

Evidence for a New Geomagnetic Reversal From Lava Flows in Idaho: Discussion of Short Polarity Reversals in the Brunhes and Late Matuyama Polarity Chrons

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K-Ar ages and paleomagnetic data for basalt samples from a new core hole (site E) at the Idaho National Engineering Laboratory (INEL) indicate that the age of the reversed polarity event recorded in Snake River Plain lavas is older than 465 ± 50 ka (1000 years before present) reported previously by Champion et al. (1981). Nine basalt flows, eight with normal polarity and one with reversed polarity, were recognized in the site E core hole. The flows above and below the reversed flow have ages of 491 ± 80 ka and 580 ± 93 ka, respectively. The inclination of the paleomagnetic field direction of the reversed flow at site E agrees with the inclination of reversed flows elsewhere at INEL which have an age of 565 ± 14 ka. These reversed flows were previously thought to be correlative with the Emperor event. We suggest that this polarity event is an older event which we name the Big Lost Reversed Polarity Subchronozone and Subchron. A review of data documenting short reversal records from volcanic and sedimentary rocks shows that there is evidence for eight polarity subchrons in the Brunhes and two besides the Jaramillo in the late Matuyama. These 10 short subchrons begin to indicate the many short events that Cox (1968) hypothesized must exist if polarity interval lengths have a Poisson distribution. These events are true subchrons, not excursions, and may or may not have low associated paleointensities, although low field strengths might explain why the reversal process aborts. The mean sustained polarity interval length since late Matuyama Chron time is 90,000 years. The similarity of this number with the 10^5 -year period of the Earth's orbital eccentricity suggests anew that linkage between geomagnetic, paleoclimatic, and possible underlying Earth orbital parameters should be evaluated.

INTRODUCTION

The geomagnetic polarity time scale is divided into polarity chron, divisions of geologic time of the order of 1 m.y. during which the Earth's field was predominantly of one polarity, and polarity subchrons, shorter periods of opposite polarity within chron. These units correspond to the time span of polarity chronozones and subchronozones, respectively, which are based on bodies of rock containing the primary magnetopolarity record. Ages of polarity chron during the past 5 m.y. and of longer lasting (0.1–0.2 m.y.) polarity subchrons are well determined [Mankinen and Dalrymple, 1979]. Cox [1968] predicted that there should be numerous undiscovered polarity intervals with durations shorter than 0.05 m.y., and some evidence for the existence of these intervals has been presented. However, documentation of these short polarity intervals is difficult to obtain. For example, sediment accumulation rates in ocean basins may be too slow to provide a sufficient thickness of material in which the polarity reversal can be recorded. Also, the polarity time scale is based on the age and polarity of terrestrial volcanic rocks; thus evidence for polarity reversals of short duration requires fortuitous extrusion of volcanic rocks during these brief periods. In addition, the Earth's magnetic field exhibits, on occasion, excursions characterized by large changes in direction without a complete reversal of the field.

Many reversed subchrons or excursions have been proposed

for the Brunhes Normal Polarity Chronozone and Chron (see, for example, *Verosub and Banerjee* [1977]) although only four or five currently have sufficient support to indicate that they may represent actual reversals of the geomagnetic field. Only two of these, the Laschamps Reversed Polarity Subchron of *Bonhommet and Babkine* [1967] and that reported by *Champion et al.* [1981] have been found in subaerial lava flows.

Wollin et al. [1971] presented evidence from sediment cores in the Caribbean and the North Pacific for five brief reversed events in the Brunhes. They estimated an age of about 400 ka (1000 years before present) for the oldest of these five events. *Ryan* [1972] subsequently named the oldest event the Emperor event. *Zubakov and Kochegura* [1976] identified a reversed event which they named the Ureki event in sedimentary deposits in Russia and suggested that the age of this event is in the range 450–550 ka. *Wilson and Hey* [1981] analyzed the axial magnetic anomaly over the Galapagos spreading center and proposed the presence of a brief reversed event having an age of 490 ± 50 ka and a duration of 10 kyr. *Champion et al.* [1981] detected reversely magnetized flows in a sequence of basalt flows in a core at the Idaho National Engineering Laboratory (INEL) in Idaho. They used K-Ar ages of the bracketing normally magnetized flows to assign an age of 465 ± 50 ka to the reversed event because they did not find material suitable for dating in the reversely magnetized flows. *Champion et al.* [1981] correlated this reversed event with the Emperor event after the prior usage of *Ryan* [1972] and also correlated the event with reversed magnetic events of similar age in sediment cores and seafloor magnetic anomalies.

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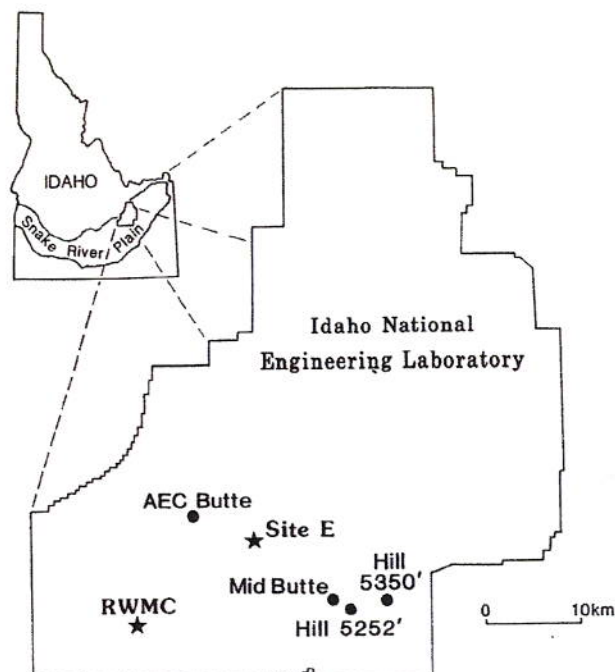


Fig. 1. Location map of the Idaho National Engineering Laboratory (INEL) showing positions of volcanic vents and sites mentioned in the text and the position of the laboratory on the eastern Snake River Plain.

We recently studied the paleomagnetism and age of a sequence of basalt flows in a new core (site E) at the INEL in Idaho. A reversely magnetized flow in this core can be correlated by paleomagnetic attributes with the reversed flows in a core from the Radioactive Waste Management Complex (RWMC) described by *Champion et al.* [1981]. We were also able to measure K-Ar ages on the reversed flows studied by *Champion et al.* [1981]. The new K-Ar data indicate that the age of these reversed lavas is 565 ± 14 ka rather than 465 ± 50 ka reported previously by *Champion et al.* [1981]. Therefore the polarity reversal in the Snake River Plain lavas is different in age from what has been called the Emperor event in sediment cores and seafloor magnetic anomalies, and a new name for this event is herein proposed for this polarity event.

A review of the status of verifiable short intervals of fully opposite polarity to the magnetic chron that they are within suggests that there is variable but good evidence for eight such events in the Brunhes and two in the late Matuyama besides the Jaramillo Subchron. Several of these events have been found in volcanic units on which ages have been measured. The events have an apparently aperiodic but regular recurrence interval of an intriguing character. We speculate that these events may constitute the best proof yet that there is a connection between the eccentricity of the Earth's orbit and polarity fluctuations of the geomagnetic field [*Wollin et al.*, 1977; *Rampino*, 1979].

Allan Cox, in a paper published in 1968, suggested that given the present frequency distribution of the lengths of polarity intervals, the shortest polarity intervals (<50 kyr) should have the greatest frequency. If that were the case, then polarity interval lengths would have a Poisson distribution. Based on this suggestion, one of us (D.E.C.) has spent portions

of the last 10 years actively looking for evidence of these events. The status of their discovery, as documented in this paper, seems to be more a case of serendipity and perseverance rather than cleverness on anyone's part. This paper is dedicated to the memory of Allan Cox and the premise that some of us are destined to spend the rest of our careers trying to verify ideas and half-baked notions that Allan imagined on sunny afternoons.

GEOLOGIC SETTING

The eastern Snake River Plain of Idaho (Figure 1) is a northeast trending physiographic province approximately 100 km wide and 300 km long that is underlain by Neogene volcanic rocks and interbedded sediments. Silicic volcanism progressed in age from southwest to northeast with the youngest volcanic rocks in the far eastern part of the Plain [*Leeman*, 1982]. Rhyolitic domes and flows are generally exposed only along the margins of the plain, but several domes, including Big Southern and East Buttes, that are surrounded by basalt flows are located in the plain. The greater part of the eastern plain is covered by late Pleistocene and Holocene basalt fields.

The INEL covers an area of about 2300 km² west of Idaho Falls, Idaho, in the eastern part of the Snake River Plain (Figure 1). The surface geology has been studied, and a number of wells have been drilled to provide information needed to evaluate potential volcanic hazards to facilities at the laboratory [*Kuntz et al.*, 1984]. *Kuntz et al.* [1980] described the petrography, age, and paleomagnetism of volcanic rocks at the RWMC, which is located in the southwestern part of the INEL. A new cored hole (site E) drilled in 1984, about 10 miles (16 km) northeast of the RWMC, provided much of the material used in this study (Figure 1).

The site E core hole was continuously cored to a depth of 185.6 m (608.9 ft). Core recovery was greater than 85%. Flow boundaries were determined by visual inspection of the core by one of us (D.E.C.) and by reference to the initial description by L. Morzel (unpublished data, 1985). Nine basalt flows and six sedimentary interbeds were recognized in the core (Figure 2). The flows range in thickness from 6.4 to 29.4 m; sedimentary interbeds and intervals of no core recovery range in thickness from 0.8 to 13.1 m. The flows are olivine basalt and are petrographically similar. All contain olivine, plagioclase, clinopyroxene, ilmenite, magnetite, glass, and accessory apatite. Alteration consists, where present, of reddish films on fracture surfaces and crystal faces of olivine and, where severe, of an opaque coating on crystal faces. Calcite is ubiquitous as a coating on vesicle walls and also occurs rarely as an alteration of the matrix of porphyritic rocks.

PALEOMAGNETISM

Procedures

More than 170 minicores, 2.5 cm in diameter, were taken from the drill core of the site E hole to determine the polarity and inclination of remanent magnetization in the basalt flows. The minicores, drilled on randomly oriented axes at right angles to the vertical axis of the original core, were cut into specimens 2.2 cm long and measured on cryogenic or spinner magnetometers. A specimen from each flow was chosen for progressive alternating field (af) demagnetization in order to determine the field strength required to remove secondary

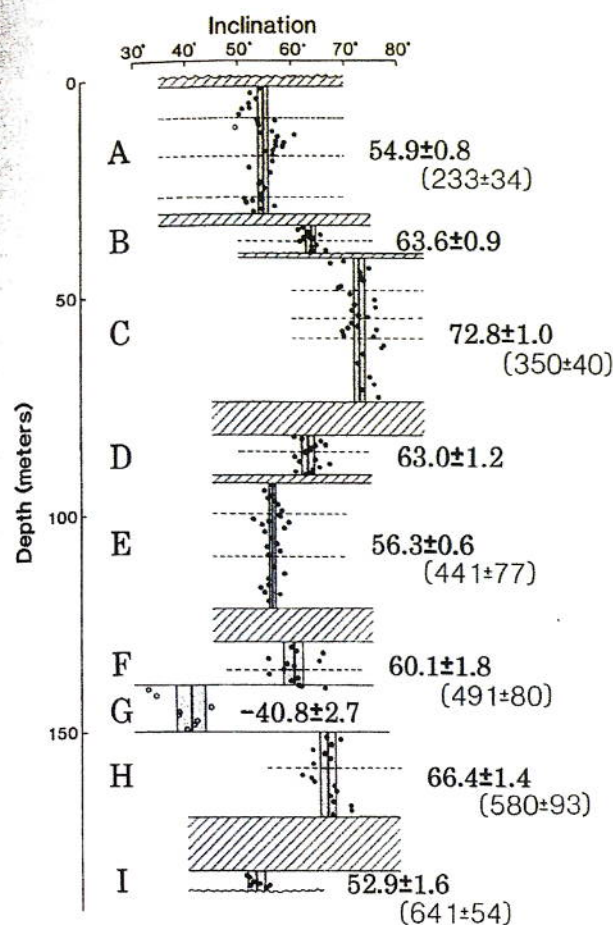


Fig. 2. Log of the core stratigraphy, K-Ar ages (in parentheses), and paleomagnetic inclination data from drill core samples at site E at INEL, Idaho. Diagonal ruling indicates sedimentary interbeds, horizontal lines are flow (solid) or flow unit (dashed) contacts, small solid points represent normal polarity data, open symbols represent reversed polarity data, and light stippling pattern represents 95% confidence limits about the mean inclination values. Uncertainty in K-Ar ages is pooled analytical standard deviation from Table 2, while error limits on magnetic inclinations are 95% confidence limits about the mean calculated by the method of *McFadden and Reid* [1982].

magnetization. Peak cleaning field strengths were usually 20 mT except for specimens from the deepest flows which have slightly larger effects of viscous remanent magnetization and were cleaned at 30 mT or higher.

In addition to the samples from the site E drill core, 420

specimens were taken from 36 surface flow outcrops to obtain the direction of remanent magnetization and polarity from these flows. Results from only four of these flows are reported here (Table 1). The samples were taken with a portable, water-cooled diamond-coring drill and oriented in the field using a sun compass. A specimen from each core was progressively demagnetized using alternating field until it was clean of secondary components. Peak field strengths required to clean the specimens differ because secondary magnetization, presumably isothermal remanence, from lightning strikes has affected many samples. Specimens from older flows or those at higher elevations were influenced most strongly by lightning and required peak field strengths as high as 100 mT. Directions of remanent magnetization from these four flows were correlated with the polarity and inclination data from flows in the drill core to verify the stratigraphic succession of mapped surface flows. This correlation additionally allowed us to use age control from surface outcrops in our drill core evaluation.

The primary remanence inclinations obtained from specimens of the site E core are shown in Figure 2. Mean inclination values for each flow were calculated using the method of *McFadden and Reid* [1982]. The data show that flows A–F and H and I cooled in fields of normal polarity, whereas flow G was erupted while the field was reversed. Inclinations are reasonably consistent within individual flows. Exceptions were one specimen from flow A and one from flow H which may represent rare, inadvertently overturned segments of the original drill cores. These data points have been inverted in Figure 2. The top two specimens from flow G are of the opposite polarity to the other specimens from this flow. This results from a thermal remagnetization of the upper part of flow G due to heating by overlying flow F.

Comparison of the paleomagnetic results from surface flows and from the site E drill core allows us to identify the vents responsible for the top three flows. Surface mapping by *Kuntz et al.* [1984] indicates that the uppermost flow (flow A) at site E is from Mid Butte located 6.5 miles (10.5 km) upslope to the SE (Figure 1). Flow B with a mean inclination of 63.6° can be correlated with flows from Hill 5350' located 10 miles (16 km) to the SE. Flow C with a steep mean inclination value of 72.8° matches those of flows from Hill 5252' located 8 miles (13 km) to the SE. Correlations of flows deeper within the site E core with surface vents are difficult to make, as the vents for these flows may well be buried by younger flows. However, the match of size, shape, and composition of olivine phenocrysts and similar inclination values of about 52.9° suggest that flow I came from AEC Butte. Additional support for this correlation provided by K-Ar ages is discussed in a later section.

TABLE 1. Paleomagnetic Data From Surface Sites at INEL and From New Mexico

Name	Site Location		N/N_0	Exp, mT	I , deg	D , deg	A_{95}	k	Polarity
	Latitude, °N	Longitude, °E							
Mid Butte	43.51	247.23	12/12	30+	52.3	340.9	2.5	302	normal
Hill 5350'	43.53	247.31	12/12	20+	62.7	352.8	2.1	442	normal
Hill 5252'	43.52	247.25	9/12	30+	71.2	358.9	0.9	3229	normal
AEC Butte	43.59	247.06	9/12	40+	53.5	359.0	1.6	986	normal
Laguna Basalt	35.08	252.25	10/12	80+	-17.7	273.9	2.5	367	transitional

N/N_0 is the number of cores used compared with the number originally taken at the site; Exp is the strength of the peak cleaning field; I and D are the remanent inclination and declination; A_{95} is the 95% confidence limit about the mean direction; and k is the estimate of the Fisherian precision parameter.

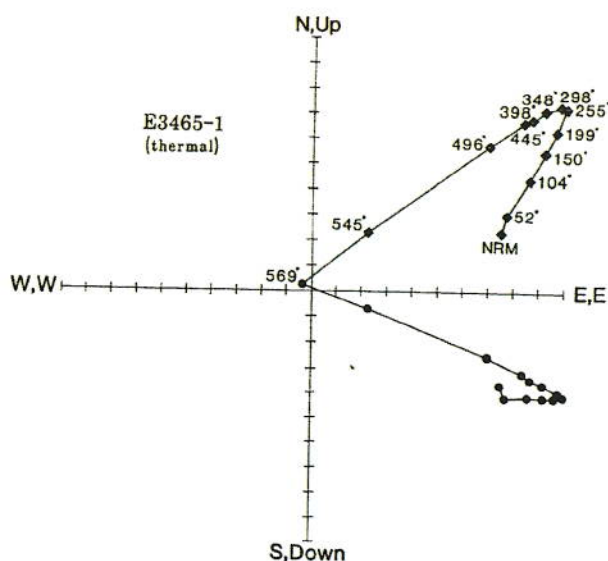


Fig. 3. Vector component diagram of sample E3465-1 from site E at INEL. Data represent position of end of the magnetic vector projected into vertical (E-W, diamonds) and horizontal (circles) planes. Plot shows two magnetic components of opposite polarity, with normal polarity component removed at lower temperatures than reversed component.

Thermal Demagnetization Experiments

From previous experience with the core from the RWMC, the specimens from flow G were not cleaned using alternating fields but instead were thermally demagnetized. This allowed us to separate the normal overprinting magnetization from the primary reversed one and to estimate the absolute declination of flow G. Vector component plots show the separation of the two polarities well (Figure 3). Using thermal demagnetization and vector subtraction of the components removed, the net angular difference in declination between the original reversed direction and the overprinting normal direction was calculated. Six of the 10 specimens from flow G have sufficient partial normal polarity overprints to calculate the relative declinations between the normal and reversed directions. The top two specimens were completely overprinted with normal polarity, and the bottom two were unaffected. The results indicate that the declination of flow G relative to flow F, which caused the overprinting, is 211° . If we assume that flow F has an absolute declination of 0° (north), then the absolute declination of flow G is 211° .

The combined declination and inclination values for flow G lie 28° from the reversed axial dipole field direction expected at the latitude of the site E well. Thus the magnetization recorded by flow G is well within the typical variation of a reversed geomagnetic field [McElhinny and Merrill, 1975]. The declination of flow G is similar to the value of 216° deduced for flows 10 and 11 in well 77-1 at the RWMC [Champion et al., 1981]. The reversed polarity interval in both wells thus has a similar direction, and they both occur at similar depths, 456–492 feet (139–150 m) in the site E well and 367–545 feet (112–166 m) in well 77-1. The much greater thickness of flows in well 77-1 likely means that this well is closer to the vent, although the exact location of the vent is still unknown. An averaging of the inclination values for flows 10A, 10B, 10C, and 11 in well 77-1 shows a progressive shall-

owing of inclination upward. Comparing the mean inclination of flow G to this progression suggests that it correlates best with flow 10C in well 77-1 (Figure 4).

The upward shallowing of inclination in flows 11–10 in well 77-1 suggests that appreciable amounts of time may have occurred between eruption of these four flows. Under ordinary conditions of secular variation, 6° of angular motion of the field direction would require about 100 years [Champion, 1980]. But studies of other Holocene volcanic fields on the Snake River Plain show that their lavas record only single directions of magnetization, indicating that all were erupted and cooled below their blocking temperatures in time periods of a few months to a few years [Champion and Shoemaker, 1977].

The apparent contradiction in these observations may be resolved if the rates of secular variation are faster during brief excursions of the geomagnetic field. Evidence for just this situation has been recently presented by Mankinen et al. [1985] in their study of the directional and intensity characteristics of the Steens Mountain polarity transition at 15.5 Ma. They measured angular rates of change of up to $60^\circ/\text{yr}$ during portions of the transition from reversed to normal polarity. These rates were fast enough that portions of single lava flows recorded different directions of magnetization as they cooled. Rates approximately 1/10 as fast as those deduced from the Steens Mountain transition would be sufficient to explain the shallowing of inclinations in flows from well 77-1 in a period of a few years or less.

AGE OF THE FLOWS

Results

From each core or surface flow sample selected for K-Ar age measurement, several hundred grams of basalt were crushed and sized to 1/2–1 mm. Aliquants weighing 23–48 g were used for argon analyses. A 10-g aliquant of crushed basalt was ground to less than 0.075 mm, and splits of this powder were used for K_2O analyses. K_2O measurements were made in duplicate on each of two splits of powder by flame photometry after lithium metaborate fusion and dissolution

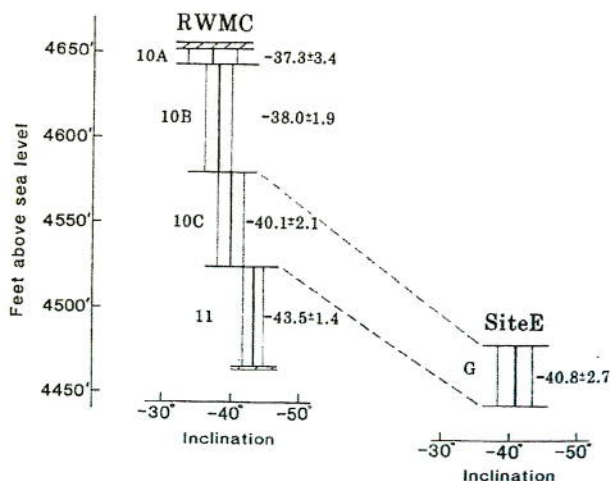


Fig. 4. Comparison of inclination values for flows 10 and 11 from hole 77-1 at the RWMC and flow G from site E, at true elevations above sea level. Plot suggests that vent for reversed polarity flows lies nearer the RWMC and uphill from site E.

TABLE 2. Potassium-Argon Data for Samples of Basalt From Drill Hole at Site E, Idaho National Engineering Laboratory, Idaho

Flow	Sample	Depth, m	K ₂ O,* wt %	⁴⁰ Ar _{rad} , × 10 ⁻¹³ mol/g	⁴⁰ Ar _{rad} , %	Calculated, 10 ³ years†	
						Sample Age	Flow Age‡
A	E3023	7	0.838 ± 0.013	2.282	1.12	189 ± 68	233 ± 34
				3.013	1.46	249 ± 70	
	E3081	25	0.739 ± 0.009	2.425	1.37	227 ± 67	
C	E3157	49	0.873 ± 0.011	2.820	1.64	265 ± 64	350 ± 40
				4.603	1.98	366 ± 74	
				4.315	1.77	343 ± 48	
E	E3352	107	0.446 ± 0.007	2.859	1.73	445 ± 104	441 ± 77
				2.806	1.61	437 ± 116	
F	E3444	135	0.180 ± 0.009	1.208	2.34	466 ± 105	491 ± 80
				1.359	2.63	524 ± 122	
H	E3508	155	0.533 ± 0.009	4.446	2.46	580 ± 93	580 ± 93§
I	E3606	185	0.455 ± 0.003	4.545	3.84	694 ± 72	641 ± 54
				3.735	2.70	570 ± 83	

*Mean and calculated standard deviation of four measurements.

† $\lambda_K + \lambda_{Ar} = 0.581 \times 10^{-10} \text{ yr}^{-1}$, $\lambda_{Ar} = 4.962 \times 10^{-10} \text{ yr}^{-1}$, $^{40}\text{K}/\text{K} = 1.167 \times 10^{-4} \text{ mol/mol}$. 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 [Taylor, 1982].

§Flow age same as single sample age.

[Ingamells, 1970]. Argon analyses were made by isotope dilution using equipment and techniques described previously [Dalrymple and Lanphere, 1969]. All samples 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 with 22.86-cm radius and nominal 90° sector magnet [Stacey et al., 1981].

Seven samples were selected for K-Ar dating from six of the eight normally magnetized flows in the site E core hole. None of the samples in the reversely magnetized flow G was suitable for dating. Champion et al. [1981] did not find samples suitable for K-Ar dating in the thicker, reversely magnetized section of basalt in RWMC 77-1 core, but a reexamination of this core yielded three samples that were suitable for dating. Kuntz et al. [1980] described two reversely magnetized flows, flows 10 and 11, in the RWMC 77-1 core. They further subdivided flow 10 into three units, 10A, 10B, and 10C, on the basis of flow breaks marked by vesicular, rubbly, oxidized basalt. The three samples suitable for dating are from units 10B and 10C and flow 11. Ages also were measured on samples from two surface flows that could be correlated with flows in the core holes. Duplicate Ar measurements were made on all samples from the site E core except for that from flow H for which only one reliable measurement was obtained. For all samples the calculated ages for individual measurements and weighted mean flow ages have large uncertainties both because of low percentages of radiogenic ⁴⁰Ar, typically 1–3%, which results from low K₂O contents (0.18–0.87 wt %), and because of the youth of the flows.

K-Ar ages and analytical data for basalt from the site E core are given in Table 2. Ages were measured on two different samples from flow A because this flow was divided into three flow units during the initial core description. However, there are no soil horizons or sedimentary breaks between these units; subsequently, it was decided to combine these three units into a single flow. The four ages for flow A are in good agreement. Duplicate ages on four other flows agree within analytical uncertainty.

The ages for the six flows in the site E corehole range from 233 ± 34 ka to 641 ± 54 ka and are in correct stratigraphic order. Although not measured because of lack of suitable material for dating, the age of flow G must be between 491 ± 80 ka and 580 ± 93 ka, the ages of the bracketing normal flows. As part of this study, we reexamined the core from hole 77-1 and selected three samples that were suitable for dating. K-Ar ages and analytical data for these samples from the two reversely magnetized flows in hole 77-1 are given in Table 3. The ages are in excellent agreement and yield ages of 565 ± 14 ka and 565 ± 78 ka for the two flows. There are flow breaks in flow 10 but no sedimentary interbeds within flow 10 or between flows 10 and 11. These two flows are similar petrographically, suggesting that both were erupted from the same vent. Therefore it is reasonable to pool the ages of flows 10 and 11 to obtain an age for the reversely magnetized section of lavas. The pooled, weighted mean age for the reversed flows is 565 ± 14 ka, which is compatible with the stratigraphic constraint provided by the ages of the bracketing normally magnetized flows F and H in the site E core hole.

K-Ar ages for surface basalt flows relevant to the discussion in this paper of magnetic polarity events in the vicinity of INEL are given in Table 4. Two of these flows can be correlated with flows intersected in various core holes. First, the basalt of AEC Butte (Figure 1) has the same magnetic inclination as flow I, the bottom flow in the site E core hole. In addition, this basalt is olivine-phyric and is markedly different from most lavas of the Snake River Plain. Surface sample 84ILe-25 from the AEC Butte flow has an age of 626 ± 67 ka, which agrees with the age of 641 ± 54 ka for flow I. Second, the basalt of Mid Butte can be correlated with flow A at site E. The age of 264 ± 48 ka for surface sample 84ILe-26 from Mid Butte agrees with the weighted mean age of 233 ± 34 ka for flow A from core samples.

Discussion

K-Ar ages were measured previously on samples of 10 flows in four different core holes at the RWMC [Champion et al.,

TABLE 3. Potassium-Argon Data for Samples of Basalt From Drill Hole 77-1, Radioactive Waste Management Complex (RWMC), Idaho National Engineering Laboratory, Idaho

Flow	Sample	Depth, m	K ₂ O,* wt %	⁴⁰ Ar _{rad} × 10 ⁻¹³ mol/g	⁴⁰ Ar _{rad} , %	Calculated, 10 ³ years†	
						Sample Age	Flow Age‡
10B	77-1-427	130	0.688 ± 0.005	5.901	4.93	596 ± 48	565 ± 14
				5.601	4.82	566 ± 46	
10C	77-1-473	144	0.672 ± 0.005	5.729	15.2	592 ± 20	
				4.974	12.1	514 ± 25	
11	77-1-543	166	0.782 ± 0.002	6.945	1.82	617 ± 134	565 ± 78
				6.050	2.23	538 ± 96	

*Mean and calculated standard deviation of four measurements.

† $\lambda_e + \lambda_{e'} = 0.581 \times 10^{-10} \text{ yr}^{-1}$, $\lambda_{\beta} = 4.962 \times 10^{-10} \text{ yr}^{-1}$, $^{40}\text{K}/\text{K} = 1.167 \times 10^{-4} \text{ mol/mol}$. 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 [Taylor, 1982].

1981]. Weighted mean ages for these flows are shown on Figure 5 beside a composite stratigraphic log prepared from data of Kuntz *et al.* [1980]. Ages were not measured directly on flows 10 and 11; the ages measured on the normally magnetized flows above and below the reversed interval were pooled. Thus Champion *et al.* [1981] assigned an age of $0.465 \pm 0.05 \text{ Ma}$ ($465 \pm 50 \text{ ka}$) to the reversed polarity event at the INEL. The Critical Value test [Dalrymple and Lanphere, 1969] indicates that at the 95% confidence level, this assigned age for the reversed polarity event and the age measured in this study on the reversely-magnetized lavas are different.

It is important to note that the ages reported by Champion *et al.* [1981] for flows 12 and 13 are not in the correct stratigraphic order. Furthermore, the ages of multiple samples from the same flow did not agree very well. This was particularly true for samples from flows 9 and 12. There is no statistically significant difference between the ages of flows 9, 12, and 13, and the pooling procedure used by Champion *et al.* [1981] was appropriate given their body of data. However, the new ages from site E permit a reevaluation of the RWMC ages. The ages of flow 9 (RWMC) and flow F (site E) (Figure 5) indicate that the age of the reversed interval is older than 500 ka. The ages of flows H and I (site E) are in correct stratigraphic order and differ in this regard from the incorrect stratigraphic order of ages for flows 12 and 13 at RWMC. We suggest that the ages of flows 12 and 13 are too young and should be dis-

garded. The new ages on flows 10 and 11 (Table 3) provide additional evidence that the ages reported by Champion *et al.* [1981] for flows 12 and 13 are too young. The critical value test [Dalrymple and Lanphere, 1969] indicates that at the 95% confidence level, a difference has been detected between the age of flow 12 and the pooled ages of flows 10 and 11. One cannot tell from this test which age is correct, only that the ages are different. However, the correct stratigraphic order of ages at site E and the stratigraphic reversal of ages reported by Champion *et al.* [1981] in core 77-1 at the RWMC suggest that the ages of flow 12 and, by the same reasoning, flow 13 are wrong.

The K-Ar ages measured in this study clearly indicate that the age suggested by Champion *et al.* [1981] for the reversely magnetized polarity event in the Snake River Plain lavas needs to be revised. The question about the name of the polarity event is more ambiguous. Champion *et al.* [1981] concluded that the reversed event recorded in basalt flows from the RWMC probably was the Emperor event of Ryan [1972]. However, the new K-Ar ages from this study indicate that the reversely magnetized basalt flows record an event that is much older than the estimated age of the Emperor event in deep-sea sediment cores. In addition, under the premise of multiple reversed events within the Brunhes, it is not clear to which event the original name of Emperor should apply. The same criticism can be invoked regarding the Ureki event of Zubakov

TABLE 4. Potassium-Argon Data for Samples of Basalt From Surface Flows in and Near the Idaho National Engineering Laboratory, Idaho, and From the Laguna Flow, Valencia County, New Mexico

Field	Vent or Name	K ₂ O,* wt %	⁴⁰ Ar _{rad} × 10 ⁻¹³ mol/g	⁴⁰ Ar _{rad} , %	Calculated, 10 ³ years†	
					Sample Age	Flow Age‡
84ILe-26	Mid Butte	0.576 ± 0.001	2.188	2.22	264 ± 48	268 ± 32
			2.258	2.53	272 ± 43	
84ILe-25	AEC Butte	0.456 ± 0.004	4.569	2.82	697 ± 98	626 ± 67
			3.691	2.70	563 ± 92	
AWL-1-86	Laguna flow	0.826 ± 0.008	1.563	1.09	131 ± 48	128 ± 33
			1.483	1.10	125 ± 45	

*Mean and calculated standard deviation of four measurements.

† $\lambda_e + \lambda_{e'} = 0.581 \times 10^{-10} \text{ yr}^{-1}$, $\lambda_{\beta} = 4.962 \times 10^{-10} \text{ yr}^{-1}$, $^{40}\text{K}/\text{K} = 1.167 \times 10^{-4} \text{ mol/mol}$. 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 [Taylor, 1982].

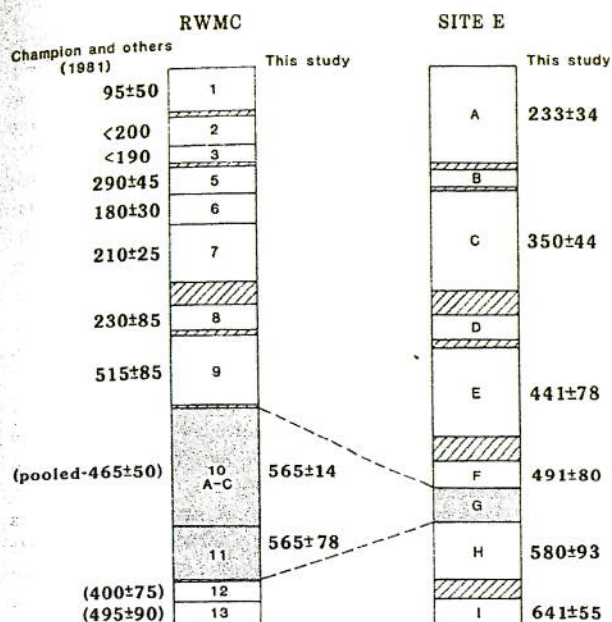


Fig. 5. Stratigraphic log and K-Ar data from core 77-1 at the RWMC originally reported by Champion *et al.* [1981] compared with stratigraphic and age data from site E. Normal polarity flows are clear of pattern, and reversed polarity flows are shown with stippling. Diagonal ruling indicates sedimentary interbeds. K-Ar dating performed in this study (Table 3) suggests that the ages in parentheses are incorrect and should be replaced.

and Kochegura [1976], whose age designation assumes linear sedimentation rates and is uncertain. Therefore we conclude that our measured polarity event and the Emperor are not correlative, and the name Emperor should not be applied to the reversed event in the Snake River lavas.

We here propose that the reversed event having an age of 565 ± 14 ka be named the Big Lost Reversed Polarity Subchronozone and Subchron after the Big Lost River which flows near and locally above these subsurface flows at the Idaho National Engineering Laboratory. The four flow units (10A-10C, 11) located between 112 m and 169 m from the surface in hole 77-1 at the RWMC are here designated the type section (Figure 4). These flow units extend laterally an unknown distance in the subsurface of the Snake River Plain, but one of them appears 10 miles (16 km) northeast of the RWMC at site E between 139 m and 150 m (Figure 2), and it is here designated a reference section (Figure 4). The age of these flow units is 565 ± 14 ka from data presented in this study, and their source vent is probably buried and at present unlocated. The core from hole 77-1 is currently on display at the RWMC in an air-support nuclear waste storage building.

Correlative Events to the Big Lost Polarity Subchron

Deep-sea sediment cores have been studied extensively for information about reversals of the Earth's magnetic field. The boundaries of the established polarity-chronologic units generally can be determined reasonably well, but short polarity intervals commonly have not been detected in abyssal plain cores. The reasons for this detection problem included the short duration of the magnetic events, the slow rate of sediment accumulation, and the process of magnetization of sedi-

ments. However, evidence for short reversed intervals has been obtained in cores from areas of much higher sediment accumulation rate.

Harrison [1974] reviewed the published paleomagnetic data for cores that penetrated the Brunhes-Matuyama boundary and older chron boundaries. There were 216 cores that penetrated the Brunhes-Matuyama boundary, and of these, 173 showed no intervals of reversed polarity within the Brunhes section. Only two cores had reversely magnetized material in the lower part of the Brunhes section that might be compatible in age to the reversed event at INEL. Harrison [1974] tabulated the position of reversed material as a percentage of the length of Brunhes age sediment in a core. If a constant rate of sediment accumulation is assumed, ages of 569 and 606 ka can be inferred for reversed material in core T3-98 from the Arctic Ocean [Steuerwald *et al.*, 1968] and core E21-21 from the southern ocean [Goodell and Watkins, 1968], respectively. Watkins [1968] found a brief interval of reversed polarity in Eltanin core 17-11 that corresponds to an age of 562 ka if a uniform sedimentation rate is assumed.

Creer *et al.* [1980] studied the paleomagnetism of a long core of marine clay at Gioia Tauro, Italy, that penetrated rocks as old as the Matuyama Reversed Polarity Chron. They correlated a split zone of reversed material near the top of the core with the Blake Reversed Polarity Subchron of Smith and Foster [1969]. Creer *et al.* [1980] detected four intervals of low positive inclination within the Brunhes below the Blake Subchron. The ages of these excursions in the Gioia Tauro core, calculated assuming a constant rate of sediment accumulation, are 271, 417, 584, and 636 ka (the ages of Creer *et al.* [1980] have been recalculated using an age of 730 ka [Mankinen and Dalrymple, 1979] rather than 700 ka for the Brunhes-Matuyama boundary). The magnetic excursion in the Gioia Tauro core termed gamma by Creer *et al.* [1980] has an age that agrees with the age of the Big Lost Subchron.

Negrini *et al.* [1987] produced evidence of a brief full reversal in Pleistocene sediments of Lake Lahontan in the Humboldt River Canyon in Nevada. They estimated an age for the event at younger than the 495 ka that they derived for the Dibekulewe ash. In a more recent evaluation of tephrochronological correlation in the Pacific Northwest, Sarna-Wojcicki *et al.* [1988] suggest an age of 0.61 Ma for the Dibekulewe tephra due to its frequent juxtaposition in sediment sections to the Lava Creek B tephra which has a K-Ar age of 0.62 Ma. This suggests that the reversed interval in the Humboldt Canyon section is only a few tens of thousands of years younger than these ages and thus is a good prospect as a correlative of the Big Lost Subchron. It also greatly modifies the conclusion that Negrini *et al.* [1987] reach with regard to the lengthy duration (115,000 years) of nongeocentric axial dipole behavior as recorded in the Humboldt Canyon sediments.

MAGNETIC EVENTS IN THE BRUNHES AND LATE MATUYAMA

Since our last review of the status of reversed events within the Brunhes [Champion *et al.*, 1981], much progress has been made confirming and dating short polarity events (Figure 6). In addition, data for two short normal polarity events in the late Matuyama have also been published. A total of 10 short-duration polarity subchrons have now been identified to have occurred since 1 Ma. Six of these events have been found in

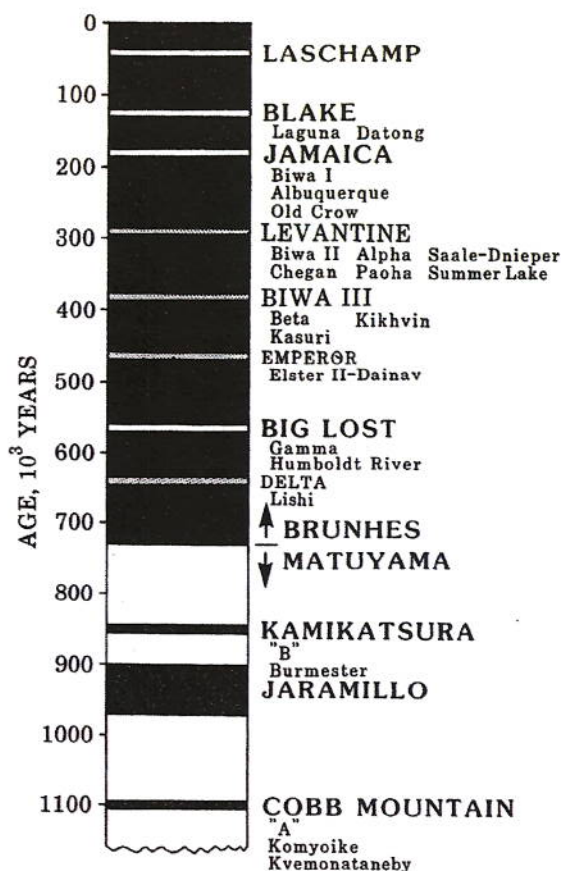


Fig. 6. Positions of well-identified reversed polarity subchrons in the Brunhes and late Matuyama Polarity Chrons. Events that have been identified and age dated from volcanic rocks shown as solid bars, those from sedimentary rocks as stippled bars. Typeface and type size of uppercase preferred subchron names represents the degree of confidence in the exact age or existence of a given magnetic subchron. Corroborative reversal records are listed in capital and lower-case letters beneath the subchron that they support.

volcanic rocks, which also have K-Ar ages. Four other events have been found in sedimentary sections of oceanic drill core, glacial loess, or pluvial lake deposits (Figure 6). Some of the subchrons recorded in sedimentary deposits in a number of independent occurrences are probably as well verified as those from volcanic deposits. We begin this discussion by dealing with sedimentary sections from which multiple events have been identified and then proceed with separate discussions of each subchron going backward in time. The current state of naming of these events is chaotic, and we have chosen a nomenclature based mainly on priority of usage. Our preferred nomenclature and estimated ages for reversed subchrons in the Brunhes recorded in sediment cores are given in Table 5. Most ages assume a constant rate of sediment accumulation during the Brunhes. All ages have been calculated or recalculated using an age of 730 ka for the Brunhes-Matuyama boundary.

Five intervals of negative inclination of remanent magnetization have been measured in a 200-m-long core from lake Biwa, Japan [Kawai *et al.*, 1972; Kawai, 1984]. Three of these intervals also have declination changes of about 180° and are considered to have recorded reversed polarity events. Ages were initially assigned to these intervals by extrapolation on

the basis of a depth-time equation derived from ^{14}C ages in the upper part of the core. Fission track ages on zircon from ash layers within the core have provided better information on the ages of these intervals. The mean ages assigned to the reversed events, which are 6–13 kyr in duration, are 100, 160, 310, and 380 ka [Kawai, 1984]. Yaskawa [1974] correlated the reversed events in the Biwa core to intervals of negative inclination in the north Pacific core V20-108 [Ninkovich *et al.*, 1966; Wollin *et al.*, 1971]. The upper event in the Biwa core corresponds to the Blake Subchron; the next two lower reversed intervals were named the Biwa I and Biwa II events. Creer *et al.* [1980] suggested that the alpha excursion at Gioia Tauro correlates with Biwa II and the beta excursion correlates with "Biwa III," an interval of negative inclination below Biwa II in the Lake Biwa core. There are no older intervals of negative inclination in the Lake Biwa core that might correlate with the gamma and delta excursions at Gioia Tauro. Ryan [1972] identified four reversed events in the Brunhes section of cores from the Caribbean and Mediterranean. He correlated the uppermost reversed interval with the Blake event and named the other reversed intervals, in descending order, the Jamaica, Levantine, and Emperor events. His estimated ages for the first two of these events were, in descending order, 200 and 300 ka, respectively. As this published work established the earliest evidence for globally distributed short reversals in the Brunhes, we adopt Ryan's [1972] names for the remainder of this discussion. It appears that the Jamaica and Levantine events can reasonably be correlated with Biwa I and II, respectively.

In addition to oceanic sediment cores, paleomagnetic results from glacial loess deposits of East Germany and western USSR indicate up to five polarity events within the Brunhes (summarized by Bucha [1983]). Researchers have found excursions at 660, 500, 370, 290, and 110 ka. Higher sedimentation rates associated with these deposits hold the promise that corollary sections may provide confirming evidence of excursions in the future.

Laschamps Subchron

Multiple studies of the reversed flows from the Chaîne des Puys of France, which constitute the evidence for the Laschamps Subchron, place its age at 42 ka [Hall and York, 1978; Gillot *et al.*, 1979; Condomines, 1978; Guerin, 1982; Condomines *et al.*, 1982]. Evidence for the Laschamps Subchron has been found in tuffaceous sediments from Japan [Hirooka *et al.*, 1977] and from alluvial deposits of the River Obj in the USSR [Kulikova and Pospelova, 1979] and possibly from Arctic Ocean sediments [Løvlie *et al.*, 1986]. Excursion directions in Icelandic lavas of the Skálamællifell region were reported first by Pierce and Clark [1978] and Kristjánsson and Guðmundsson [1980]. Levi *et al.* [1987] reported a K-Ar age of 50 ± 13 ka for these lavas, and this occurrence may also represent a transitional manifestation of the Laschamps Subchron.

Blake Subchron

The Blake Subchron has been found so frequently in oceanic sediment cores that there is little doubt about its existence. Sedimentation rates suggest that its age is somewhat older than 100 ka. For instance, an excursion recorded in sediment cores from Baffin Bay and correlated with the Blake has an estimated age between 129 and 161 ka based on sedimentation

TABLE 5. Mean Ages of Short Reversed Events or Magnetic Excursions in the Brunhes Chron

Source of Data	Blake	Jamaica/ Biwa I	Levantine/ Biwa II/ Alpha	Biwa III/ Beta	Emperor	Big Lost/ Gamma	Delta
Core E21-21 [Goodell and Watkins, 1968]		146		387	454	606	
Core T3-98 [Steuerwald et al., 1968]	124	182		336		569	
Core V20-108 [Wollin et al., 1971]	110	188	284		417		
Lake Biwa [Kawai, 1984]	100	160	310	380			
Gioia Tauro [Rampino, 1981] [Creer et al., 1980]	115		260	400		560	620
Eastern Mediterranean [Ryan, 1972]	105	200	300		460		
Core E17-11 [Watkins, 1968]						562	627
This study	128					565	

Ages are in 1000 years.

rate and correlation with oxygen isotope curves [Aksu, 1983]. The inclination record of a long drill core taken in the deposits of Lake Bonneville near Burmester, Utah, shows several meters of reversed polarity near the top of the section [Eardley et al., 1973]. They identify this interval as the Blake Subchron, and a calculation of its age, assuming constant sedimentation rates, is 125 ka. Sasajima et al. [1984] produced conclusive evidence for a short complete reversal in the Keno and Kogashira dacitic pyroclastic flows which contain zircon on which fission track ages have been measured ranging from 0.10 to 0.13 Ma. In an investigation of a basalt flow in the Datong region of China, which is sandwiched between the Lishi and Malan loesses, Chun et al. [1983] found evidence of reversed polarity directions. The baked zone immediately beneath the basalt yielded a thermoluminescence age for quartz of 160 ± 80 ka, and the authors correlated the reversed rocks with the Blake Subchron. A more recent evaluation of the age of the Lishi/Malan boundary suggests it is between 70 and 140 ka [Liu et al., 1985]. A recent study by Mankinen et al. [1986] on volcanic rocks of Long Valley caldera in California failed to find evidence for the Blake though numerous units with K-Ar ages between 95 and 115 ka were sampled. Mankinen et al. suggested that this may indicate that the Blake occurred prior to this time interval or that the polarity event is so short that it was not recorded by episodic volcanism.

We believe that the Blake Subchron may be older than previously thought because of age and paleomagnetic data that we have collected from the Laguna basalt flow in the Bandera Field of west central New Mexico (Tables 1 and 4). The direction of magnetization recorded by the flow represents a transitional direction of the geomagnetic field. Low natural remanent magnetization (NRM) intensity of the specimens is consistent with weak field strength associated with transitional fields. Whole rock K-Ar ages of 131 and 125 ka on a sample of basalt yielded an age estimate of 128 ± 33 ka for the flow. Although no independent stratigraphic evidence exists to confirm the age of the Laguna basalt flow, we suggest that it may be used as an indication of the age of the Blake Subchron. This age constitutes the first evidence from volcanic rocks for the age of the Blake Subchron.

Jamaica Subchron

A short-duration, full reversal of the magnetic field, identified as the Blake, has been located at several locations in loess and silt sections in Alaska and Yukon Territory [Westgate et al., 1985]. The Old Crow Tephra occurs about 3 m above the reversely magnetized strata. Thermoluminescence and fission track measurements suggested an age of 86 ± 6 ka for the Old Crow Tephra. The reversed strata have been correlated with the Blake Subchron. A more recent reevaluation of the fission track dating, accounting for partial track fading, suggests that the best weighted mean age for the Old Crow is 149 ± 13 ka [Westgate, 1988]. We therefore propose that the reversed strata below may well represent the Jamaica/Biwa I Subchron rather than the Blake Subchron.

In Japan, Hayashida [1984] produced evidence for the Jamaica/Biwa I Subchron from the paleomagnetic study of Pleistocene sediments that he could correlate with the Lake Biwa core using volcanic ash stratigraphy. The direct association of the reversed strata with a volcanic ash that has a fission track age of 0.17 Ma is strong supporting data. By his thorough stratigraphic documentation, Hayashida very effectively counters the low level of continuing criticism of the Biwa core work [Kukla and Zijderveld, 1977].

Radiometric ages that support the existence and age of the Jamaica/Biwa I Subchron may have been found in lava flows of the Albuquerque volcanic field of New Mexico [Brown et al., 1985, J. W. Geissman et al., Brunhes Chron geomagnetic excursion recorded during the latest Pleistocene, Albuquerque volcanoes, New Mexico, submitted to *NATO ASI Conference Proceedings*, 1988]. Sites in eight flows from the Albuquerque volcanoes have a direction of magnetization that has easterly declination and moderate negative inclination, after large, random, secondary components were removed. They named this event the Albuquerque Excursion and, using K-Ar age control from three superposed flow units, assign a preferred age of 70 ± 33 ka. However, only one of six argon extractions yielded more than 1% radiogenic ^{40}Ar . If the age of 0.17 ± 0.05 Ma calculated from this extraction is combined with a whole rock K-Ar age of 0.19 ± 0.04 reported by Bachman et al. [1975], also from a 1% radiogenic ^{40}Ar extraction,

the resulting mean age is 182 ± 31 ka. We consider this the best estimate of the age of the excursion direction in these lavas, and we propose that it is on the transition path either to or from the fully reversed directions of the Jamaica Subchron.

Levantine Subchron

As stated above, Ryan [1972] published evidence for and named the Levantine event as a short reversed polarity interval in the Brunhes. His estimated age for the event was 300 ka, in close agreement with the 310 ka age of the Biwa II event [Kawai, 1984]. A short stratigraphic interval of sediment having fully reversed polarity was reported from two localities separated by 50 km in the Mono Lake basin of California [Liddicoat et al., 1980]. A tephra layer within this reversed interval, originally thought to correlate to 50–150 ka rhyodacites of the Long Valley caldera, has instead been recently shown to have widespread correlatives, a source in central Oregon and a rather older age, one more in line with its stratigraphic position above the Bishop Tuff (A. Sarna, personal communication, 1988). Correlation of glacial detritus from the Sierra Nevada with the oxygen isotope time scale suggests that the sediments in and around the reversed strata in the Mono Lake basin are approximately 290 ka (K. Lajoie, personal communication, 1988). In the sediments of two adjacent Pleistocene lake basins, Tululake (H. Rieck, personal communication, 1988) and Summer Lake [Negrini et al., 1988], evidence has also been found for a short reversed polarity event at about 300 ka. In a compilation of paleomagnetic data from the Pleistocene deposits of the Ponto-Caspian region of eastern Europe, Kochegura and Zubakov [1978] reported that numerous workers found anomalous or reversed directions in strata to which ages of 270–280 ka were assigned; they named this the Chegan event. Bucha [1983] presented eastern European data, tied to the oxygen isotope age scale, for deposits of the Saale-Dnieper glaciation which were assigned an age of 275 ka. In a discussion of the processes of magnetization of deep-sea sediments, Watkins, [1968] presented evidence of a short reversed polarity interval in core *Eltanin* 11-8; the age of this interval calculated relative to the Brunhes-Matuyama boundary is 298 ka. And last, our recalculation of the age of the α event of Creer et al. [1980] is 260 ka. If Rampino [1981] is correct in his inference that the double Blake events of Creer et al. [1980] is in fact the Blake and Jamaica events juxtaposed by irregular sedimentation rates, then his estimates for the age of the Jamaica event is 295 ka.

Biwa III Subchron

Although it was not highlighted in the original description of the Biwa core paleomagnetism [Kawai, 1972], a short interval of fully reversed inclinations below the other reversed events has come to be known as Biwa III. In his latest discussion of the core results, Kawai [1984] has estimated an age of 380 ka for this subchron. Bucha [1983] stated that reversed polarity directions from deposits of the late Okan glaciation are correlative with the Biwa III Subchron. In particular, reversed directions in sediments of the Likhvin alluvium produced thermoluminescence ages of about 375 ka [Velichko, 1975; Nikisorova and Krasnov, 1976]. In a study of the Plio-Pleistocene deposits of the Osaka Group, Torii et al. [1974] produced variable polarities including fully reversed directions from the Kasuri ash after cleaning. Fission track ages on apatite in the ash are 370 ± 40 ka and 380 ± 30 ka [Nishi-

mura and Sasajima, 1970]. Creer et al. [1980] suggest from the Gioia Tauro core that an event they call β has an age of 400 ka. Last, Negrini et al. [1988] note an interval of declination disturbance in their Summer Lake section, in a stratigraphic interval just above an ash correlated with an ash dated at 0.36–0.37 Ma. We propose this also may be a manifestation of the Biwa III Subchron.

Emperor Subchron

During our study of the Idaho cores in which the reversed directions were assigned to a newly named subchron we re-evaluated the data supporting and defining the Emperor event of Ryan [1972]. At first, we viewed the event as having such a poor definition as to make it unuseable, but subsequent publications have supported its designation. The event was defined by Ryan [1972] as a short zone of fully reversed inclinations near the base of core V12-122. Proximity of the U-V boundary of Ericson et al. [1961] and Termination VI of Broecker and van Donk [1970] in the strata within 2 m of the reversed zone dictates the age of the zone to be about 460 ka and certainly less than 480 ka, unless there is an undetected unconformity in the core [Imbrie et al., 1973]. Kochegura and Zubakov [1978], in their Ponto-Caspian summary, suggested a reversed polarity event that they call Ureki starting at 550 ka and having a duration of 100 kyr. Bucha [1983] correlated reversed polarity sediments associated with Elster II and late Okan (Dainav) glacial deposits. The current best estimate of the oxygen isotope interval corresponding to this glaciation is stage 12, an interval in the mid-400 ka time range [Imbrie et al., 1984]. Wilson and Hey [1981] analyzed the axial magnetic anomaly over the Galapagos spreading center and concluded that the anomaly contained a brief field reversal having an age of 490 ± 50 ka and a duration of about 10 kyr. Age assignment and error estimates are predicated on an assumption of linear spreading rates at the fast spreading Galapagos Ridge. As in the case of age assignments from sedimentation rates, nonlinearity could bias their determination.

Delta Subchron

In the earliest part of the normal polarity section (Brunhes) of their Gioia Tauro core, Creer et al. [1980] found evidence of excursion directions for a magnetic event they called δ (delta). Their estimated age for this excursion was 620 ka, a number that Rampino [1981] did not revise. Watkins [1968] found evidence for a short reversed interval in *Eltanin* core 17-11 that can be assigned an age of 627 ka assuming constant sedimentation rates. Liu et al. [1988] found evidence of a short completely reversed section in the sixth soil down in the Lishi Loess Series in the Xifeng area of China. The estimated age of this soil using stratigraphic and magnetic polarity controls is 630–640 ka [Liu et al., 1985]. At present, we feel that this is the best age estimate for the "Delta" Subchron.

Kamikatsura Subchron

Evidence for short opposite polarity events are not limited to the Brunhes Chron; recent publications have presented data for events in the late Matuyama Chron as well. Maenaka [1983] documents a brief interval of shallow normal polarity younger than the Jaramillo Subchron. The event is recorded in sediments of the Osaka Group centered around the Kamikatsura ash. Although an age was not measured directly for this ash, Maenaka [1983] did associate the event with an age

of 0.85 ± 0.03 Ma obtained from basalt by Hirooka and Kawai [1967] from another area of SW Japan. Mankinen et al. [1981] also report an age of 0.84 ± 0.03 Ma on sanidine from a dacite from the Clear Lake area of California, for which they found normal polarity. Watkins [1968] suggested the existence of a normal polarity event of short duration that he called "B" in the late Matuyama. After correction for revision of the polarity time scale boundaries his best estimate for the age of this normal event was 850 ka. Eardley et al. [1973] in their Burmester core work also discovered a short normal interval above the Jaramillo that corresponds to an age of 860 ka assuming constant sedimentation rate between the top of the Jaramillo and the Brunhes/Matuyama boundary. Wang et al. [1980] have found short normal polarity intervals in numerous sections of loess that correspond to an age of 850 ka. Although evidence of a short normal polarity interval was found in the Louchan area of China in loessal sediments of the late Matuyama Chron, Heller and Liu [1984] interpreted them to be incompletely removed Brunhes age overprints. But, as the brief normal polarity record occurs in a drill core and an adjacent natural exposure at the same stratigraphic level, we interpret them to be replicate samples of a short-duration geomagnetic event. The event occurs in the middle of loess 9 of the Lishi loess series, which has an estimated age range of 770–870 ka [Liu et al., 1985]. Taking the above data into account, we estimate the best age for the Kamikatsura Subchron to be 850 ka.

Cobb Mountain Subchron

The underlying data defining and supporting the pre-Jaramillo normal polarity event called the Cobb Mountain Subchron has been described by Mankinen et al. [1978] and Mankinen and Gromme [1982]. They considered the best estimate of the age of this completely normal polarity event to be 1.10 Ma on the basis of numerous K-Ar ages of lavas from different global locations. Watkins [1968] also found evidence of this short-duration normal event, which he named the "A" event, in four Eltanin oceanic sediment cores. After correction for revision of the polarity time scale boundaries, his proposed age is also 1.10 Ma. The age of the Cobb Mountain Subchron is better documented than the ages of several younger magnetic subchrons.

Summary

A review of the status of short polarity events within the Brunhes and late Matuyama Chrons indicates that the data base documenting them is quite extensive, and the data suggest that there may be more subchrons than were generally believed. Our tally shows eight subchrons in the Brunhes and two, besides the Jaramillo, in the late Matuyama. Although the records are variable in quality and presumably fidelity, the best records from lavas, ash layers, or sediment sections that had fast sediment accumulation rates show all these events to be directionally fully opposite in polarity to the chron that they are within.

The reader will have to decide for himself whether our process of identification and correlation of events is or is not influenced by the "reinforcement syndrome" of Watkins [1972]. We believe that the directional effects referenced here can be documented independently, and then their similar or identical time frames can be used to legitimately correlate

geomagnetic phenomena into a relatively small number of subchrons. Some readers may disagree and feel we have been unduly influenced into a circularity of identification [Verosub, 1975]. The evidence for the existence and age of some polarity subchrons is stronger than for other subchrons. The typefaces in Figure 6 are intended to convey a three-level ranking of our estimates. The Emperor and Delta subchrons would both benefit from additional occurrences, either in a dateable volcanic unit or in a high-deposition rate sedimentary section. The age estimates for these two events may require 10,000–20,000 years of adjustment when such new data are available.

Allan Cox in a paper on polarity interval lengths presented the idea that given the frequency distribution of polarity interval lengths he could establish, there must be many undiscovered short polarity events [Cox, 1968]. As such the process of polarity reversal would be Poisson in character. Though many authors have modeled reversal as the more general gamma process, in part as a means of explaining the lack of short events, a recent analysis by McFadden and Merrill [1984, p. 3361] still states as a conclusion, "there is reasonable evidence that reversals are an essentially Poisson process." If all polarity epochs are as equivalently populated with short subchrons as the Brunhes seems to be, perhaps Allan was correct.

Data on whether the strength of the magnetic field during these short events is low or not are variable and incomplete. The intensities of remanence in the two reversely magnetized basalt flows studied in this paper are one third to one half that which one might expect from mineralogically similar basalt flows, suggesting that the paleointensities might be low. However, until proper Thellier analyses are performed, this is only speculation. Failure of the "event" to achieve normal field intensity levels would be a convenient mechanism to explain why these polarity events do not become transitions producing polarity change. Certainly for some of these events, such as the Laschamps, there already exists clear evidence that low field intensity is a characteristic attribute [Roperch et al., 1988]. Paleointensity levels in sediments will be difficult to interpret because of uncertainty as to the exact mechanism of their magnetization. In particular, reversed polarity events in the Brunhes will have a variable normal polarity virtual remanent magnetization (VRM) overprint, dependent on the sedimentary carrier, that will diminish the remanent intensity. Demagnetization characteristics of brief reversals in sediments might be used to establish low paleointensities.

It is interesting also to note that although these short subchrons could have produced only excursion records without developing the full opposite polarity, the best records of these subchrons show that they are fully reversed. So where are all the excursion records? If one imagines a simple continuum of more and more dynamic directional phenomena, then typical secular variation would be the norm, followed by exceptional secular variation, excursions, short incomplete reversals, and full polarity transitions in a decreasing order of frequency. The time range for a completed cycle of secular variation compared to that of the length of a polarity interval is approximately 3 orders of magnitude (300–500 versus 200,000–1,000,000 years). Some of the subchrons that we have summarized perhaps "should" have only been excursions, if this concept of a continuum has any validity. Our current guess would be that excursions events, such as the one well documented at Mono Lake [Denham and Cox, 1971; Liddicoat and Coe, 1979], may represent less frequent phenomena

than the short polarity subchrons that we have documented in this paper.

Last, the appearance of Figure 6 merits a brief discussion. If one views the polarity effects on the figure, whether they be brief, incomplete intervals of opposite polarity or full polarity transitions, as timing marks of some kind, they denote regular intervals. Even granting the uncertainty existing in some of the ages, this regularity is not strictly periodic in character, although it could represent a periodic function masked by another stochastic process. A simple mean of the polarity interval lengths shown in Figure 6 is 90,000 years. This number is temptingly close to the 100,000 year main orbital eccentricity period of the Earth, a signal which produces 50% of the climatic variation ascribed to the Milankovitch cyclicity. Geomagnetic parameters of direction and intensity variation may also tie to these possible periods. This concept does not originate with us and instead has been discussed repeatedly in the past [Wollin et al., 1977; Rampino, 1979]. What has been lacking previously was a documented record of the geomagnetic polarity variation history in the recent past. Perhaps the improved status of these polarity subchrons in the Brunhes and late Matuyama will renew and improve the focus of this continuing discussion.

CONCLUSIONS

The new data from the Snake River Plain of Idaho provide evidence for the age of a well-defined brief interval of reversed polarity in the early part of the Brunhes Normal Polarity Chronozone and Chron. This polarity reversal was thought to be the Emperor event by Champion et al. [1981] and assigned an age of 465 ± 50 ka. However, our new data indicate that the age of the reversed lavas is 565 ± 14 ka. The name Emperor should not be applied here because as discussed above the best estimate for the age of the Emperor Subchron in core V12-122 is about 460 ka. We propose that the polarity reversal recorded in lava flows at INEL be named the Big Lost Reversed Polarity Subchronozone and Subchron.

A review of the status and character of short polarity events within the late Matuyama and Brunhes chronos suggests that there is abundant evidence of variable quality indicating 10 short-duration subchrons besides the Jaramillo. These subchrons are not excursions and produce directions of magnetization essentially opposite to those of the chron that they are within. This may indicate that well-documented excursions such as the Mono are more infrequent than short polarity events. These subchrons occur in a regular, but aperiodic pattern, but if one adds in the known polarity boundaries, they have a mean occurrence frequency of 90,000 years. If one views these subchrons as "failed" reversals and groups them with successful polarity transitions, they can be viewed as timing marks driven by an underlying common source. Linkage of this geomagnetic variation with climatic variation, perhaps driven both by basic orbital parameters, continues to need to be evaluated.

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the status section of the paper that makes it much more readable. Discussions with and encouragement from Ken Hoffman rebuilt the manuscript at a critical stage. Last, conversations and ideas from Gene Shoemaker helped the more speculative final section of the paper.

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