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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

by

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ABSTRACT

The petrography, age, and paleomagnetism were determined on basalt from 23 lava flows comprising about 1200 feet of core from four coreholes in the Idaho National Engineering Laboratory (INEL). The four coreholes, Well 80, NRF 89-04, NRF 89-05, and ICPP 123, are located in the southwestern part of the INEL. Paleomagnetic measurements were made on 192 samples of basalt, and K-Ar ages were measured on 19 basalt samples. All of the samples have normal magnetic polarity and were erupted during the Brunhes Normal Polarity Epoch. Basalt lava flows in ICPP 123 can be satisfactorily correlated with lava flows in the previously studied corehole at Site E, but correlations cannot be made with confidence between ICPP 123 and the other three coreholes studied in this investigation.

INTRODUCTION

The U.S. Geological Survey currently is studying the petrology, petrography, geochemistry, paleomagnetism, and age of basalt lava flows in several coreholes at the Idaho National Engineering Laboratory (INEL), located between Arco and Idaho Falls in southeastern Idaho (Fig. 1). The current program is a continuation of studies begun in 1974 to evaluate potential volcanic hazards at INEL. These studies included geologic mapping and various studies of surface lava flows such as petrologic and paleomagnetic investigations and radiometric age measurements. Similar investigations were carried out on selected drill cores.

The present project was begun in 1989 with the objective of studying in some detail core samples from several wells in the INEL. Funding for the research project has been provided by the U.S. Department of Energy. The specific coreholes named in the 1989-project proposal were Well 80, TAN CH#1, NRF 89-04, NRF 89-05, ICPP 123, 2-2A, and WO-2. The purpose of the proposed investigations was to develop a three-dimensional stratigraphic framework for geologic and hydrologic studies including potential volcanic hazards to facilities at the INEL and movement of radionuclides in the Snake River Plains aquifer.

This report is a progress report on current investigations. We plan to issue progress reports as work is completed on specific coreholes. This report will cover paleomagnetic measurements, potassium-argon (K-Ar) age measurements, and petrographic characteristics of basalt lava flows in Well 80, NRF 89-04, NRF 89-05, and ICPP 123.

GEOLOGIC SETTING

The INEL covers an area of about 2300 km^2 in the eastern Snake River Plain (Fig. 1), which is a northeast trending physiographic province that is underlain by Neogene and Quaternary volcanic rocks and interbedded sediments. Rhyolitic flows are generally exposed only along the margins of the plain, but several domes, surrounded by basalt flows, are located in the plain. Most of the eastern plain is covered by late Pleistocene and Holocene basalt-lava fields.

The surface geology of the INEL has been studied and a number of wells have been drilled to provide subsurface information. Kuntz and others (1984) published a geologic map of the INEL and adjoining areas; the map was later revised (Kuntz and others, 1990) to include subsequently acquired geologic and paleomagnetic data and radiometric ages. Kuntz and others (1980) described the petrography, age, and paleomagnetism of basalt flows penetrated in five cored holes at the Radioactive Waste Management Complex (RWMC) in the southwestern part of the INEL (Fig. 1). A new cored hole (site E) drilled about 10 miles (16 km) northeast of the RWMC was studied in detail by Champion and others (1988).

Lava flows at the INEL are very similar petrographically. All are tholeiitic olivine basalt that contain olivine, plagioclase, clinopyroxene, ilmenite, magnetite, glass, and accessory apatite. In general, there are significantly different textural varieties between adjacent basalt flows even though the mineralogy remains similar. In the subsurface, some lava flows are separated by sedimentary interbeds though the distribution and thickness of these interbeds is highly variable.

K-Ar ages of surface flows in the INEL range from 165 ± 22 ka (10^3 yr) to 1216 ± 50 ka (Kuntz and others, 1990). The oldest age reported on a lava flow in the subsurface is 641 ± 54 ka on the deepest flow in the site E well (Champion and others, 1988).

Surface lava flows and vents in the southern part of the INEL have normal polarity and were erupted during the Brunhes Normal Polarity Chron. Some surface lava flows and vents in the northern part of the INEL are reversely magnetized and were erupted during the Matuyama Reversed Polarity Chron. In well 77-1 at the RWMC there are two lava flows with reversed polarity (Champion and others, 1981); a K-Ar age of 565 ± 14 ka was measured on these flows (Champion and others, 1988). A reversed flow having a magnetic inclination similar to flows 10 and 11 in well 77-1 occurs in the corehole at site E. These reversely magnetized flows were erupted during a polarity event named the Big Lost Reversed Polarity Subchronozone and Subchron by Champion and others (1988).

ANALYTICAL TECHNIQUES

Selected cores were carefully logged and sampled for petrographic studies using standard procedures. The logging involved description of core material, location of tops and bottoms of lava flows, and preparation of lithologic logs. Lava flows were sampled for thin section analysis at appropriate intervals. Samples were taken within flows to represent the top, middle, and bottom, and also to represent textural varieties of the flows. Depths were measured by tape measure from known depths recorded on wooden plugs in the core boxes. The color of flows was determined by comparison to standard color chips in the Munsell Soil Color Charts. Textures and minerals were identified using a hand lens. Sizes of crystals were determined from thin sections using a micrometer ocular.

For paleomagnetic studies, 2.5 cm-diameter cores were drilled at right angles to the axis of the original core, which was generally 6 cm in diameter, to provide samples for magnetic analysis. Generally seven samples of core were taken from each flow or flow unit subject to the constraints of their thicknesses. The mini-core specimens were trimmed to 2.2-cm lengths, and these specimens were measured using cryogenic and spinner magnetometers. Progressive alternating field demagnetization using a commercial tumbling demagnetizer was performed on each specimen to remove any components of secondary magnetization. The primary remanence inclinations measured on individual basalt specimens are shown on the logs for the cores studied (Figs. 3-5). Mean inclination values for each lava flow and 95% confidence limits about the mean value were calculated using the method of McFadden and Reid (1982).

Thin sections of 51 samples of basalt from the four drill cores were examined petrographically to determine those most suitable for K-Ar dating. 19 samples were chosen for analysis; these samples met the usual criteria of acceptability for whole-rock K-Ar dating (Dalrymple and Lanphere, 1969; Mankinen and Dalrymple, 1972). The samples were crushed and ground to a size of 1/2 to 1 mm. An aliquant (10 g) of the sized master sample was pulverized to less than 74 μm, and this powdered material was used for the K_2O measurements. The K_2O measurements were made in duplicate on each of two splits of powder by flame photometry after lithium metaborate fusion and dissolution (Ingamells, 1970). Argon analyses were made by isotope dilution mass spectrometry using techniques described previously (Dalrymple and Lanphere, 1969). Aliquants of the 1/2-1 mm master sample were baked overnight in vacuum in an argon extraction system at 280°C. Ar mass analyses were done on a computerized multiple-collector mass spectrometer having 22.86-cm radius and nominal 90°-sector magnet (Stacey and others, 1981). The analytical error for an individual age measurement was calculated using the method of Cox and Dalrymple (1967). Weighted mean ages for lava flows were calculated using the method of Taylor (1982).

RESULTS

Twenty-two lava flows were identified in the three cored holes, Well 80, NRF 89-05, and ICPP 123, that were studied petrographically. The core from NRF 89-04 was not studied petrographically, but the same four lava flows occur in both NRF 89-04 and NRF 89-05; there may be a fifth flow at the bottom of well 89-04. The 22 lava flows range in thickness from 4.5' to 127.5' and average 46.1'. A flow that consists of several flow units (for example, flow 2 in well NRF 89-05 [77' thick, 6 flow units] and flow 5 in well ICPP 123 [39' thick, 4 flow units]) suggests emplacement relatively close to the vent. A flow that consists of a single flow unit (for example, flow 1 in well NRF 89-05 [86' thick] and flow 7 in well ICPP 123 [98' thick]) suggests emplacement at a relatively greater distance from a vent. Flows that are 2 to 3 times the thickness of an average flow (for example, flow 1 in well NRF 89-05 and flows 7 and 12 in well ICPP 123) are assumed to have been ponded; that is, they accumulated in a depression where the outlet was restricted or blocked. These depressions may have formed in strictly geomorphic ways, such as a closed depression between several shield volcanoes or a depression along the course of a stream. The depressions may also have formed in structural ways, such as slumping of surface rocks in volcanic rift zones, slumping related to compaction of underlying sedimentary or volcanic deposits, or, perhaps, faulting.

Most flows investigated in this study do not have significant amounts of cinder, breccia, or rubble at on near their uppermost surfaces. This suggests that most of the flows are pahoehoe and not slab pahoehoe or a'a flows.

Basaltic lava flows of the Snake River Plain are remarkably similar in gross petrographic character. However, two objectives of this study were to determine (1) whether or not individual flows possessed unique lithologic and petrographic characteristics, and, if so, (2) whether these characteristics could be used to "fingerprint" individual flows and correlate them between adjacent core holes. The answer to the first question is a qualified "yes." It appears that each flow has a set of lithologic and petrographic characteristics that are reasonably consistent from top to bottom of the flow. The characteristics are also consistent from one flow unit to another in a flow that consists of multiple flow units. These characteristics can be used to distinguish a flow from overlying and underlying flows and from other flows in the same corehole. The changes in lithologic and petrographic characteristics from flow to flow also commonly correlate with abrupt changes in paleomagnetic inclination. This lends additional credence to the idea that each flow possesses a unique set of lithologic and petrographic characteristics. The answer to the second question posed above is not yet known because, to date, flows have not been studied in closely spaced core holes to determine whether lithologic and petrographic characteristics can be used for correlation purposes. Detailed core descriptions are given in Appendix A.

K-Ar ages were measured on 19 basalt samples from the four coreholes. Duplicate age measurements were made on each sample, and individual ages were pooled to yield sample ages. The ages ranged from 219 ± 50 ka to 819 ± 39 ka. The uncertainty in sample ages generally ranged from 5 to 15 percent of the sample age. As discussed below, the ages in a given corehole generally fall in the proper stratigraphic sequence. Individual ages have rather large uncertainties which reflect both the youth of the basalts and low contents of radiogenic ^{40}Ar. The latter results from low K_2O contents and large contents of non-radiogenic ^{40}Ar.

Paleomagnetic measurements were made on 192 basaalt samples from the four coreholes. The averaged mean inclination value for individual lava flows or flow unit groups varied between 76.0° to 53.4°, within the usual range of inclination due to geomagnetic secular variation. The precision of these mean values, reported as two standard errors of the mean (α_{95}), ranges between 0.7° to 17.0°; the modal value is near 2°. Data of this precision generally allows us to differentiate or correlate flows or flow units, when combined with the stratigraphic constraints from the physical core logging. Macroscopic and thin-section data were used to differentiate several lava flows that have indistinguishable mean inclination values.

Similar mean inclination values can be randomly acquired by two successive lava flows, even though they are 10,000's of years different in age. In the absence of stratigraphic or chronologic evidence to the contrary, petrographic differentiation should prevent false correlation of flows which are really different volcanic events. Alternatively, flows of differing lithology having the same mean inclination value, and which are not separated by a sedimentary interbed, may well represent the same eruptive event in time, but may have been erupted from two distinct vents and may represent two different magma batches. Such circumstances have been demonstrated in the surface paleomagnetic work presented in Kuntz and others (1990). Our work on these four drill cores did not allow a choice between these alternatives.

The results for individual core holes are discussed below.

WELL 80

Well 80 is a 204-ft-deep corehole located northwest of the Idaho Chemical Processing Plant (ICPP) about two-thirds of the way to the Test Reactor Area (TRA) (Fig. 1). Well 80 contains four lava flows separated by eolian and alluvial sedimentary interbeds. A log of the core stratigraphy, paleomagnetic inclinations, and location of samples used for paleomagnetic and K-Ar age measurements is given in Figure 2.

Paleomagnetic measurements

Remanent magnetic polarity and inclination values were measured on 28 samples taken from four lava flows in well 80. All flows sampled have normal polarity; they were erupted during the Brunhes Normal Polarity Epoch. Four independent inclination groups are apparent in the length of the core; their mean inclination values, in descending order, are:

	depth	inclination
Flow 1	44 - 73'	54.5° ± 1.3°
Flow 2	76 - 136'	76.0° ± 2.4°
Flow 3	144 - 162'	59.6° ± 4.8°
Flow 4	177 - 204'(+)	53.9° ± 1.9°

The mean inclination values for flows 2 and 3 do not include all the data shown on figure 2. The top sample taken in flow 2 at 79', and the top two samples taken in flow 3 at 145' and 149', were difficult to magnetically clean and thus are probably magnetically overprinted by reheating from the overlying flow. Both flows 1 and 4 have relatively shallow mean inclination values which are similar to the 53.5° inclination value from nearby AEC Butte. As noted below, the age of flow 1 is much younger than the age of basalt from AEC Butte (Kuntz and others, 1990), and AEC Butte cannot be the source for flow 1. Flow 4 and AEC Butte have similar K-Ar ages; thus, AEC Butte is the likely source for flow 4. Because of its proximity to the postulated source vent, flow 4 is likely to be much thicker than the 27' sampled in well 80.

K-Ar age measurements

Duplicate K-Ar ages were measured on nine samples from the Well 80 core--two samples each from flows 1 and 2, three samples from flow 3, and two samples from flow 4. Ages and analytical data are given in Table 1. The results from flows 1 and 2 are internally consistent. The ages of 419 ± 33 ka and 461 ± 24 ka for flows 1 and 2, respectively, also are in the correct stratigraphic order. The three samples from flow 3 gave inconsistent results. Two of the ages, 267 ± 21 ka and 272 ± 17 ka, are much younger than the ages measured on flow 2. The third age, 435 ± 21 ka, is not analytically different than the age of flow 2 and is considered a minimum age for flow 3. The flow is only 20 ft thick and may have suffered alteration during the time the overlying sedimentary interbed was accumulating. The two samples from flow 4 also yielded ages that are internally inconsistent. The duplicate measurements on each sample agreed very well, but the two sample ages do not agree within analytical uncertainty. Flow 4 is olivine phyric which is markedly different from most Snake River Plain lavas. It also has a characteristic shallow magnetic inclination that agrees well with the inclination of surface lava flows at nearby AEC Butte (Fig. 1). The K-Ar age of a lava from AEC Butte is 626 ± 67 ka (Kuntz and others, 1990). Flow I from the core at Site E has a similar shallow inclination and a K-Ar age of 641 ± 54 ka (Champion and others, 1988). Thus, we believe that flow 4 was erupted from AEC Butte, and the best estimate of the age of flow 4 is the age of 643 ± 64 ka measured on sample 80-198.

NRF 89-04 AND 89-05

Wells NRF 89-04 and NRF 89-05 are located in the eastern part of the U.S. Naval Reactors Facility (Fig. 1); NRF 89-04 is about 500 ft north of NRF 89-05. NRF 89-04 and NRF 89-05 were cored to depths of 248 ft and 242 ft, respectively. Only the core in NRF-05 was logged and sampled for petrographic studies. There are four lava flows in NRF 89-05, designated 1 to 4. Sedimentary interbeds separate flows 1 and 2 and flows 2 and 3; a sediment interbed is not present between flows 3 and 4. Flows 1,3, and 4 are simple flows consisting of single flow units; flow 2 is compound and consists of 6 flow units. K-Ar and paleomagnetic measurements were made on the entire core in well NRF 89-05 and on the bottom 50 ft of core in well NRF 89-04. This interval in NRF 89-04 seems to contain two flows separated by a thin sediment interbed. A log of the core stratigraphy, paleomagnetic inclinations, and location of samples used for paleomagnetic and K-Ar age measurements is given in Figure 3.

Paleomagnetic measurements

Remanent magnetic polarity and inclination values were measured on 54 samples from five lava flows in coreholes NRF 89-04 and NRF 89-05. All lava flows sampled have normal polarity; they were erupted during the Brunhes Normal Polarity Epoch. Although 5 distinct flows were identified in logging and petrographic studies, only 4 independent inclination groups were recognized in paleomagnetic data from core NRF 89-05. Their mean inclination values in descending order are:

	depth	inclination
Flow 1 (89-05)	21 - 107'	73.3° ± 1.5°
Flow 2 (89-05)	118 - 194'	55.6° ± 0.7°
Flow 3 (89-05)	196 - 208'	61.5° ± 17.0°
Flow 4 (89-05)	208 - 242'	66.5° ± 3.0°

The mean inclination values for flows 1 and 2 do not include all of the data shown on Figure 3. The uppermost four samples from flow 1 and the uppermost two samples from the fourth of six flow units of flow 2 (2D, 156'-166') are likely rotated by physical distortion of the lava flow surfaces after the lava flows had cooled and become magnetized.

The difference in inclination values between flows 3 and 4 does not indicate that the flows are independent because the number of samples taken is small and the mean inclination value of flow 3 has poor precision. Petrographic evidence establishes that the flows 3 and 4 are different eruptive units.

Samples taken between 196' and 248' in core NRF 89-04 indicate that there are 2 flows in that interval separated by a 3' sedimentary interbed. We feel that the upper flow correlates with flow 4 in core NRF 89-05 because they share nearly identical mean inclination values. The lower flow represents a fifth flow, not sampled in NRF 89-05; preliminary inclination data from nearby cores suggests that flow 5 is much thicker than the 27' sampled in NRF 89-04. The two flows have mean inclination values listed below:

	depth	inclination
Flow 4 (89-04)	196 - 218'	66.1° ± 3.0°
Flow 5 (89-04)	221 - 248'	71.2° ± 2.1°

K-Ar age measurements

Duplicate K-Ar ages were measured on four samples from the NRF cores--two from NRF 89-04 and two from NRF 89-05. Three ages were measured on one sample from 89-05. Ages and analytical data are given in Table 2. The overall data set contains stratigraphic inconsistencies that cannot, at present, be resolved completely.

The ages measured on sample 89-05-79 from flow 1 agree very well and indicate an age of 303 ± 30 ka for flow 1. The ages of sample 89-05-179 from flow 2 agree fairly well, but are much too old and inconsistent with the stratigraphy of the overall core. The age of flow 4 in NRF 89-04 (sample 89-04-231) also seems much too old. This flow has normal magnetic polarity, but the measured age of 89-04-231, 819 ± 39 ka, is the same, within analytical uncertainty, as the age of the Brunhes-Matuyama polarity boundary. In a nearby corehole, NRF 6P, there are at least three flows having normal polarity below flow 3 (D.E. Champion, unpub. data). This suggests, but does not prove, that the measured age of sample 89-04-231 is too old. Likewise, one of the ages measured on sample 89-05-235 is much older than the other two measurements. If the age of 758 ± 58 ka is not included, then the preferred age of sample 89-05-235 is 533 ± 37 ka.

The 4-ft-thick sedimentary interbeds at depths of 192-196 ft in both NRF 89-04 and 89-05 are undoubtedly correlative. The preferred interpretation of the K-Ar data from the two NRF wells is:

Flow	Preferred Age (ka)
1	303 ± 30
2	not known
3	492 ± 56
4	533 ± 37

ICPP 123

Well ICPP 123 is a 744-ft-deep corehole located near the southwest corner of the Chemical Processing Plant (Fig. 1). Fourteen lava flows were recognized in the ICPP 123 core. The boundaries between many of the flows are occupied by sedimentary interbeds. However, petrographic evidence indicates that four pairs of flows and one sequence of four flows, not separated by sedimentary interbeds, are independent flows. A log of the core stratigraphy, paleomagnetic inclinations, and locations of samples used for paleomagnetic and K-Ar age measurements is given in Figure 4.

Paleomagnetic measurements

Remanent magnetic polarity and inclination values were measured on 110 samples taken from 14 lava flows in corehole ICPP 123. All lava flows sampled have normal polarity; they were erupted during the Brunhes Normal Polarity Epoch. The boundaries between the flows are typically occupied by sedimentary interbeds of appreciable thickness, representing significant passage of time. In was not clear from the paleomagnetic data alone that flows 2 and 3, 9, 10 and 11, and flows 13 and 14 were independent eruptive events, but they are distinct petrographically. A tabular listing of mean inclination values and the footages to which they apply, together with possible correlative flows at Site E (Champion and others, 1988), are presented below:

	depth	inclination	correlative flow at Site E
Flow 1	34 - 106'	53.4° ± 1.3°	A?
Flow 2	113 - 117'	56.5° ± 12.9°	
Flow 3	118 - 154'	54.2° ± 2.8°	
Flow 4	163 - 206'	72.7° ± 1.1°	C
Flow 5	209 - 248'	61.7° ± 1.7°	D
Flow 6	248 - 279'	58.3° ± 2.4°	
Flow 7	284 - 382'	57.2° ± 2.1°	E
Flow 8	382 - 420'	60.0° ± 1.4°	F
Flow 9	424 - 497'	65.9° ± 1.8°	
Flow 10	497 - 509'	60.9° ± 7.3°	
Flow 11	509 - 564'	68.7° ± 1.8°	H
Flow 12	564 - 687'	54.8° ± 2.6°	I
Flow 13	691 - 724'	56.4° ± 2.7°	
Flow 14	724 - 741'	57.6° ± 3.3°	

K-Ar age measurements

Duplicate K-Ar ages were measured on five samples from the ICPP 123 core--one sample each from flows 1, 7, 11, 12, and 14. Ages and analytical data are given in Table 3. The K-Ar ages are in satisfactory agreement with the stratigraphic order of the flows. The age of sample ICPP 123-674 from flow 12 is older than that of sample ICPP 123-737 from flow 14, but the difference is just outside of experimental error. The age of ICPP 123-674 is considered to be too old based on correlations between ICPP 123 and Site E, which is about 2 miles ENE of ICPP 123 (Fig. 1). Paleomagnetic inclinations from the Site E core (Champion and others, 1988) and the ICPP 123 core suggest that flows 1, 7, 11, and 12 in ICPP 123 correlate with flows A, E, H, and I, respectively, at Site E. A comparison of K-Ar ages in the two cores based on these correlations is as follows:

ICPP 123	Site E
flow 1: 219 ± 50 ka	flow A: 233 ± 34 ka
flow 7: 466 ± 39	flow E: 441 ± 77
flow 11: 619 ± 22	flow H: 580 ± 93
flow 12: 737 ± 29	flow I: 641 ± 54

SUMMARY

Petrographic descriptions were made on nearly 1200 feet of core from Well 80, NRF 89-05, and ICPP 123. Paleomagnetic measurements were made on 23 lava flows in these three coreholes and an additional 52 feet of core from NRF 89-04: K-Ar ages were measured on 19 samples of basalt from the four cores.

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APPENDIX A: Petrographic descriptions

Summary of petrographic characteristics

Basalt lava flows were sampled for thin section analysis at appropriate intervals. Samples were taken within flows to represent the top, middle, and bottom, and also to represent various textural varieties of the flow. Thin sections were studied by standard petrographic methods.

Basaltic lava flows of the Snake River Plain are remarkably similar to one another in terms of gross petrographic characteristics. Olivine, plagioclase, clinopyroxene, titanomagnetite, and ilmenite are the major mineral phases, apatite is rare. Nearly all thin sections examined are bimodal in terms of crystal size distribution; larger crystals of olivine, plagioclase, and rarely clinopyroxene, are set in groundmass of these same minerals plus ilmenite, titanomagnetite. The larger crystals are typically 1-3 mm in longest dimension. Crystals constituting the matrix are typically <0.5 mm.

Most flows are hypocrystalline but some are holocrystalline. Glass free of inclusions is extremely rare in Snake River Plain basalt flows. Typically, the glass contains small areas of pinkish-tan clinopyroxene and discrete microlites of opaque minerals that are <0.05 mm in longest dimension. The glass is mainly intersertal in most samples and rarely it occurs as a lining on vesicle walls.

Common textures are microporphyritic-porphyritic, glomerophyric, and diktytaxitic. Microporphyritic rocks contain larger crystals ~1 mm in a matrix consisting of crystals typically <0.5 mm; porphyritic rocks contain larger crystals 1-3 mm in a matrix containing crystals typically <0.5 mm. Many basalt flows are glomerophyric, containing clots of 2 or 3 to as many as 20 olivine crystals. Rarely the clots consist of olivine and plagioclase crystals. Open spaces in diktytaxitic rocks are mostly <1 mm. A rare but distinctive texture observed in some flows is here termed "starburst" texture, a special type of glomerophyric texture. This term describes clots of plagioclase or plagioclase+olivine crystals that appear to approximately radiate from a crystallization center. Another distinctive texture, here termed "waist" texture, has plagioclase crystals radiating upward and downward, but not to the side, of a central olivine crystal.

Large olivines, 0.5-3 mm, are typically euhedral and less commonly subhedral. Some crystals are skeletal and contain irregular-shaped inclusions of glass. Nearly all large olivines contain inclusions of opaque and transluscent minerals. The opaque inclusions are typically <0.05 mm, equant, and 4-sided, suggesting that they are of the titanomagnetite-ulvospinel series. The transluscent inclusions are <0.05 mm, dark brown to cinnamon brown, and equant, suggesting that they are chromian spinel.

Plagioclase crystals are lath-shaped and have typical length:width ratios of 6:1 to 12:1. Crystals having length:width ratios less than 6:1 are termed "stubby" in these descriptions. Most plagioclase crystals show little or no evidence of zoning, but some show complex zoning relationships and inclusions of glass, olivine, and pyroxene. Phenocrysts of plagioclase and glomerophyric clots of plagioclase are rare in the thin sections examined. Plagioclase crystals in the matrix of most rocks are typically stubby. Trachyitic texture formed by aligned plagioclase crystals is common.

The size, form, and texture of clinopyroxene is highly variable in Snake River Plain basalts. Large (2-5 mm), subhedral, equant, ophitic crystals occur in the middle and lower parts of some thick flows. Small (0.5-2 mm), anhedral, subophitic, equant to blade-shaped crystals are common in many flows. Smaller (<1 mm) anhedral, subophitic to intergranular, blade- and spindle-shaped clinopyroxene crystals are common in the upper and lower parts of thick flows and throughout thin flows. Some flows appear to have no clinopyroxene, but careful examination of the glassy component reveals clinopyroxene as tiny spindle- and/or blade-shaped crystals, many of which are interlayered with feathery or blade-shaped opaque minerals.

Opaque minerals occur typically in two forms. Blade- or needle-shaped crystals are most likely ilmenite. Discrete, equant crystals or clots of equant crystals are most likely titanomagnetite or titanomagnetite-ulvospinel.

Alteration of basalt flows is generally minor in the thin sections examined. Weak alteration is expressed by reddish oxidation of cleavages and fractures in olivine crystals in the matrix, relatively moderate alteration is expressed by reddish oxidation along cleavages and fractures and also on the outer surfaces of both smaller crystals in the matrix and larger crystals of olivine. The most severe alteration observed involves films of opaque minerals on the outer surfaces of olivine crystals and the conversion of glass to a mass of opaque minerals and pyroxene. Plagioclase and clinopyroxene were not observed to be altered in any of the thin sections studied.

Well 80

Flow 1 (28.5' thick, 43'10" to 72'5")

The upper and lower parts of the flow are dark gray (2.5YR/4/0), the middle part is lighter (2.5YR/5/0). The upper 6' and lower 1.5" of the flow are vesicular, vesicles are typically 2-4 mm; the middle part of the flow is massive. Clean fractures inclined about 45^{o} occur in the flow at about 60'. In hand sample, the matrix of the rock is distinctly diktytaxitic throughout its entire length. Neither the top nor bottom of the flow is cindery.

The texture of flow 1 is typically glomerophyric (olivine) and the matrix of the rock is diktytaxitic throughout. Olivine crystals are euhedral, roughly equant, and are about 0.6-1.2 mm. Plagioclase crystals are <1.5 mm. Blade-shaped, anhedral clinopyroxene is intergranular at the top, ophitic in the center, and subophitic at the base;

all clinopyroxene crystals are <1 mm. Ilmenite blades are <0.8 mm and equant titanomagnetite is <0.3 mm. Titanomagnetite exceeds ilmenite. The flow is unaltered.

Approximately 3.5' of reddish yellow (5YR/7/6) non-calcareous loess separates flows 1 and 2. The core material is broken and much of it is missing.

Flow 2

Flow 2 is 60' thick, extending from 76' to 136'. The upper 13' and the lower 3' of the flow are dark gray (2.5YR/4/0) and the middle 34' is gray (2.5YR/5/0). The upper 10' contains spherical vesicles 1-5 mm diameter, the lower 0.5' contains vesicles <3 mm diameter, and the middle part of the flow is massive. A 2'-thick layer containing vesicles <1 mm is centered at 111'. The matrix of the rock is typically diktytaxitic throughout and is fine grained, containing visible olivine, clinopyroxene, and plagioclase, all <2 mm.

Flow 2 is porphyritic (olivine), glomerophyric (olivine), ophitic in the center, and the matrix of the rock is diktytaxitic throughout. The largest olivine crystals are euhedral and 0.8-1.6 mm. Equant olivine granules in the matrix are <0.3 mm. Short, stout plagioclase laths are <1 mm. Subophitic clinopyroxene is <1 mm in the upper 10', ophitic clinopyroxene is 1-3 mm in the center, and subophitic clinopyroxene is <2 mm in the lower 10" of the flow. All clinopyroxene is anhedral. Ilmenite is <0.4 mm, titanomagnetite euhedra are <0.5 mm, and titanomagnetite exceeds or is approximately equal to ilmenite. Olivine in the central 3/4 of the flow is altered to opaque films on crystal surfaces and reddened fracture-cleavage surfaces.

Flows 2 and 3 are separated by an 8.5'-thick sediment interbed extending from 136.5' to 144'. The upper part is weak-red (10R/5/2) fine sand, silt, and loess. The lower part is pinkish gray (7YR/7/2) fine sand and silt. This was originally an eolian deposit.

Flow 3

Flow three is 18' thick, extending from 144' to 162'. The upper part of the flow is dark reddish gray (10R/3/1), indicating baking and oxidation by the overlying flow. The middle and lower parts are dark gray (2.5YR/4/0). The upper 8' and the lower 2' of the flow contain vesicles <2 mm in diameter. The vesicles in the upper part are filled by calcite. The matrix of hand samples of the flow are diktytaxitic and contain olivine and plagioclase crystals <2 mm in longest dimension.

The flow is glomerophyric (olivine) and nonporphyritic. Olivine crystals are subhedral-euhedral, <0.8 mm in the upper and lower parts, but as large as 1.5 mm in the middle. Granules of olivine in the matrix are <0.5 mm. Plagioclase crystals are <0.8 mm and most crystals in the matrix are <0.4 mm. Clinopyroxene crystals are anhedral, subophitic, and <0.6 mm in the upper and lower parts of the flow and subhedral, subophitic and <2.0 mm in the central part. Ilmenite needles and blades are <0.3 mm in the upper part and increase to <0.6 mm in the lower part, whereas titanomagnetite euhedra decrease from ~1 mm at the top to ~0.3 mm at the base of the flow. Ilmenite exceeds or is approximately equal to titanomagnetite in volume. The flow is only slightly altered in its upper parts; olivine crystals in the matrix have slightly oxidized, reddish films on surfaces and fractures-cleavages.

Flows 3 and 4 are separated by a 15-foot-thick sediment interbed that extends from 162' to 177'. The upper 1.5 feet of the interbed is pinkish-gray (7.5YR/7/2) gravel that consists of 1-4 cm, subrounded pebbles of basalt, granite, and sparse sedimentary rocks. Pinkish-gray coarse sand and fine gravel consisting of grains of the same rocks, all <2 cm, occur in a 1'-interval below the gravel. The gravel and sand represent an alluvial deposit. The bottom 12 feet of the interbed consist of pinkish-gray fine sand and silt that represent an eolian (loess?) deposit.

Flow 4

Well 80 penetrated 26.5' of flow 4, from 177' to total well depth of 203'7". Basalt in flow 4 is dark gray (2.5YR/4/0) in the upper 10' and gray (2.5YR/5/0) in the lower 16'. The upper 6' of the flow contains vesicles <2 mm and the matrix of the rock is dense. The next 18' of the flow is massive and the matrix is diktytaxitic. The lower 2.5' contains vesicles <1 mm and the matrix is partly diktytaxitic to dense. Hand samples contain conspicuous crystals of olivine and plagioclase <2 mm in the upper 5' and these same minerals increase to ~3 mm in the lower part of the flow. The rock has a distinct felty texture in the middle and lower parts.

In thin section, the rock is distinctly glomerophyric, containing clusters of olivine, plagioclase, and olivine + plagioclase crystals. The olivine and plagioclase phenocrysts, 1-3 mm, are set in a matrix of the same minerals plus pyroxene that are all <1 mm. Euhedral olivine crystals are <1.4 mm at the top and bottom and reach 2.5 mm in the middle of the flow. Complexly zoned plagioclase crystals that commonly contain glass inclusions are <2 mm at the top and bottom and reach 3 mm in the middle of the flow. Plagioclase crystals have a starburst arrangement throughout the flow. Clinopyroxene is typically intergranular and is <0.4 mm at the top and bottom and <0.8 mm in the middle of the flow. Ilmenite blades and titanomagnetite euhedra are <0.5 mm throughout the flow; titanomagnetite exceeds ilmenite.

Well NRF 89-05

Flow 1 is overlain by 21' of sediment. The upper 7' consists of weak red (2.5YR/5/2) nonbedded sand and silt, which we infer to represent alluvial deposition. The lower 14' consists of weak red (2.5 YR/5/2) pebbles, granules and sand grains of basalt and limestone, representing alluvial material.

Flow 1 (86' thick, 21'-107')

The upper 45' of the flow is dark gray (2.5YR/4/0). The middle 30' is gray with a tan tinge (5YR/6/1 and 10YR/6/1). The lower 14' of the flow is gray (5YR/6/1), becoming dark gray (2.5YR/4/0) in the bottom foot. The upper 30' of the flow is vesicular; mostly spherical, caliche-lined vesicles are as large as 15 mm in the upper 5' and decrease in abundance and in diameter to 1 mm at a depth of about 50'. The flow is massive from 51' to 105' and then vesicular, containing spherical vesicles <15 mm, in the lower 2 feet. The flow is mostly massive, but locally weakly diktytaxitic in the upper 2/3 of the flow. Near-vertical, loess-filled joints occur within the interval 43' to 83'. The rock contains moderate-abundant, conspicuous crystals of olivine <5 mm in a matrix of crystals <1 mm.

In thin section, the flow is distinctly glomerophyric (olivine) throughout and locally diktytaxitic. Olivine crystals observed in thin section are euhedral and mostly <2 mm. Olivine in the matrix is <0.2 mm. Large, complexly-zoned plagioclase laths range from 0.8 mm near the top to crystals as long as 1.6 mm near the middle of the flow. Plagioclase decreases to <1.2 mm near the bottom. Clinopyroxene occurs as anhedral, subophitic crystals <2 mm in the upper 2/3 of the flow, as anhedral, ophitic crystals <2.5 mm in the lower 1/3, and as intergranular-subophitic crystals <0.4 mm in the matrix of the rock in the lowest 2' of the flow. Ilmenite needles and blades are <0.7 mm and some crystals have skeletal-trellis shapes. Titanomagnetite euhedra are typically <0.4 mm. Titanomagnetite is approximately equal to ilmenite throughout the flow.

An 11-foot sedimentary interbed, extending from 107' to 118' separates flows 1 and 2. The upper 5' consists of reddish-brown (5YR/5/3) pebbles and granules of basalt, rhyolite, and limestone. The next 5' is reddish-brown sand and the lowest 1 foot is yellowish-red (5YR/5/6) sandy clay.

Flow 2 (77 feet thick, 118' to 194')

Flow 2 consists of 6 flow units (2A, 2B, 2C, 2D, 2E, and 2F, top to bottom), having flow-unit breaks at 128', 133', 156', 166', and 185'. The flow units have different textures and structures but are remarkably similar in petrographic characteristics, thus each flow unit is described separately in terms of hand-sample character but the petrographic character is summarized for the entire compound flow.

In its upper 3 feet, basalt in flow unit 2A is oxidized reddish-gray (5YR/5/2), is diktytaxitic, and contains vesicles < 10 mm. The lower 7 feet is dark-gray (2.5YR/4/0), diktytaxitic, mostly massive basalt.

Flow unit 2B consists of rusty, vesicular cinders in the top 1 foot, and then changes to dark-gray (2.5YR/4/0) rock containing elongated vesicles <15 mm in the lower 4 feet.

The upper 2' of flow unit 2C consists of dusky-red (2.5YR3/2), vesicular cinders in a clayey matrix. The intermediate 10' is dark-gray (2.5YR/4/0), partly diktytaxitic, and contains vesicles <10 mm. The lower 16' is gray (2.5YR/5/0), massive, and partly diktytaxitic.

Flow unit 2D is dark-gray (5YR/4/1) and diktytaxitic throughout. Vesicles are ~10 mm diameter at the top and increase to 25 mm about 7' below the top. The lower 3' is massive.

Flow unit 2E, 24' thick, is dark gray (5YR/4/1) in the upper 8' and changes to dark gray (2.5YR/4/0) in the lower 16'. It is mostly massive, but dense in the upper 1' and weakly vesicular in the lower 3'.

Flow unit 2F (9' thick) is dusky red (2.5YR/3/2) in the upper 2' and dark gray (2.5YR/ 4/0 and 5YR/4/1) in the lower 7". The flow unit is mostly vesicular, containing nearly spherical vesicles <10 mm, but the middle 2' is massive.

Hand specimens from all flow units in flow 2 are typically fine grained and contain olivine and plagioclase crystals as large as 2 mm. In thin section, the rock is typically glomerophyric (olivine), porphyritic (olivine), and weakly to strongly diktytaxitic. Olivine is quite similar in all flow units; euhedral crystals are typically <2 mm and locally are skeletal. Olivine crystals in the matrix are <0.4 mm and mostly <0.2 mm. The largest plagioclase do not exceed 2 mm and most crystals are <0.4 mm in all flow units. Clinopyroxene is typically anhedral, intergranular, and <0.4 mm, but locally shows unique variation. For example, ophitic crystals as large as 2 mm occur in the center of flow unit 2C. Distinct clinopyroxene crystals are absent in the lower part of flow unit 2E and all of flow unit 2F, but absorption colors indicate that clinopyroxene constitutes a significant part of the microcrystalline matrix. Ilmenite blades and needles are <0.5 mm and mostly <0.2 mm and titanomagnetite granules are <0.3 mm and mostly <0.1 mm throughout the flow Titanomagnetite ≥ ilmenite throughout the flow. Flow units 2A and 2B are essentially unaltered. Flow units 2C and 2D are moderately to severely altered and contain extensive opaque minerals that are distributed throughout the matrix and occur as films on olivine crystals. The olivines in flow units 2E and 2F are moderately altered, having some opaque-mineral films on outer surfaces and reddish oxidation along cleavages and fractures.

Flows 2 and 3 are separated by a 2-foot-thick interbed of loess. The loess is yellowish red (5YR/5/6) in the upper foot and reddish yellow (5YR/6/6) in the lower foot.

<u>Flow 3</u> (12' thick, 196'-208')

The upper 5' are very dark gray (5YR/3/1), the middle 4' are gray (7.5YR/5/0) and the bottom 3' are very dark gray (2.5YR/3/0). The upper 5' contains spherical vesicles <10 mm that are partly filled or lined by caliche and minor zeolites. The middle 3' are massive and the lower 4' are vesicular, notably containing pipe vesicles as long as 15 mm and spherical vesicles <10 mm that are lined by dark reddish brown (2.5YR/3/4) glass. Hand samples contain plagioclase <1 mm and olivine that increases from ~1 mm at the top to ~5 mm at the bottom

The rock is distinctly glomerophyric (olivine), porphyritic (olivine), and diktytaxitic. The largest olivines observed in thin section are euhedral and <2 mm, granular olivine in the matrix is <0.3 mm. Plagioclase laths are < 1.2 mm and most crystals in the matrix are <0.4 mm. Clinopyroxene spindles <0.5 mm are intergranular, confined to the matrix, and interlayered with opaque minerals. Opaque minerals are very fine grained, all <0.2 mm, and confined to the matrix. The rock is unaltered.

Flows 3 and 4 are not separated by a sedimentary interbed.

Flow 4 (>33' thick, 208' to TD 241.5')

The upper 13' of flow 4 is very dark gray (2.5YR/3/0) and the remaining 20' is dark gray (2.5YR/4/0). The upper 13' contains nearly spherical vesicles <20 mm, most being <5 mm. The flow is partly diktytaxitic above 220' and strongly diktytaxitic below that depth. Hand samples contain plagioclase and olivine <2 mm in the upper 12"; plagioclase crystal length increases to as much as 4 mm and olivine crystals decrease in long dimension to <1 mm in the lower 20 feet.

The flow is characterized by glomerophyric (olivine, olivine+plagioclase) and starburst (plagioclase, plagioclase+olivine) textures. The largest olivine crystals observed in thin sections are <0.5 mm and granules in the matrix are <0.2 mm. The largest plagioclase crystals are 1.5-2.5 mm throughout the flow and crystals in the matrix are typically <0.4 mm. Clinopyroxene crystals are intergranular and <0.2 mm in the upper 10' and become subophitic and increase to <1.8 mm in the lower 23'. Ilmenite blades and needles are typically 0.5 mm in the upper part and 0.8-1.6 mm in the lower part. Titanomagnetite is <0.4 mm throughout the flow. Ilmenite $\geq$ titanomagnetite.

Well ICPP 123

Flow 1 is overlain by 32' of stratified and unstratified gravel, sand, and silt. The upper 4' is mainly gravel and interstitial silt. Fine to coarse sand and gravel occur between 4' and 6'. Gravel, nonstratified silt, gravel and interstitial silt, and gravel lacking interstitial silt occupy the zone between 8' and 12'. Gravel and sand occur between 12' and 21'. The interval between 21' and 24' is missing. Coarse sand and gravel occurs between 24' and 27'. The interval between 27' and 35', including the sediment-basalt contact, is missing. The color assigned to the entire sediment sequence above flow 1 is light brownish gray (10YR/6/2). Rock types constituting gravel and coarse sand in the sediment sequence are granite, rhyolite, basalt, quartzite, and rare limestone.

Flow 1 (74' thick, 32' to 106')

Basalt in hand specimen is uniformly gray (2.5YR/5/0) in the lower 2/3 of the flow, but is 7.5YR/6/0 in the upper 1/3. The upper 23' is vesicular, containing oblong (10x30 mm) and roughly spherical (<10 mm) vesicles; the lower 51' is massive. The lowest 1' is very dense, nonvesicular, and nondiktytaxitic. The flow is diktytaxitic throughout and, except for the bottom 1',contains moderate to abundant plagioclase and olivine crystals <3 mm.

In thin section, the rock is glomerophyric (olivine) and diktytaxitic. The largest olivine crystals are roughly equant, euhedral, and 0.8-1.6 mm. Olivine crystals in the matrix are <0.2 mm. Plagioclase laths are <0.6 mm in the upper 1/3 and increase to <1.6 mm in the lower 2/3 of the flow. Clinopyroxene occurs as subophitic blades <1.2 mm in the upper 1/3 and as ophitic to subophitic, oblong, anhedral crystals <3.5 mm in the lower 2/3 of the flow. Ilmenite blades decrease from 0.6 mm near the top of the flow to <0.3

mm near the bottom of the flow. Titanomagnetite euhedra increase from <0.2 mm near the top to <0.4 mm near the bottom of the flow. Titanomagnetite≥ilmenite.

Flows 1 and 2 are separated by a 6.5'-thick interbed of dense, hard, baked, unstratified sand, silt, and silty clay. The sediment is red (2.5YR/4/8) at the top and reddish brown (2.5YR/5/4) at the bottom

<u>Flow 2</u> (4.5' thick, 112.5' to 117')

Basalt in flow 2 is very dark gray (2.5YR/3/0) at the top and dark reddish gray (5R/4/1) at the bottom. The rock contains oblong vesicles (2x15 mm) at the top, spherical vesicles (~3 mm) at the bottom, and abundant plagioclase and rare olivine crystals <1 mm throughout.

The rock is glomerophyric (olivine), porphyritic (olivine), and diktytaxitic. Large olivine crystals are euhedral and <1.2 mm. Plagioclase crystals are as large as 0.7 mm, but most crystals are <0.2 mm. Clinopyroxene is intergranular, <0.2 mm, and confined to the matrix. Titanomagnetite euhedra are <0.3mm, ilmenite crystals are <0.1 mm, and titanomagnetite~ilmenite.

Flows 2 and 3 are separated by a 1'-thick interbed of reddish brown (5YR/4/3) massive silt, clay, and minor sand.

<u>Flow 3</u> (36' thick, 118' to 154')

Basalt in the upper 2' of flow is slightly oxidized and dark reddish gray (10R/4/1). The lower 34' consists of dark gray (2.5YR/4/0) to gray (5YR/5/1) basalt. The upper 8.5' of the flow contains oblong and spherical vesicles as large as 20 mm. The vesicles are coated by thin layers of caliche and zeolite minerals. The lower 28' of the flow is dense. The flow is conspicuously non-porphyritic in hand specimen and contains crystals that are typically 1.5 mm throughout.

The rock is mainly non-porphyritic and massive in thin section, but is weakly diktytaxitic in the lower 5 feet. The largest olivine crystals are <0.5 mm and most are <0.1 mm. Plagioclase crystals are also <0.5 mm and stubby. Pyroxene crystals are anhedral, <1.2 mm, and ophitic in the middle and subophitic near the top and bottom of the flow. Ilmenite needles are as long as 1.5 mm in the middle and ilmenite and titanomagnetite are <0.3 mm in the upper and lower parts of the flow. Titanomagnetite is about as abundant as ilmenite. The bottom several feet of the flow exhibit slight alteration in the form of reddish-brown coats on the smallest olivine crystals.

Flows 3 and 4 are separated by a 9'-thick interbed of unstratified silt and clay that is weak red (10R/4/4) at the top and reddish brown (5YR/5/3) at the bottom. The grain size suggests the sediment was deposited as loess.

Flow 4 (43' thick, 163' to 206')

Flow 4 consists of 2 flow units; the break between the flow units is at 175.5'. Flow 4 is dark gray (2.5YR/4/0) and gray (2.5YR/5/0) in the upper 9', and very dark gray (2.5YR/3/0) and 5YR/3/1) in the middle 8', and gray in the lower 26'. The upper 5' of the upper flow unit contains vesicles as large as 5 x 15 mm, but most are <0.5 mm. The lower 7' of the flow unit is massive. The upper 2' of the lower flow unit is microvesicular, the next 8' contains abundant, nearly spherical vesicles <20 mm. The middle 20' of the lower flow is massive, but the lower 1' contains abundant vesicles <10 mm. Hand specimens in both flow units are distinctly diktytaxitic and contain olivine and plagioclase crystals that are mostly <1 mm.

Flow 4 is distinctly glomerophyric (olivine) and diktytaxitic in thin section. The largest olivine crystals are euhedral and <2 mm, most crystals are <0.5 mm. Plagioclase crystals are <0.5 mm near the top and increase to about 1 mm near the bottom of the flow. The largest clinopyroxene crystals are subophitic and <0.6 mm at the top, increasing to <2.4 mm at the base of the flow. Clinopyroxene crystals in the matrix are anhedral, intergranular, and <0.6 mm throughout the flow. Ilmenite needles decrease in length from ~0.5 mm at the top to ~0.2 mm at the base of the flow. Titanomagnetite crystals are <0.3 mm throughout the flow. Titanomagnetite approximately equals ilmenite. Alteration of the flow is minor; some clinopyroxene is altered in the top part and olivine crystals are slightly altered on outer surfaces near the base.

Flows 4 and 5 are separated by a 3'-thick interbed of red cindery silt and clay.

Flow 5 (39' thick, 209' to 248')

Flow 5 consists of 4 flow units; contacts between flow units occur at 214.5', 219', and 239'. Flow 5 is very dark gray (5YR/3/1) in the upper 2' and gray (2.5YR/5/0) to dark gray (2.5YR/4/0) in the lower 37'. The upper 9' of the flow contains abundant, nearly spherical vesicles 5-20 mm in diameter. Vesicles at the top of the flow are partly filled by caliche. A 2'-thick vesicle-rich zone between 239' and 241' contains small, spherical vesicles <5 mm whose inner surfaces are coated by oxidized glass, features that indicate that the vesicle-rich zone is the top of a flow unit. The lower 3' of flow 5 are also vesicular, the remainder of the flow is massive. Nearly vertical, clay-coated joints occur in the flow near 242'. Hand samples from flow 5 are distinctive in that they contain phenocrysts of plagioclase that are as long as 5 mm in the upper part of the flow and as long as 3 mm in the lower part of the flow. The lower 3/4 of the flow is diktytaxitic, the upper 1/4 is not.

Flow 5 is distinctly porphyritic (plagioclase) throughout. The upper 6' of the flow is also glomerophyric (plagioclase). In thin section as well as in hand sample, the largest olivine crystals are <0.6 mm throughout the flow, most crystals are <0.4 mm. Olivine is weakly glomerophyric in the upper 2/3 of the flow. Unique features of this flow are that olivine crystals contain few if any opague inclusions and some crystals are zoned near the middle of the flow. Plagioclase crystals display a pronounced starburst texture in the upper part of the flow, but a less-distinct starburst texture in the middle and lower parts. In thin section, the largest plagioclase crystals are <3 mm in the upper part of the flow, they increase to 4 mm long in the middle of the flow, and are <1.5 mm in the lower part of the flow. Plagioclase crystals in the matrix are typically <0.4 mm throughout the flow. Clinopyroxene crystals <0.5 mm are confined to the matrix in the upper and lower parts of the flow where they are fibrous, intergranular, partly skeletal, and intergrown with opague minerals. In the middle of the flow, clinopyroxene is <1 mm, intergranular to subophitic, and intergrown with ilmenite. Very slender needles of ilmenite are typical of flow 5; they are <0.3 mm in the upper part of the flow, <0.7 mm in the middle, and <0.5 mm in the lower part. Titanomagnetite crystals are mostly euhedral and <0.2 mm throughout the flow, but some crystals are skeletal in the upper part. Ilmenite exceeds or is equal to titanomagnetite.

Flows 5 and 6 are not separated by an interbed.

<u>Flow 6</u> (31'-thick, 248' to 279')

Flow 6 consists of two flow units, the contact between the units is at 270'. The upper 1' of flow 6 is altered and slightly oxidized to dark reddish brown (5YR/4/1) basalt. The remainder of the flow ranges from very dark gray (2.5YR/3/0) through dark gray (2.5YR/4/0 and 5YR/4/1) to gray (2.5YR/5/0). The darker rocks tend to be massive, the lighter rocks tend to be vesicular. For the upper flow unit, the upper 8' contains abundant, nearly spherical vesicles 5-10 mm and the lower 14' is massive. For the lower flow unit, the upper 2' and the lower 3' contain abundant spherical vesicles 3-8 mm in diameter. The middle 4' of the lower flow unit is massive. Vesicles in the upper part of the lower flow unit contain minor amounts of tan dust, suggesting a relatively long time between emplacement of the two flow units. In hand sample, flow 6 is characterized by diktytaxitic texture and large olivine phenocrysts 2-3 mm throughout.

The upper and lower parts of the flow are porphyritic (olivine) and glomerophyric (olivine). The largest olivine crystals observed in thin section are euhedral and <2 mm. Olivines in the matrix are rounded and typically <0.2 mm. The largest plagioclase crystals are stubby, <0.8 mm at the top, and <1.2 mm in the middle and at the bottom of the flow. Plagioclase crystals in the matrix are typically <0.5 mm. Clinopyroxene crystals are ophitic and <2.5 mm in the center and subophitic and <1.5 mm in the upper and lower parts of the flow. Ilmenite and titanomagnetite crystals are both <0.2 mm throughout the flow and titanomagnetite is approximately equal to ilmenite. The flow is unaltered at the top; olivine crystals are slightly altered in the middle and bottom parts of the flow.

Flows 6 and 7 are separated by a 4.5'-thick interbed that, as of 6/12/91, was missing, either from lack of core retrieval or from removal by previous sampling.

Flow 7 (98'-thick, 284' to 382')

Flow 7 appears to be a single flow unit, which is quite remarkable for a flow that is nearly 100'-thick.

Flow 7 is remarkably uniform in color, dark gray (2.5YR/4/0) to gray (2.5YR/5/0), throughout. The upper 25' of the flow contains partly clay-filled vesicles that are 2-6 mm in diameter. The lower 73' of the flow is mainly dense and massive, except for two thin, vesicular layers that occur at 331-333' and 338-341'. These zones contain spherical vesicles 1-5 mm in diameter. Vertical, caliche-filled joints occur in three zones, each 2-6' thick, centered at 322', 342', and 371'. Hand samples from flow 7 are typically dense-massive and contain moderate to abundant crystals of olivine that are 1-3 mm. The flow is weakly diktytaxitic above 316' and nondiktytaxitic below that depth.

In thin section, the rock is distinctly porphyritic (olivine), glomerophyric (olivine), and weakly diktytaxitic to dense. The largest olivine crystals observed in thin section are euhedral and 1-2 mm. Large olivines near the base of the flow are skeletal. Rounded olivine crystals in the matrix are typically <0.1 mm. The largest plagioclase crystals are stubby and 1-2 mm. Plagioclase crystals in the matrix are typically <0.4 mm. Clinopyroxene is ophitic-subophitic and 1-3 mm in the central part of the flow. At the top, clinopyroxene is subophitic and <0.5 mm. At the bottom, clinopyroxene is subophitic and <1.5 mm. Ilmenite is needle-shaped and <0.25 mm at the top and more equant and 0.2-0.5 mm in the middle and bottom parts of the flow. Titanomagnetite is equant, locally skeletal, and <0.4 mm. Titanomagnetite exceeds ilmenite.

Flows 7 and 8 are not separated by a sedimentary interbed.

Flow 8 (38'-thick, 382' to 420')

The upper 1' of flow 8 is cindery, rubbly, and gray (2.5YR/5/0). Surprisingly, it is not oxidized to red as might be expected because this flow is overlain by such a thick flow. The entire flow is gray (2.5YR/5/0) to dark gray (2.5YR/4/0). The upper 7' and the lower 2' contain oblong vesicles as large as 15 x 30 mm. Most vesicles are nearly spherical and <5 mm. The middle part of the flow is massive. The flow is distinctly diktytaxitic throughout. A 3'-thick zone of vertical, caliche-filled joints occurs in massive rock at 403'. Hand samples from flow 8 are characterized by abundant olivine crystals and clots of olivine crystals as large as 4 mm and distinct diktytaxitic texture.

In thin section, the rock is porphyritic (olivine), glomerophyric (olivine), and is distinctly diktytaxitic in the upper 2/3 and a less-distinctly diktytaxitic in the lower 1/3 of the flow. The largest olivine crystals are as long as 3.5 mm in the upper 1/2 and as long as 5 mm in the lower 1/2 of the flow. Most large olivines are euhedral throughout the flow and skeletal in the lower part. Olivine crystals in the matrix are typically <0.5 mm. The largest plagioclase crystals are stubby and <1.5 mm; plagioclase in the matrix is <0.5 mm. Large clinopyroxene crystals are ophitic to subophitic, anhedral, and 1-2 mm. Smaller crystals are anhedral, subophitic, and <0.4 mm. Ilmenite crystals are mostly equant and <0.4 mm, titanomagnetite is typically <0.3 mm and equant, except that it is trellis-shaped in the upper part of the flow. Titanomagnetite is approximately equal to ilmenite. The flow is essentially unaltered although there is a slight alteration of the surface of olivines in the middle of the flow.

Flows 8 and 9 are separated by a 10.5'-thick interbed which consists of nonbedded, reddish-brown (5 YR/4/4) sandy silt. The grain size of this interbed suggests that it is an eolian (sand dune?) deposit or possibly a coarse loess.

Flow 9 (73'-thick, 423.5' to 496.5')

Flow 9 appears to be a single flow unit, but there are prominant vesicular zones within the flow that may constitute flow unit breaks. The upper 4' and the lower 6.5' of the flow contain nearly spherical vesicles <5 mm in diameter. A 4'-thick vesicular zone centered at 445' contains oblong vesicles as large as 5 x 20 mm and a 14'-thick vesicular zone centered at 460' contains oblong vesicles as large as 10 x 40 mm. Most vesicles throughout the flow contain thin coats of caliche. The remainder of the flow is massive and dense. The flow is mainly gray (2.5YR/5/0) in massive parts and dark gray (2.5YR/4/0) and very dark gray (2.5YR/3/0) in vesicular parts. Vertical joints that lack caliche or fine-sediment coatings or fillings occur in two zones in massive rock at 472' and 477'. Hand samples are typically diktytaxitic, contain moderate to abundant crystals of olivine and plagioclase <2 mm, and display a felty texture.

In thin section, the rock is non-porphyritic in the upper 1/3, porphyritic (olivine) and glomerophyric (olivine) in the middle, and porphyritic (olivine) in the bottom 1/3 of the flow. The flow is distinctly diktytaxitic throughout. The largest olivine crystals are euhedral, locally skeletal, and 1-2 mm. Olivine in the matrix is typically <0.3 mm. Larger plagioclase crystals and 0.8-1.6 mm, most crystals are 0.3-0.5 mm. Clinopyroxene crystals are subophitic to intergranular and <1.2 mm, most crystals are <0.5 mm. Ilmenite needles are <0.8 mm in the middle and <0.4 mm in the top and bottom of the flow. Titanomagnetite euhedra are <1 mm in the middle and <0.5 mm in the top and bottom of the flow. Titanomagnetite is approximately equal to ilmenite. The flow is weakly altered at the top and bottom, but slightly more altered (reddish films on surfaces and fractures in olivine) in the middle of the flow.

Flows 9 and 10 are not separated by an interbed.

Flow 10 (12.5'-thick, 496.5' to 509')

The upper 2' of the flow is oxidized to dusky red (10R/3/2). The remainder of the flow is gray (2.5YR/5/0) in massive parts and dark gray (2.5YR/4/0) in vesicular parts. The upper 8' and the lower 1' contain nearly spherical vesicles <10 mm. The middle 3' is massive and dense. In hand sample, the rock contains olivine and plagioclase crystals 1-2 mm, the matrix is slightly oxidized to light red, and the rock is distinctly dense rather than diktytaxitic.

In thin section, rocks are porphyritic (olivine), weakly diktytaxitic, and the matrix is extensively altered. The largest olivine crystals are euhedral, partly skeletal, and somewhat altered. Large plagioclase crystals are stubby and <0.6 mm, most crystals in the matrix are 0.2-0.6 mm. Clinopyroxene is intergranular and <0.3 mm. The matrix of the rock is too altered to determine characteristics of the opague minerals.

Flows 10 and 11 are not separated by an interbed.

<u>Flow 11</u> (54.5'-thick, 509'-563.5')

The upper 3' of the flow is oxidized to reddish black (10R/2.5/1) and dark reddish gray (10R/3/1). The lower 2' of the flow is very dark gray (5YR/3/1) and the middle parts are mostly gray (2.5YR/5/0). The upper 10' and the lower 6' contain oblong vesicles having longest dimensions <30 mm, but most vesicles are <10 mm. The middle 40' of the flow is massive and dense. Vertical joints coated by caliche occur in the massive zone at depths of 538' and 553'. Hand samples are diktytaxitic and contain rare olivine and plagioclase <2 mm.

In thin section, the rock is distinctly even grained and not porphyritic. It is glomerophyric (olivine) and diktytaxitic. Olivine crystals are <1 mm at the top and as large as <1.6 mm at the bottom, but most crystals are 0.6-1.2 mm throughout the flow. Plagioclase crystals are mostly uniform in size, 0.3-0.7 mm. Clinopyroxene is ophitic to subophitic, subhedral, and <1.2 mm at the top and subophitic to intergranular, anhedral, and <1.6 mm at the base of the flow. Ilmenite and titanomagnetite are <0.3 mm. Titanomagnetite exceeds ilmenite. The upper part of the flow is moderately altered; olivine has oxidation films on outer surfaces and fractures and opague minerals are scattered throughout the matrix. The base of the flow is only slightly altered.

Flows 11 and 12 are not separated by an interbed.

<u>Flow 12</u> (127.5'-thick, 563.5' to 687')

Flow 12 consists of 3 flow units; the upper flow unit is 10.5'-thick, the middle flow unit is 6.5'-thick, and the lower flow unit is 110.5'-thick. Flow unit boundaries occur at 574' and 580.5'.

The upper several feet of the upper flow unit are dark reddish gray (10R/3/1) and the middle and bottom parts are gray (2.5YR/5/0). The upper 4.5' of the upper flow unit contains vesicles <10 mm and the lower 5.5' is massive. Vesicles are caliche-filled in the upper 6". Vertical joints having thin coats of caliche occur in the massive part at 572'. The flow unit is weakly to moderately diktytaxitic, contains moderate to abundant plagioclase <3 mm and rare olivine <1 mm, and has a conspicuous felty texture.

The upper foot of the middle flow unit is weak red (10R/4/2) and the remaining part is dark gray (2.5YR/4/0). The flow unit is vesicular throughout; vesicles contain calcareous clay and are <10 mm. The rock is diktytaxitic and contains abundant plagioclase <5 mm and rare to moderate olivine <2 mm.

The upper 1' of the lower flow unit is dark reddish gray (10R/4/1). It changes through very dark gray (5YR/3/1) and dark gray (2.5YR/4/0) to gray (2.5YR/5/0), which extends from ~600' to ~630'. From ~630' to ~680', the rock has a distinct tan or reddish-gray (5R/6/1, 10R/6/1) color. The lower 5' of the flow unit is dark gray (5YR/4/1). The upper 17' of the flow unit contains vesicles as large as 5 x 30 mm. The lower 99' is massive and dense, except for 0.5-1"-thick vesicular layers at 622' and 630'. Contrasting types of vertical joints occur in the massive part at 608' (not filled), 641' (coated by calcareous loess), and 652' (filled by noncalcareous loess). Hand samples from the lower flow unit are diktytaxitic, locally felty, and contain conspicuous pyroxene, olivine, and plagioclase <2 mm.

In thin section, the upper two flow units are porphyritic (plagioclase), glomerophyric (olivine and plagioclase), and weakly diktytaxitic. The largest olivine crystals observed are <1 mm and they contain many inclusions of glass. Many plagioclase crystals are 2-3 mm and glomerophyric clots of 3-4 crystals are common. Plagioclase in the matrix is mainly <1 mm. Clinopyroxene crystals are subophitic, anhedral, and <1 mm. Ilmenite and titanomagnetite are <1 mm, and titanomagnetite is approximately equal to ilmenite. Both flow units exhibit slight alteration of olivine.

The lower flow unit is not porphyritic, but is glomerophyric (olivine). The flow unit is strongly diktytaxitic in the upper and middle parts and weakly diktytaxitic in the lower part. Olivine crystals are as large as 2.5 mm in the middle and <1.5 mm in the upper and lower parts. Olivine in the matrix is <0.5 mm. Plagioclase crystals are as large as 3 mm in the upper part and decrease to <1 mm in the lower part. Many plagioclase crystals are porous and contain inclusions of glass, opague minerals, and pyroxene. Starburst texture appears in the lower part of the flow unit. Crystals in the matrix are <0.8 mm. The plagioclase crystals appear to have a fairly uniform size, thus contributing to the nonporphyritic character of the rock. Clinopyroxene crystals are <1.2 mm, anhedral, and intergranular to subophitic in the upper and lower parts, and <4 mm, ophitic and anhedral in the middle part. Smaller crystals in the matrix are <1 mm. Ilmenite is <0.3 mm in top and bottom parts, and 0.4-0.8 mm in the middle. Titanomagnetite is <0.4 mm throughout. Titanomagnetite exceeds or is equal to ilmenite. The flow unit is essentially unaltered.

Flows 12 and 13 are separated by a 4'-thick interbed composed of reddish-brown, unstratified silt.

<u>Flow 13</u> (33.5'-thick, 691' to 724.5')

Flow 13 is dark reddish gray (10R/3/1) in the upper 1', dusky red (2.5YR/3/2) in the next 2', and dark reddish gray for 2' below that. The lower 25' of the flow is gray (5YR/5/1). The upper 7' of the flow contains vesicles as large as 5 x 15 mm. Vesicles in the upper 2' are partly filled by caliche and vesicles at 696' contain zeolites. The lower 25' of the flow is massive and dense. The upper 1/2 of the flow is weakly to moderately diktytaxitic, the bottom 1/2 is not diktytaxitic. Near-vertical joints occur in the massive part of the flow at 712'. The rock contains scattered olivine crystals <2 mm.

In thin section, the rock is distinctive in that it is not porphyritic, not glomerophyric, and very weakly diktytaxitic. The largest olivine crystals are <1.5 mm and euhedral. Plagioclase crystals are porous and contain glass and mineral inclusions. Most plagioclase crystals are 0.4-1 mm in longest dimension. Clinopyroxene is subophitic, anhedral and <1.6 mm. Ilmenite is <0.5 mm, titanomagnetite is <0.4 mm, and titanomagnetite exceeds ilmenite. The flow is essentially unaltered.

Flows 13 and 14 are not separated by an interbed.

Flow 14 (16'-thick, 724.5' to 740.5')

Flow 14 is red (2.5YR/4/6) at the top, changes to dusky red (2.5YR3/2/) at 729', and dark reddish gray (10R/4/1) at 731'. Below 734', the flow is dark gray (5YR/4/1 and 2.5YR/4/0) to the base. The upper 10' and the lower 1.5' of the flow contain vesicles as large as 3 x 10 mm. The vesicles in the upper part of the flow are partly filled by non-calcareous loess. The middle 5' of the flow is massive and dense. The flow is diktytaxitic in hand specimen and has a fine-grained texture in which all crystals appear to be <1 mm, except in the middle part of the flow, where plagioclase crystals are <2 mm.

In thin section, the rock is porphyritic (plagioclase) throughout and glomerophyric (olivine) near the top. Olivine crystals are mostly <0.4 mm and confined to the matrix. The largest plagioclase crystals increase from ~1.5 mm near the top to ~2.3 mm near the bottom of the flow, where phenocrysts are porous and contain inclusions of opague minerals and clinopyroxene. Plagioclase in the matrix is typically <0.6 mm. Rare clinopyroxene is fibrous to intergranular and confined to the matrix in the upper part of the flow. Near the base, clinopyroxene crystals are slightly more numerouintergranular to subophitic, anhedral, and <0.3 mm. Ilmenite needles are <0.3 mm thrghout. Titanomagnetite is <0.3 mm at the top and <0.6 mm at the bottom, where many crystals are skeletal. Titanomagnetite is approximately equal to ilmenite. The matrix of the flow is altered to a mass of opaque minerals interspersed with plagioclase and clinopyroxene in the upper part of the flow. The matrix is only slightly altered in the lower part of the flow.

Well ICPP-123 bottomed in sediment at 743'. The sediment is unstratified silt and clay that is red (10R/4/8) at the top and dark gray (2.5YR/4/0) at the bottom. The grain size and texture of the sediment suggests that it is loess.

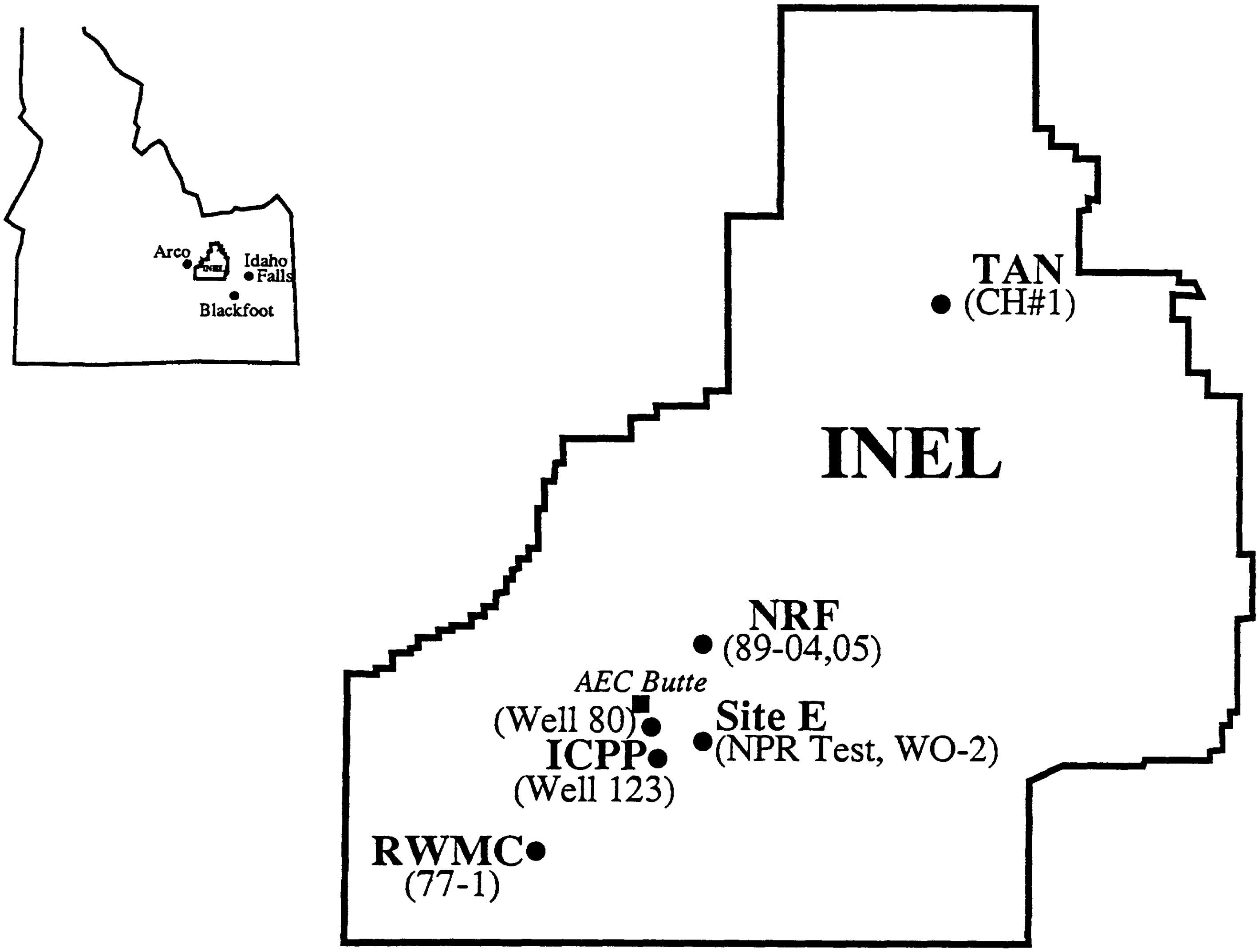

Figure 1: Location map showing the boundary of the Idaho National Engineering Laboratory, certain facilities areas, and the coreholes studied in this investigation.

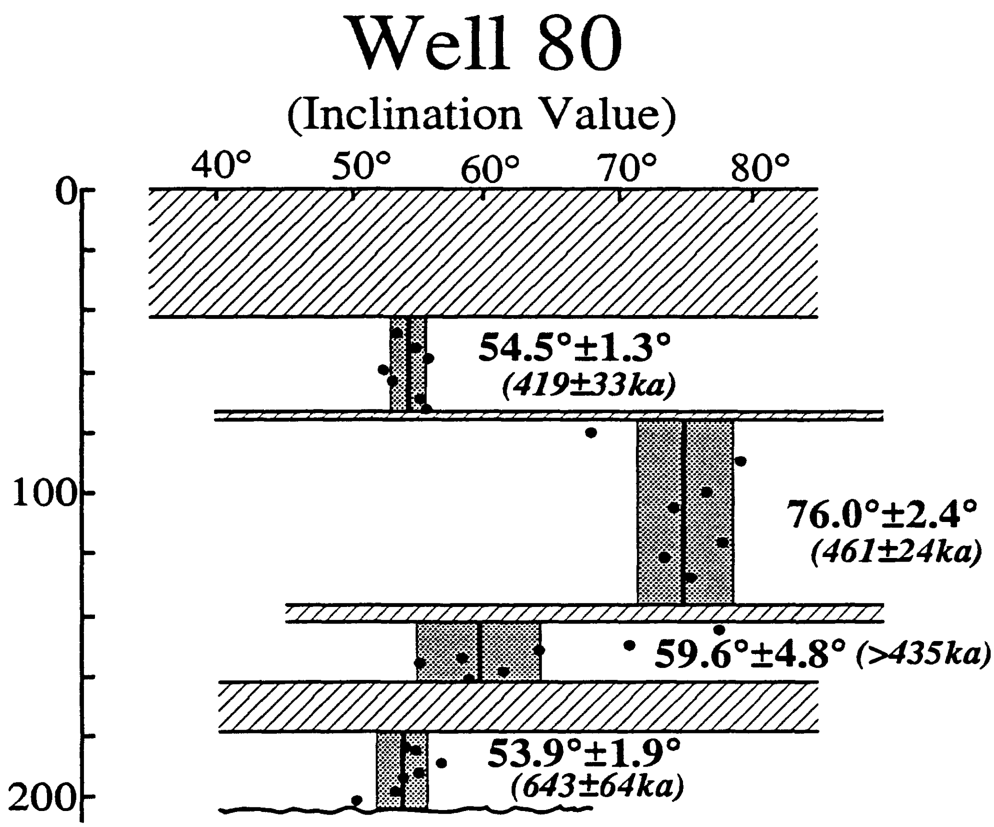

Figure 2: Log of core stratigraphy, K-Ar ages (in parentheses), and paleomagnetic inclination data in Well 80 at the INEL. Diagonal ruling indicates sedimentary interbeds, horizontal lines are flow contacts, solid points represent polarity data for individual samples, and light stippling pattern represents 95% confidence limits around the mean inclination values.

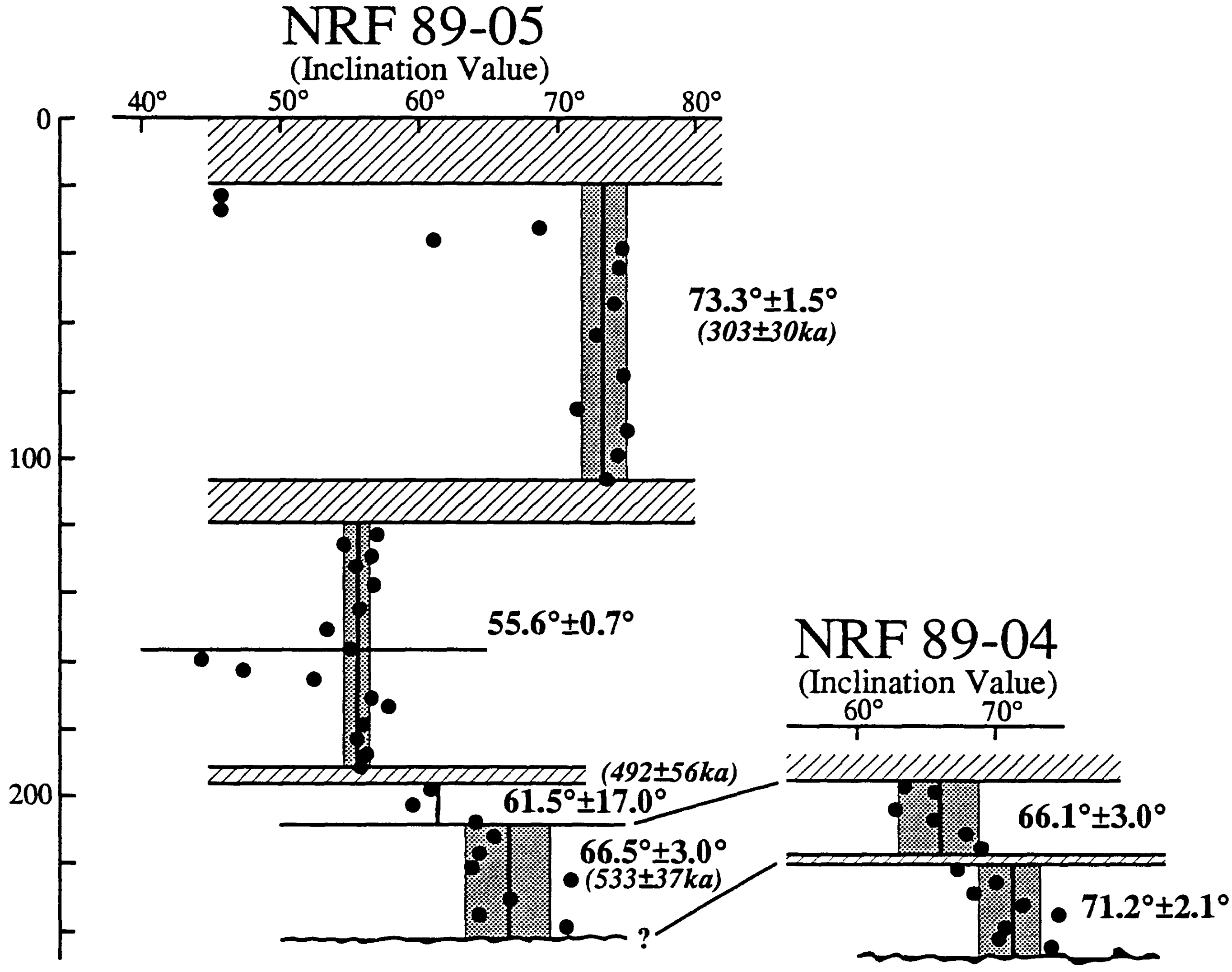

Figure 3: Log of the core stratigraphy, K-Ar ages (in parentheses), and paleomagnetic inclination data in coreholes NRF 89-04 and NRF 89-05. Symbols the same as Fig. 2.

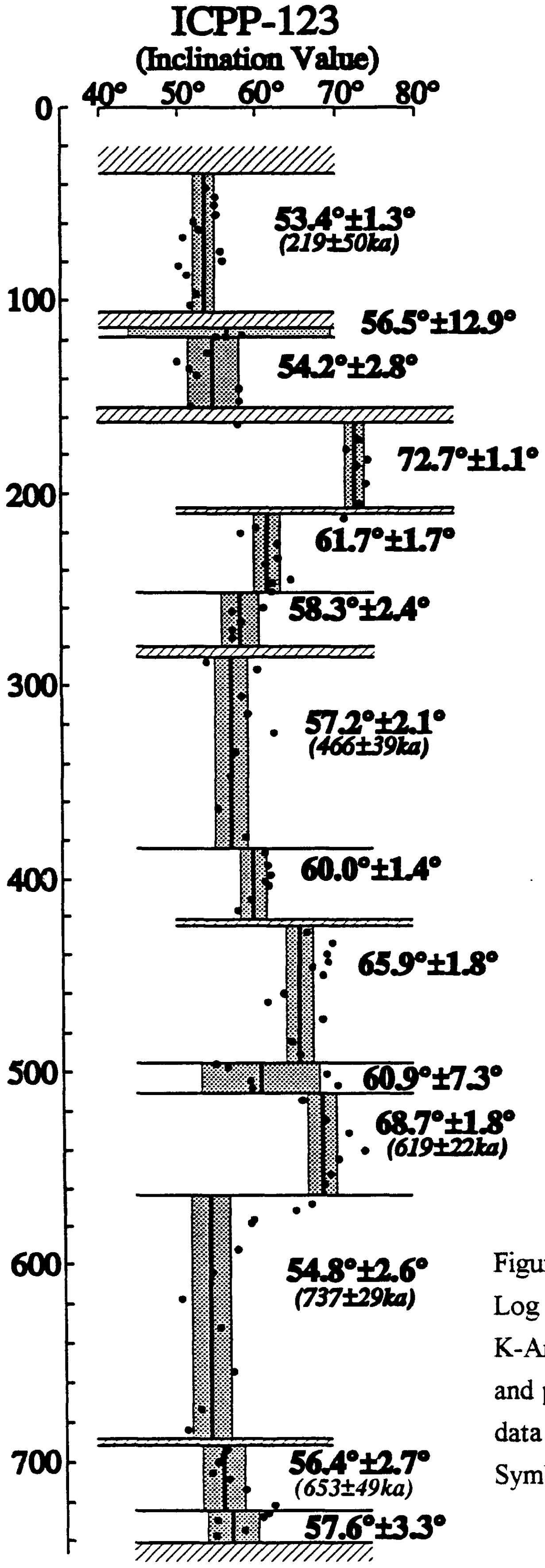

Figure 4:
Log of the core stratigraphy, K-Ar ages (in parentheses), and paleomagnetic inclination data in corehole ICPP 123. Symbols the same as Fig. 2.

Table 1: Potassium-argon ages and analytical data for basalt samples from corehole 80, Idaho National Engineering Laboratory

Flow	Sample	Depth (ft)	K_2O* wt %	$^{40}Ar_{rad}$ (10^{-13} mol/g)	$^{40}Ar_{rad}$ %	Calculated ages, 10^3 yr@ sample age		flow age#
1	80-15	51	0.671 ± 0.003	3.853	2.5	399 ± 63	387 ± 44	419 ± 33
				3.636	2.4	376 ± 61		
1	80-55	55	0.661 ± 0.002	4.397	2.7	462 ± 68	459 ± 49	
				4.338	2.5	456 ± 71		
2	80-99	99	0.604 ± 0.005	4.196	4.2	483 ± 46	424 ± 32	461 ± 24
				3.200	3.2	368 ± 45		
2	80-127	127	0.605 ± 0.001	4.560	3.8	523 ± 54	506 ± 36	
				4.284	4.1	492 ± 48		
3	80-154	154	0.616 ± 0.001	1.900	3.8	214 ± 34	267 ± 21	
				2.675	5.5	301 ± 27		
3	80-155	155	0.605 ± 0.002	3.873	7.9	445 ± 28	435 ± 21	>435
				3.684	7.4	423 ± 32		
3	80-158	158	0.633 ± 0.002	2.887	6.5	317 ± 24	272 ± 17	
				2.043	4.7	224 ± 25		
4	80-194	194	0.569 ± 0.003	4.015	5.0	490 ± 39	490 ± 28	
				4.013	4.7	490 ± 41		
4	80-198	198	0.546 ± 0.004	5.153	2.8	656 ± 91	643 ± 64	
				4.960	2.8	631 ± 89		

*Mean and standard deviation of four measurements.

@$\lambda_\varepsilon = 0.581 \times 10^{-10} yr^{-1}$, $\lambda_\beta = 4.962 \times 10^{-10} yr^{-1}$, $^{40}K/K = 1.167 \times 10^{-4}$ mol/mol. Errors are estimates of the standard deviation of analytical precision.

#Weighted mean of the sample ages, where weighting is by the inverse of the variance, and weighted standard deviation.

Table 2: Potassium-argon ages and analytical data for basalt samples from coreholes NRF 89-04 and NRF 89-05, Idaho National Engineering Laboratory

Flow	Sample	Depth (ft)	K_2O* wt %	$^{40}Ar_{rad}$ (10^{-13} mol/g)	$^{40}Ar_{rad}$ %	calculated ages, 10^3 yr@ sample age	flow age#
1	89-05-79	79	0.522 ± 0.002	2.100	2.7	279 ± 45	303 ± 30
				2.435	3.6	323 ± 41	
2	89-05-179	179	0.332 ± 0.001	3.204	4.3	669 ± 75	712 ± 52
				3.610	4.7	754 ± 74	
3	89-04-212	212	0.448 ± 0.002	3.820	1.6	591 ± 149	492 ± 56
				3.067	3.1	475 ± 61	
4	89-05-235	235	0.646 ± 0.003	5.138	4.0	552 ± 55	609 ± 35
				7.047	5.1	758 ± 58	
				4.815	4.0	518 ± 50	
4	89-04-231	2321	0.576 ± 0.001	7.161	6.0	864 ± 58	819 ± 39
				6.478	6.2	782 ± 53	

*Mean and standard deviation of four measurements.

@ $\lambda_\varepsilon = 0.581 \times 10^{-10} yr^{-1}$, $\lambda_\beta = 4.962 \times 10^{-10} yr^{-1}$, $^{40}K/K = 1.167 \times 10^{-4}$ mol/mol. Errors are estimates of the standard deviation of analytical precision.

#Weighted mean of the sample ages, where weighting is by the inverse of the variance, and weighted standard deviation.

Table 3: Potassium-argon ages and analytical data for basalt samples from corehole ICPP 123, Idaho National Engineering Laboratory

Flow	Sample	Depth (ft)	K_2O* wt %	$^{40}Ar_{rad}$ (10^{-13} mol/g)	$^{40}Ar_{rad}$ %	Calculated ages, 10^3yr@ sample age	flow age#
1	123-49	49	0.643 ± 0.005	2.140	1.4	232 ± 68	219 ± 50
				1.895	1.1	205 ± 73	
7	123-335	335	0.466 ± 0.006	3.010	3.4	448 ± 54	466 ± 39
				3.650	3.6	487 ± 56	
11	123-540	540	0.620 ± 0.008	5.624	10.3	629 ± 32	619 ± 22
				5.439	10.4	609 ± 31	
12	123-674	674	0.482 ± 0.004	5.217	5.2	752 ± 43	737 ± 29
				5.027	5.0	724 ± 40	
14	123-737	737	0.770 ± 0.008	7.220	3.7	652 ± 70	653 ± 49
				7.234	3.8	653 ± 68	

*Mean and standard deviation of four measurements.

@ $\lambda_\varepsilon = 0.581 \times 10^{-10} yr^{-1}$, $\lambda_\beta = 4.962 \times 10^{-10} yr^{-1}$, $^{40}K/K = 1.167 \times 10^{-4}$ mol/mol. Errors are estimates of the standard deviation of analytical precision.

#Weighted mean of the sample ages, where weighting is by the inverse of the variance, and weighted standard deviation.