist only where the width and height of natural-gamma spikes were distinct from background (basalt) levels. Boundaries between sediment and basalt were interpreted at the midpoints of the top and bottom shoulders of the natural-gamma interbed signal.

A relative confidence flag (high, medium, or low) was entered under the Confidence_Composite_unit field to qualify the degree of confidence with which a composite unit assignment was made. The degree of confidence was qualitatively based (high, medium, or low) on the proximity of coreholes to boreholes with established composite unit stratigraphy and on how well composite units could be correlated between these and the new coreholes. Where confidence was low, an alternative composite unit designation was entered under the Alt_Comp_Unit field to record the next most likely designation.

The depth to the base of each sedimentary or basalt unit (in feet below top of well), regardless of lithology, was entered under the DepthBase field. For holes with lithologic logs, the thickness of sedimentary interbeds interpreted only from lithologic logs was entered under the Thickness_Lith field. Only logged sediment thicknesses were considered. Missing intervals in lithologic logs due to poor core recovery did not contribute to this thickness, although in some cases, sediment likely existed but was not recovered. Sediment interbed thickness interpreted only from natural-gamma logs was entered under the Thickness_Geophys field. If no natural-gamma spike was observed corresponding to an interbed recognized in a lithologic log, a thickness value of 0 was entered to record the failure of the geophysical log to detect the interbed. For holes with only geophysical logs, it was not possible to identify sedimentary interbeds that were not recorded by natural-gamma logs. In this situation, some fraction of interbeds presumably were not recorded. For holes with both lithologic and natural-gamma logs, the most likely interbed thickness was determined using lithologic and natural-gamma logs and entered under Thickness_Inferred. This represents the best quality thickness data available on the basis of both lithologic logs and natural-gamma signatures of interbeds. The relative confidence in the inferred thickness was entered under the Confidence_Thickness field. The degree of confidence (high, medium or low) was based on the explicitness of the base and top of interbeds as recorded by lithologic logs, geophysical logs, or both.

Table A1. List of fields under which data were entered in the database with a brief description of each field.

Field Name	Description
Boring_name	Name of core
X_ALB	Albers projection coordinate
Y_ALB	Albers projection coordinate
AltWell	Altitude of top of well
DepthLog	Depth of recorded well log
Source_Flag	Data source: "1" if non-USGS, "2" if USGS
StratUnit_type	Unit type: sediment or basalt
Composite_unit	Composite unit number
Confidence_Composite_unit	Confidence in composite unit designation: high, medium, low
Alt_comp_unit	Where confidence is low, alternative composite unit designation
Confidence_Thickness	Confidence in thickness of unit: high, medium, low
DepthBase	Depth of base of interbed unit
Thickness_Lith	Thickness of interbed based only on lithologic log
Thickness_Geophys	Thickness of interbed based only on geophysical logs
Thickness_Inferred	Inferred thickness of interbed based on both lithologic and geophysical logs

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