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Repeating waveform initiated by a 180-190 ka geomagnetic excursion in western North America: Implications for field behavior during polarity transitions and subsequent secular variation

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Abstract. New paleomagnetic, lithologic, and stratigraphic data are presented from the sediments of Lake Chewaucan in the Summer Lake Basin, Oregon. The new data place better age constraints on the sediments and improve the accuracy of the previously published paleomagnetic record from this locality. A complex, yet distinct, waveform is observed in all three components of the paleomagnetic vector. The waveform begins as the 180-190 ka Pringle Falls/Long Valley/Summer Lake II geomagnetic excursion and continues for two cycles after the excursion, until the record is interrupted by an unconformity that we correlate to the oxygen isotope stage 6/5e boundary. The waveform's directional morphology in virtual geomagnetic pole (VGP) space is defined by two clockwise loops followed by a distinctive counterclockwise, clockwise, counterclockwise looping sequence. The VGP paths of the two cycles after the excursion are rotated 180° about Earth's spin axis with respect to the VGP paths of the excursion cycle. The waveform also consists of a relative paleointensity variation which repeats during the two cycles after the excursion. The average paleointensity of the postexcursion waveform repetitions is high relative to the extremely low values that occur during the excursion. This observation indicates that excursion-initiated secular variations can occur after the field fully recovers from the low intensities which commonly typify excursions. Because of the similarities noted previously between this excursion and full polarity transitions (Tric et al., 1991), our new observations constrain models for a wide range of field behavior including polarity transitions, excursions, and secular variation.

Introduction

The occurrence of several geomagnetic excursions during the Brunhes Chron have been proposed in the last 20 years [e.g., *Champion et al.*, 1988]. Refinements in the records from original sample locations and replication of the records from distant locations have led to the confirmation of a few of these events as true geomagnetic field behavior. This has led to a better understanding of geomagnetic field behavior which, in turn, justifies the use of excursions and subsequent secular variations as correlation tools for problems in Pleistocene stratigraphy [*Lund et al.*, 1988; *Levi and Karlin*, 1989; *Tric et al.*, 1991; *Negrini and Davis*, 1992].

In two studies where a postexcursion secular variation record was acquired in addition to the excursion record, repeating cycles of a distinct excursion waveform were observed in declination and inclination time series [*Lund et al.*, 1988; *Levi and Karlin*, 1989]. *Lund et al.* [1988] observed five repetitions of a waveform after and including the 28-30 ka Mono Lake Excursion in a sedimentary record from a series of localities near Mono Lake, California. The waveform was defined by both declination and inclination variations through time, with constant relative phase. Notably, the repeating cycles were observed only after the excursion in the record of *Lund et al.* [1988]. Indeed, the secular variation before the excursion had been previously shown to be much lower in amplitude [*Liddicoat and Coe*, 1979].

Levi and Karlin [1989] also observed several repetitions of a waveform in the upper part of their inclination record from sediments recovered in Deep Sea Drilling Project site 480 in the Gulf of California. The general morphology of the repeating inclination waveform in the DSDP 480 record was found to resemble the inclination part of the repeating waveform recorded in the Mono Lake sediments [*Levi and Karlin*, 1989]. In addition to the repetitions that occurred after the Mono Lake Excursion, *Levi and Karlin* [1989] observed similar features back to 54 ka including an exceptionally high-amplitude event that they correlated with the Laschamp event at 50 ka. They also noted that the time interval including the

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entire set of repeating waveforms more or less corresponded to a period of diminished dipole moment [*Salis*, 1987; *McElhinny and Senanayake*, 1982; *Barbetti and Flude*, 1979]. This series of observations led them to conclude that the entire period from about 50 to 20 ka was a period of general geomagnetic field instability characterized by large-amplitude, pulse like inclination features.

These two studies raise important questions regarding the relationship between geomagnetic secular variation and excursions. For example, is the Mono Lake Excursion a solitary, high-amplitude event which initiated a distinct series of waveform repetitions, or are the Mono Lake Excursion and subsequent repetitions of its waveform simply some of the many instabilities noticeable only through a long-duration "window" in the intensity of the dipole field? Indeed, are repetitions of a waveform always associated in one way or another to excursions or can they occur independently of excursions? Clearly, paleomagnetic records of other excursions including preexcursion and postexcursion secular variation are needed to answer these questions.

In this paper we refine a preliminary paleomagnetic study in which repetitions of waveforms were reported to be associated with an excursion of middle to late Pleistocene age. In the original study, *Negrini et al.* [1988] observed waveform repetitions both before and after an unconfirmed excursion of middle to late Pleistocene age in a sedimentary record from the Ana River Canyon near Summer Lake, Oregon. The excursion has since been confirmed with records from two other localities in the western United States [*Herrero-Bervera et al*, this issue]. However, the repeating nature of the secular variations and their temporal relationship to this excursion as put forth by *Negrini et al.* [1988] remain in question because of the preliminary nature of that study. Here, we conduct a more rigorous analysis of the repeating waveforms using a refined data set from the Summer Lake locality based on recent developments in the stratigraphy, rock magnetism, and relative paleointensity of the original section and on two new directional records from the Ana River Canyon.

Stratigraphy

The Ana River section comprises a sequence of lacustrine sediments exposed in a canyon near the town of Summer Lake, Oregon (Figure 1). An initial stratigraphic framework for these sediments of pluvial Lake Chewaucan was based on lithology, tephrochronology, and radiocarbon dating [*Allison*, 1945, 1983; *Davis*, 1985; *Negrini et al.*, 1988]. *Allison* [1945] named the tephra layers and the interlying clays and silts from the top few meters of section using a numerical scheme starting with the smallest number at the bottom. Even numbers correspond to light colored layers (generally tephra layers) and odd numbers correspond to the interlying clays and silts. *Davis* [1985] incorporated *Allison's* [1945] original tephra names and added names of new tephra layers based on an alphabetical scheme starting at the top of the section and working down. In this paper we use the terminology of *Davis* [1985] unless otherwise noted.

The original chronostratigraphy has since been improved by recently published thermoluminescence dating of ash layers [*Berger*, 1991], correlation of paleomagnetic secular variation (PSV) features with a relatively well-dated PSV reference record [*Negrini and Davis*, 1992], improvements in the regional tephra stratigraphy of western North America [*Sarna-Wojcicki et al.*, 1991], and new data presented here.

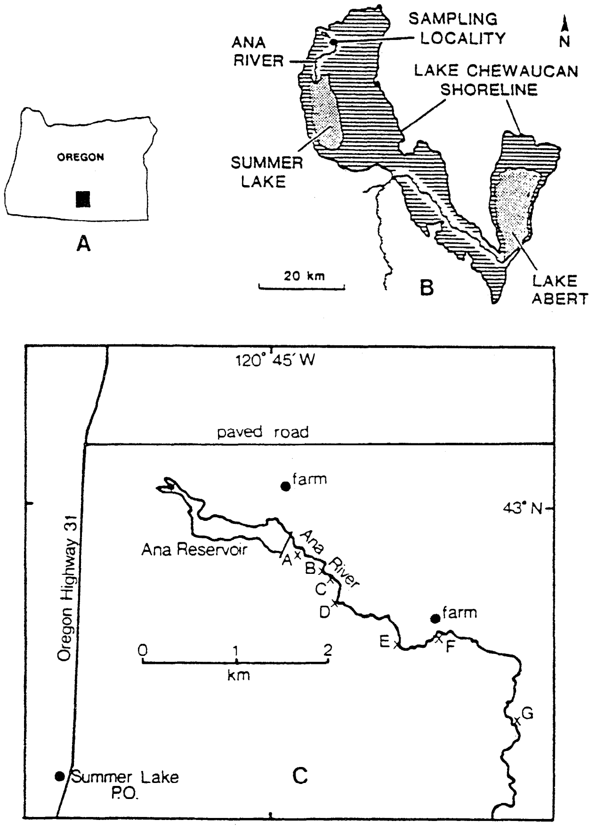

Figure 1. (a) Map showing location of Lake Chewaucan Basin, Oregon. (b) Map of Lake Chewaucan Basin. Horizontal rules indicate extent of Pleistocene pluvial highstand. Stippled pattern indicates location of modern remnant lakes. Location of Ana River Canyon sampling locality is also indicated at north end of western arm. (c) Detailed map of sampling localities. Locations of sampled sections discussed in the text are indicated with crosses.

The new chronostratigraphy is summarized in Table 1 and Figure 2. The shaded deposition rate curve in Figure 2 represents a best estimate constrained primarily by the age control from Table 1 but also by presumed changes in overall sedimentation rate at the basin margin caused by alternating pluvial (continuous and high rate of sedimentation) and interpluvial (discontinuous and low rate of sedimentation) conditions. The ages assumed for the boundaries between pluvial and non-pluvial conditions are those of the boundaries between glacial and interglacial periods from *Martinson et al.* [1987] and *Winograd et al.* [1988]. A brief discussion of the age control in Table 1 is given below and is arranged by dating method.

Thermoluminescence

Seven of the tephra layers present in the Ana River sequence have been dated directly with the thermoluminescence method [*Berger*, 1991] as indicated by the solid circles and corresponding error bars in Figure 2. Notably, the thermoluminescence dates of tephra layer R (165 ± 19 ka) and tephra layer N (102 ± 11 ka) are significantly different even

Table 1. Summary of Age Control for Ana River Outcrop

Dated Interval or Horizon	Depth Relative to Tephra 12, cm	Age, ka	Dating Method	Reference
Mono Lake Excursion to top of section	16-261 above	28.9-16.7	paleomagnetic correlation	*Negrini and Davis* [1992]
Tephra D (Mt St Helens Mp)	147 above	18.1-20.8	radiocarbon	*Davis* [1985]
Trego Hot Springs Tephra	113 above	23.5 ± 2.5	thermoluminescence	*Berger* [1991]
Tephra 12 (Mt St Helens Cy)	0	35-50	radiocarbon	various dates summarized by *Sarna-Wojcicki et al.* [1991], *Crandell* [1987], and *Davis*[1985]
Tephra 12 (Mt St Helens Cy)	0	47.0 ± 2.0	thermoluminescence	*Berger* [1991]
Tephra 6 (Pumice Castle)	105 below	72 ± 6	K-Ar	*Davis* [1985] and *Bacon* [1983]
Tephra 2	141 below	63.7 ± 7.2	thermoluminescence	*Berger* [1991]
Tephra N	421 below	102.3 ± 11	thermoluminescence	*Berger* [1991]
Tephra R	489 below	165 ± 19	thermoluminescence	*Berger* [1991]
Tephra V	677 below	140 ± 25	tephrochronology and K-Ar	*Sarna-Wojcicki et al* . [1991]
Tephra GG	913 below	187 ± 11	Ar-Ar	*Herrero-Bervera et al.* [1994]
Tephra KK	1118 below	160 ± 25	tephrochronology and K-Ar	*Sarna-Wojcicki et al.* [1991]
Tephra KK	1118 below	179 ± 16	thermoluminescence	*Berger* [1991]
Tephra LL	1162 below	160 ± 35	thermoluminescence	*Berger* [1991]

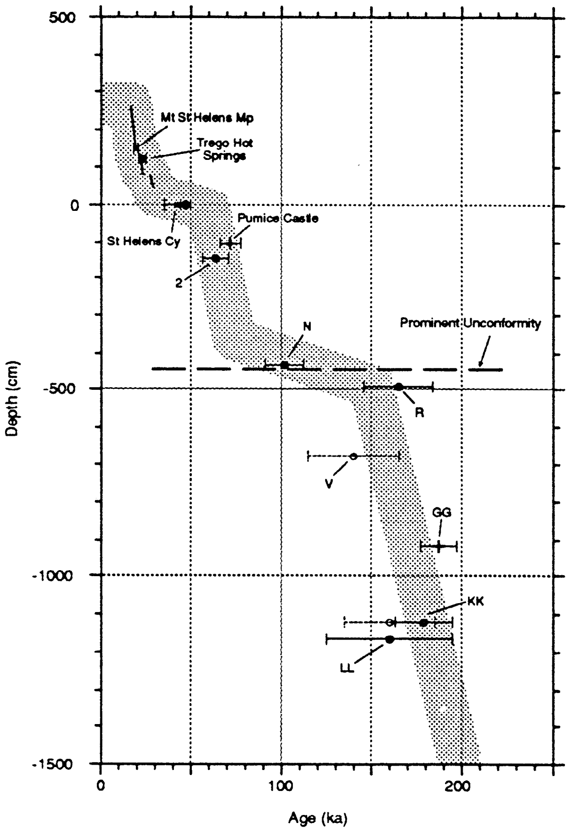

Figure 2. Depth versus age for Lake Chewaucan sedimentary sequence. Solid circles represent thermoluminescence dates. Crosses represent radiometric dates. Solid line represents age control from correlation of paleomagnetic secular variation. Open circles represent age constraints tied into section by tephrochronology. Heavy dashed line represents major unconformity correlated to the marine oxygen isotope stage 6/5e transition. Shaded curve represents estimate for chronology of Lake Chewaucan sediments.

though they are very close together in the section. This result is consistent with the following observations suggesting a major zone of unconformities between these two tephras in a depth range from 425 to 381 cm. First, this zone is marked by ostracod lag deposits which suggest winnowing of finer grains as the paleolake shore dropped below the elevation of the deposit. The most prominent of these lag deposits is found at the base of this zone. Second, shallow water conditions are implied by the presence of carbonate-coated ostracods in this zone (A. Cohen of the University of Arizona, written communication, 1993). Moreover, a prominent tephra layer (N1) is absent in exposures farthest away from the depocenter of the basin [*Davis*, 1985]. Because this zone of unconformities is the only one in the entire sedimentary section exposed in the Ana River Canyon and because of the age of the bounding tephra layers, we correlate this zone with marine oxygen isotope stage 5e which begins at approximately 130-145 ka [*Martinson et al.*, 1987; *Winograd et al.*, 1988].

Radiometric Methods

Many of the tephra layers in the Ana River sequence have been correlated to layers present at other sites in the western United States. Several of these tephra layers (correlatives of beds D, F, 12, 8, 6, 4, and GG) have been dated directly by the radiocarbon, potassium-argon, or ^{40}Ar/^{39}Ar methods [e.g., *Davis*, 1985; *Sarna-Wojcicki et al.*, 1991]. The ages of other tephra layers are bracketed by dated underlying and overlying chronostratigraphic datums, and their ages are estimated by interpolation between dated levels (e.g., V and KK; Figure 2). These data are beginning to provide a spatial and temporal framework by which individual ages can be evaluated.

Tephra layers in the lower part of the Ana River section, from bed KK up to bed V, correlate well with tephra layers present at other sites in the western United States (Table 2 and Figure 3), including a well-exposed stratigraphic section along the Deschutes River at Pringle Falls, Oregon (A. Sarna-Wojcicki, unpublished data, 1993) and cored sections at Tulelake, California [*Rieck et al.*, 1992], and Walker Lake,

Table 2. Electron Microprobe Analysis of the "Orange Ash Bed Set" and Related Ash Beds

Ash Bed Name	SiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	CaO	TiO_2	Na_2O	K_2O
Summer Lake V (DR-25)	72.84	14.23	2.68	0.17	0.06	1.07	0.23	5.21	3.51
Tulelake 1193	73.34	14.22	2.61	0.15	0.07	1.11	0.22	4.82	3.47
Summer Lake DD (DR-37)	69.40	15.55	3.41	0.62	0.11	1.89	0.60	6.12	2.31
Pringle Falls 88-K	69.76	15.33	3.64	0.58	0.10	1.91	0.51	5.81	2.35
Summer Lake EE (DR-38)	70.37	15.46	3.05	0.46	0.09	1.54	0.50	6.12	2.41
Pringle Falls 88-H	70.53	15.04	3.28	0.49	0.10	1.68	0.51	5.95	2.41
Summer Lake GG (DR-40)	69.30	15.37	3.68	0.55	0.11	1.86	0.59	6.13	2.41
Pringle Falls 88-D	69.96	15.61	3.62	0.50	0.10	1.80	0.47	5.49	2.45
Summer Lake II (DR-35)	71.68	14.64	3.02	0.28	0.08	1.22	0.35	5.92	2.81
Pringle Falls 88-S	72.16	14.66	3.12	0.26	0.09	1.25	0.33	5.40	2.83
Summer Lake JJ (DR-30B) (brown, basaltic shards)	57.52	16.29	9.22	3.04	0.15	6.15	1.59	4.53	1.51
Shevlin Park Andesite (SPAT-1)	58.95	14.87	9.22	3.15	0.18	6.31	1.60	4.17	1.55
Summer Lake JJ (DR-30W) (clear, silicic shards)	73.27	14.45	2.27	0.16	0.05	0.96	0.20	5.62	3.01
Walker Lake (WL5-42-1a)	73.46	14.29	2.30	0.17	0.06	0.98	0.17	5.53	3.04
Summer Lake KK (DR-33)	62.79	16.28	6.19	1.98	0.11	4.73	0.98	4.82	2.11
Tulelake (T-1228; 53.13 m)	62.57	16.40	6.16	2.35	0.14	4.94	0.97	4.40	2.08
Tulelake (T-2023S.29MTB;1)	63.60	16.31	5.88	1.99	0.09	4.44	0.96	4.55	2.17
Tulelake (T-2023; 53.07 m)	63.50	16.03	5.67	2.02	0.10	4.61	0.98	4.70	2.09
Tulelake (T-2019a; 53.12 m)	64.33	16.17	5.48	1.76	0.09	4.26	0.95	4.55	2.40
Tulelake (T-2019b; 53.12 m)	64.43	16.15	5.43	1.76	0.10	4.24	0.94	4.57	2.39
Medicine L. Andes. Tuff (194Ma)	64.56	16.09	5.37	1.60	0.08	4.08	0.89	4.88	2.45
Walker Lake (WL4-57)	64.20	15.88	5.51	1.77	0.10	4.54	0.86	4.96	2.18
Tulelake (T-2019c; 53.12 m)	66.35	15.82	4.67	1.38	0.08	3.59	0.84	4.61	2.65
Medicine L. Andes. Tuff (194Mb)	66.46	15.39	4.68	1.31	0.07	3.54	0.86	4.94	2.74
Medicine L. Andes. Tuff (194Mc)	67.03	15.34	4.42	1.20	0.06	3.36	0.84	4.84	2.92
Wadsworth ash bed (WADS-1)	67.60	15.37	4.34	1.28	0.07	3.60	0.83	4.54	2.37
Wadsworth ash bed (HC-7)	66.14	16.59	4.37	1.29	0.06	3.74	0.87	4.52	2.41
Wadsworth ash bed (LD-65)	67.14	15.75	4.45	1.29	0.07	3.68	0.93	4.36	2.43

These tephra layers are underlined and arranged in stratigraphic order. Tephra layers from other sites in the western United States that are considered to be correlative with the layers at Summer Lake are shown beneath each of the Summer Lake layers in the table. These other sites are Pringle Falls, Oregon; Tulelake, Medicine Lake, California; Walker Lake and Wadsworth , Nevada. Replicate analyses of correlatives of tephra layer KK (Summer Lake) are given. This layer is bimodal, and both modes are rather heterogeneous. Values given are in oxide weight percent. Data for Summer Lake beds are from *Davis* [1985]. Data for the remaining samples are by C. E. Meyer, analyst, U.S. Geological Survey.

Nevada [*Sarna-Wojcicki et al.*, 1988]. This set of tephra layers provides excellent chronostratigraphic control in proximity to the geomagnetic excursion reported here. Tephra layer KK, a heterogeneous, polymodal dacitic tuff, is correlated to an ash in the Tulelake core (T-1228, T-2019, T-2023; Figure 3), where its age is estimated to be 160 ± 25 ka [*Rieck et al.*, 1992; *Sarna-Wojcicki et al.*, 1991]. This age is consistent with a thermoluminescence date on layer KK of 179 ± 16 ka determined by *Berger* [1991]. A somewhat more silicic, less iron-rich mode of this ash bed correlates well with the Wadsworth Bed, present in the Eetza Formation south of Pyramid Lake, Nevada (Table 2). Tephra layer GG at the Ana River section correlates well with tephra layer D at Pringle Falls. This correlation is further supported by correlation of the underlying and overlying tephra layers at these two localities (bed II with S, EE with H, and DD with K; Figure 3). Layer D had been dated recently by the $^{40}Ar/^{39}Ar$ method on plagioclase phenocrysts obtained from pumices, yielding an age of about 187 ± 11 ka [*Herrero-Bervera et al*, this issue]. Layer V is correlated to a layer at Tulelake (T1193) which has an estimated age of ~140 ± 25 ka [*Rieck et al.*, 1992].

Correlation of Paleosecular Variation Features

The age of the top 2 m of section exposed in the Ana River Canyon has been determined to within several hundred years by correlating the paleosecular variation (PSV) features recorded in this sequence with the PSV record from the relatively well-dated Wilson Creek section from the Mono Lake basin [*Lund et al.*, 1988; *Negrini and Davis*, 1992]. This part of the chronostratigraphy is indicated in Figure 2 by the solid lines. The ages inferred by this method agree well with ages determined independently using radiocarbon and thermoluminescence methods and they are also consistent with minor unconformities implied by lithostratigraphic features in the uppermost part of the section [*Negrini and Davis*, 1992].

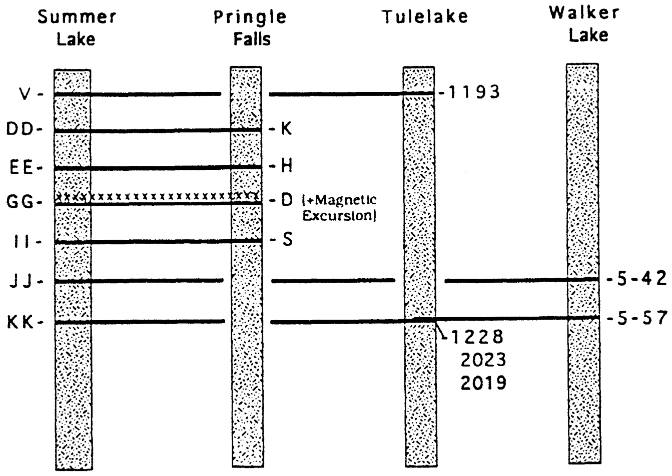

Figure 3. Correlation of tephra layers from the lower part of the Summer Lake sequence with tephra from other localities in the western United States.

Paleomagnetism

Previous paleomagnetic studies from the Ana River locality demonstrated the existence of strong and stable magnetizations throughout most of the section [*Negrini et al.*, 1984, 1988; *Negrini and Davis*, 1992]. Two geomagnetic excursions were reported in these studies. The younger excursion (Summer Lake I) and the secular variation above it have been extensively studied [*Negrini et al.*, 1984; *Negrini and Davis*, 1992] and have been correlated to the Mono Lake Excursion and subsequent repetitions of its waveform [*Lund et al.*, 1988; *Liddicoat and Coe*, 1979].

Here we present two additional paleomagnetic records from the older part of the section at the Ana River Canyon. The two new records combined with a recent study of the rock magnetism and relative paleointensity of the sequence [*Roberts et al.*, 1994] confirm the reliability of the original record and enable us to study the relationship between the older excursion recorded here (the Summer Lake II Excursion) and the preceding and subsequent secular variation.

Sampling

The original paleomagnetic record from the Summer Lake locality [*Negrini et al.*, 1988] was based primarily on a study of the outcrop at section C along the banks of the Ana River Canyon (Figure 1). Only one sample (2 cm x 2 cm x 1.5 cm) was taken for each 2.5 cm of section down the entire 15-m section.

We revisited the Summer Lake locality to improve the quality of the paleomagnetic record from the sediments containing the older excursion, upward to the younger excursion. In the new study we took a minimum of three samples per horizon from (1) a sampling column within a few meters of the original sampling column at section C; and (2) a second outcrop located at section D, 200 m downriver from the original outcrop (Figure 1).

Rock Magnetism

We subjected a sequence of pilot samples to a progressive, step-wise alternating field demagnetization (AFD) at levels of 0, 5, 10, 15, 20, 30, 40, 50, and 60 mT. As expected, the results for nonexcursion samples were identical to those reported in the initial study [*Negrini et al.*, 1988] which demonstrated a stable remanence after the removal of a viscous remanence at an AFD level of 10-25 mT (Figure 4a). Samples from the small interval containing the Summer Lake II excursion interval exhibited a strong overprint (Figure 4b). The presence of this overprint leads to our exclusion of the excursion samples from our analysis as explained at the end of this section of the paper. Every remaining sample was then subjected to demagnetization levels of 0, 15, and 25 mT. The typical angular change of the remanence direction between the last two AFD levels was <3° which supports the results of this pilot study and those results of the original study. After demagnetization to 25 mT a mean direction was calculated for every horizon. The associated α_{95} value for the typical horizon is 5-6°.

The median destructive field (MDF) for all of the samples ranges from 10 to 25 mT. A variety of rock magnetic experiments reported by *Roberts et al.* [1994], including saturation isothermal remanent magnetization (SIRM) acquisition and thermal demagnetization experiments, indicate a mineralogy dominated by magnetite. Measurements of susceptibility to anhysteretic remanent magnetization (ARM) acquisition (χ_{ARM}), susceptibility (κ), and various hysteresis parameters indicate that the magnetic grain size for all of the samples fall within the PSD range of 1-15 μm for magnetite grains. Furthermore, variations in χ_{ARM}/κ and saturation remanence indicate that the maximum magnetite concentration is only 12 times that of the minimum concentration and that the concentration variation for the majority of the samples is within a factor of six. All of the above results imply that the magnetic mineralogy and grain size of the Lake Chewaucan sediments are conducive for the acquisition of accurate paleomagnetic directions, an implication supported empirically by the results of *Negrini et al.* [1988] on the basis of intrabasinal and extrabasinal reproducibility of the original paleomagnetic record. Also, the characteristics of the remanence-bearing grains meet the criteria proposed by *King et al.* [1983] and *Tauxe* [1993] as neccessary for the determination of relative paleointensity from these sediments [*Roberts et al.*, 1994].

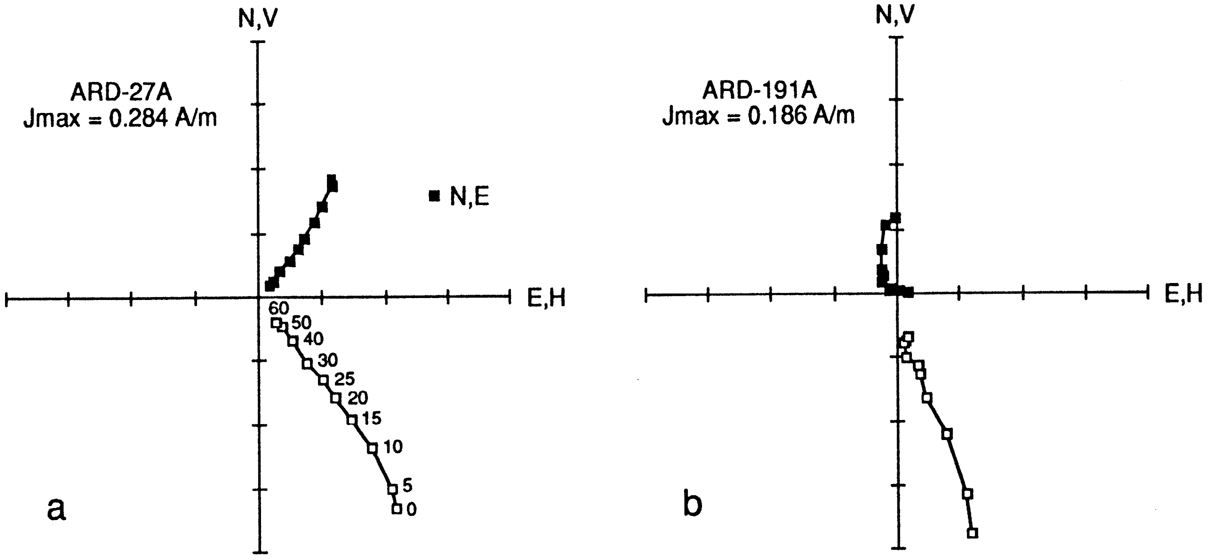

Figure 4. Vector component plots showing demagnetization behavior of representative samples from (a) outside and (b) inside the excursion intervals. Maximum values of axes are normalized to the maximum magnetization value for each sample. The solid squares correspond to north and east components. The open squares correspond to horizontal and vertical components. Demagnetization levels, shown for the horizontal and vertical components in Figure 4a, are the same for all plots. Note that the plots for the nonexcursion samples demonstrate straight line demagnetization paths to the origin after a slight change in slope corresponding to the removal of a soft viscous remanence. In contrast, the excursion samples demonstrate a strong overprint.

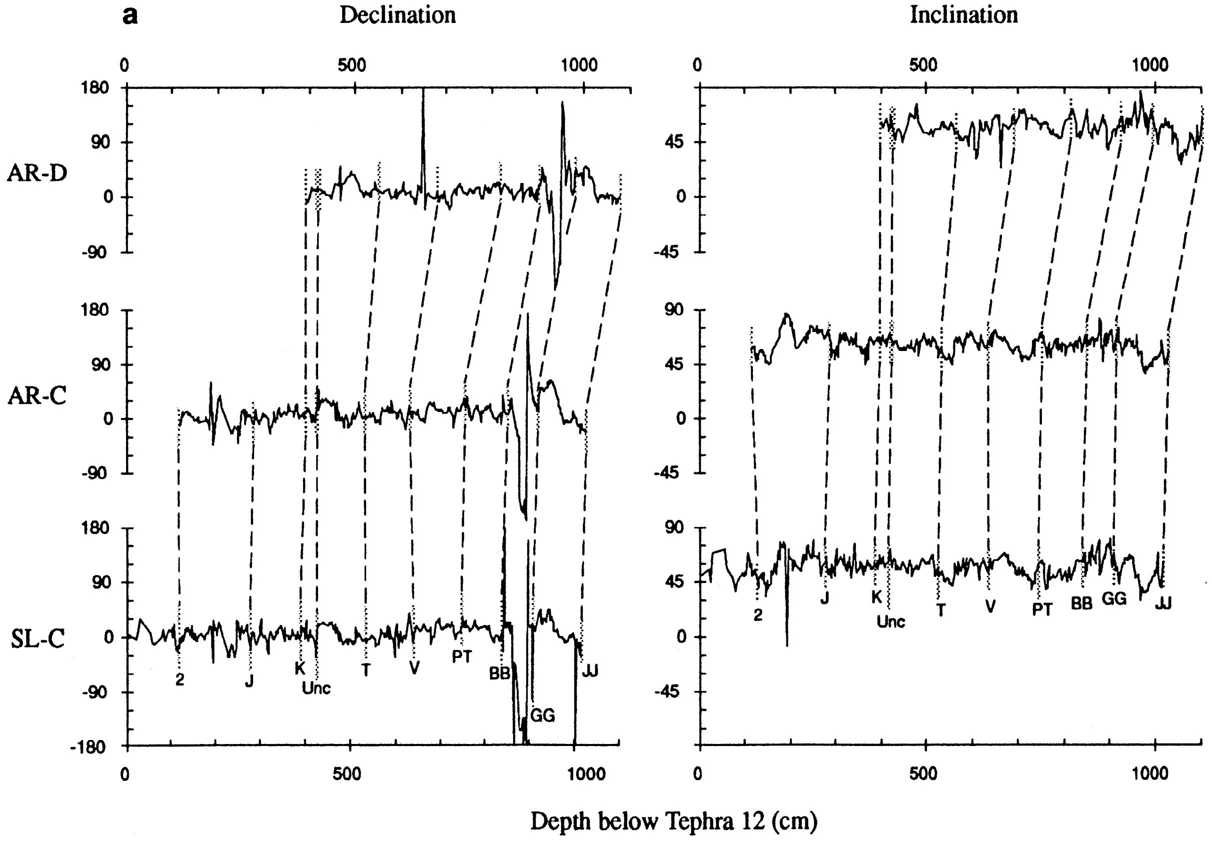

Figure 5. (a) Correlations of declination and inclination records from AR-D, AR-C, and SL-C sections. (b) Correlations of NRM intensity and volume susceptibility records from the same sections. Stratigraphic positions of prominent tephra layers and unconformity are indicated to facilitate correlation between data sets.

Results

Comparisons of records within the Summer Lake Basin. The paleomagnetic inclination and declination of the two new sets of samples from sections AR-C and AR-D are plotted in Figure 5a. The data from the 25 mT AFD level are used because this level is associated with stable directions (see above discussion and *Negrini et al.* [1988]). The data from the original study (15 mT) are also plotted and labeled SL-C. The intensity of natural remanent magnetization (NRM) and κ are plotted for the same data sets in Figure 5b. The stratigraphic positions of several tephra layers and the unconformity correlated to marine oxygen isotope stage 6/5e boundary are also plotted in Figure 5. Except for tephra layer PT, the unconformity and all tephra have been discussed in earlier publications [*Negrini et al.*, 1988; *Davis*, 1985]. Tephra layer PT, an uncorrelated volcanic ash, is less than 0.5 cm thick, and is salmon-pink colored with silt-sized particles consisting primarily of glass shards.

All four magnetic parameters are in close agreement from one data set to another. Also, the multiple sampling per horizon of the two new data sets (AR-C and AR-D) has sharpened the accuracy of our paleomagnetic determinations. For example, in the AR-C declination record, a series of waveforms with eastward plateaus separated by westward spikes are evident from the PT tephra up to the unconformity. These features were among the repeating waveforms originally noted by *Negrini et al.* [1988] in the SL-C declination record but only after that record was smoothed. Their recognition in an unsmoothed record indicates the improved quality of the new data.

To further demonstrate the improved accuracy of the new data we have plotted on an expanded scale the four magnetic parameters from the part of the AR-C and AR-D records which include the Summer Lake II Excursion (Figure 6). Figure 6 includes lithostratigraphic features correlated between sections. Correlations can easily be made from section to section using any of the four magnetic parameters.

Composite paleomagnetic record from the Summer Lake Basin. A composite record including directions and relative paleointensity is plotted in Figure 7 for the entire sequence of Lake Chewaucan sediments exposed in the Ana River Canyon. From the bottom of the section to a depth of 1024 cm, the data are from section C of the original study [*Negrini et al.*, 1988]. New data from section C are shown from a depth of 1024 to 143 cm, and new data from section E are shown from 143 to 0 cm. Previously published data from section E are shown from 0 cm to the top of the section [*Negrini and Davis*, 1992; *Negrini et al.*, 1988]. Except for the bottom part of the record, all data are based on at least three samples per horizon. κ was used as the normalizing parameter for relative paleointensity in Figure 7 rather than the more usual anhysteretic remanent magnetization (ARM) or isothermal remanent magnetization (IRM) because κ data were available for all of the samples. In contrast, ARM and IRM data were available only for the bottom 14 meters and, then, for every fifth horizon only. Thus only the NRM/κ paleointensity estimates are as detailed as the declination and

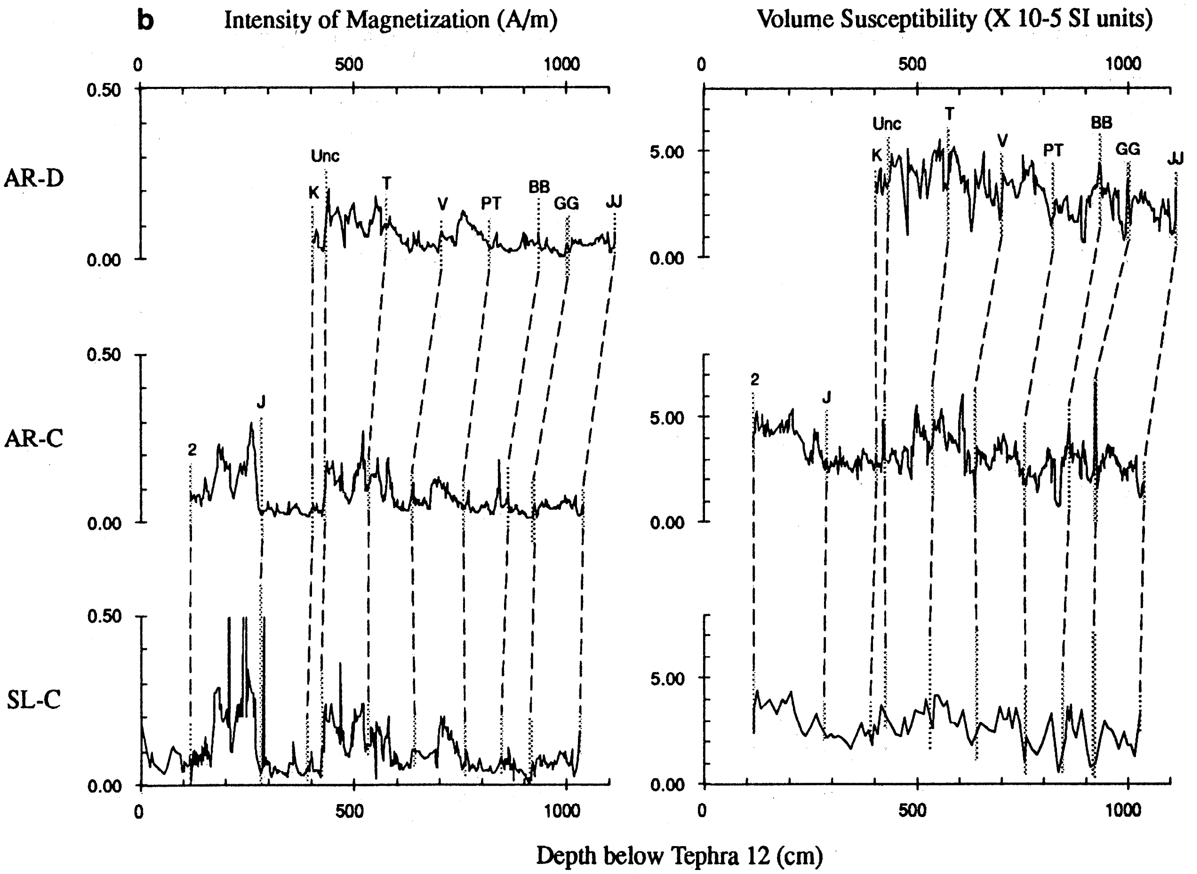

Figure 5. (continued)

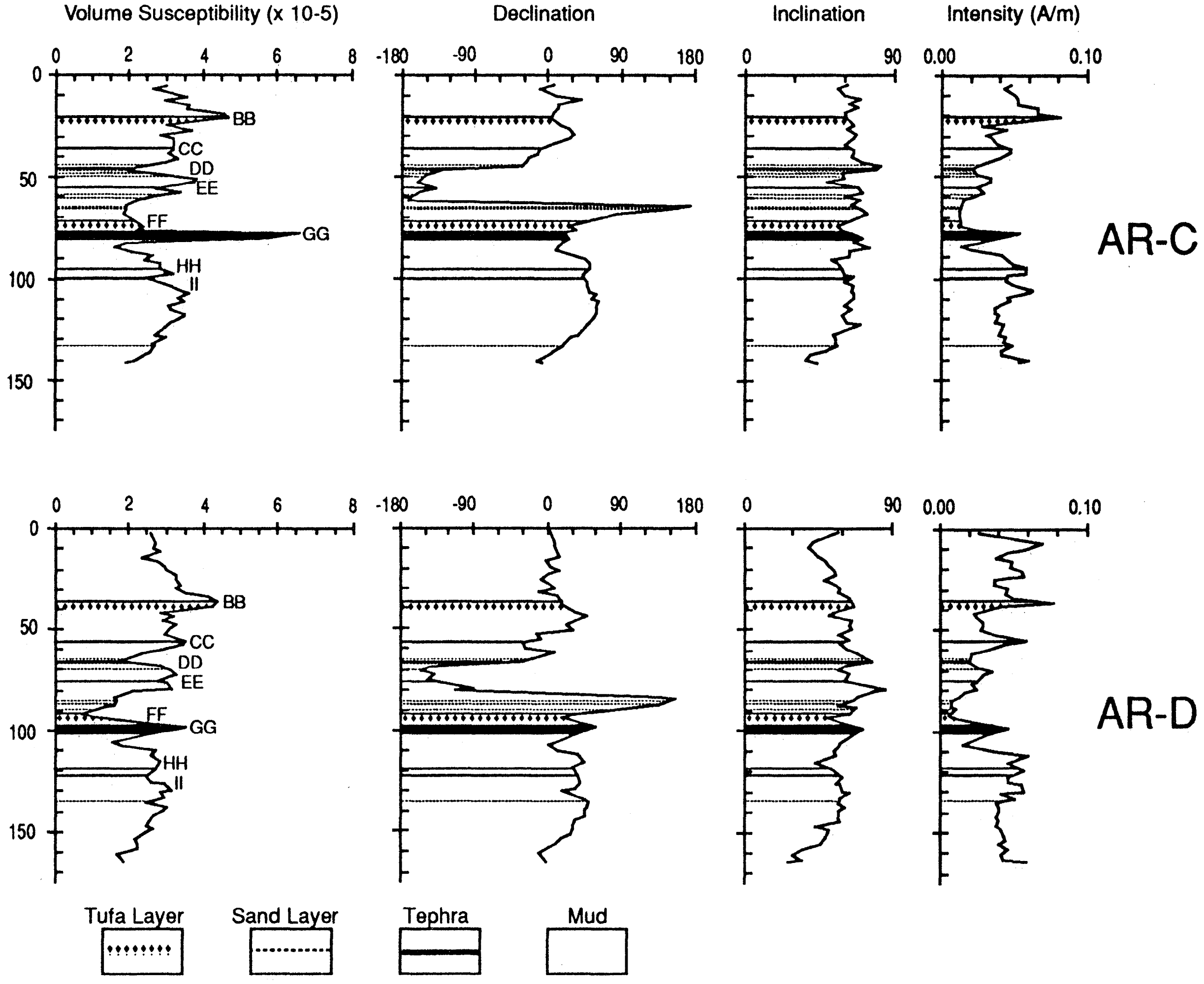

Figure 6. Correlation of magnetic data from Summer Lake II Excursion zone plotted on an expanded scale. Stratigraphic postions of correlative lithologic features from both sections demonstrate the precise correlations possible using any of the magnetic parameters.

inclination data in Figure 7. Though susceptibility is usually not as reliable a normalization parameter as ARM or IRM [*Tauxe*, 1993], ***Roberts et al.*** [1994] have demonstrated that for the Summer Lake sediments, all three normalization methods provided consistently similar paleointensity estimates.

Comparisons with records from other basins. The Summer Lake II Excursion has now been correlated with the Pringle Falls and Long Valley Excursions by *Herrero-Bervera et al.* [this issue] using the tephra correlations described earlier in this paper. The correlation of the three excursion records is summarized in Figure 8. Because of the consistent positions of correlated tephra layers in distinctive declination records from distant localities, there is little doubt that the excursions are the same. However, it is evident that the inclination record and the latter part of the declination record from Summer Lake are attenuated. The apparent difference in the fidelity of the declination and inclination records during the main part of the excursion is the result of limitations in the presentation of vector data as scalar components and is not a manifestation of varying fidelities in the acquisition of declination versus inclination. This assertion is supported by a virtual geomagnetic pole (VGP) plot of the data from the main part of the excursion (Figure 9) which reveals that the Summer Lake sediments record the general morphology of the excursion (a clockwise swing about the sampling site) but that the VGP path is simply attenuated. Comparisons with records from other basins demonstrate that the Summer Lake I record of the Mono Lake Excursion is also attenuated [*Negrini et al.*, 1984; *Negrini and Davis*, 1992]. In contrast, comparisons of paleomagnetic directions from Lake Chewaucan sediments above and below volcanic ashes with paleomagnetic directions recorded by thermoremanent magnetizations in correlative welded tuffs [*Negrini et al.* 1988; *Gardner et al.*, 1992] and comparisons of secular variation above the Summer Lake I Excursion with secular variation above the Mono Lake Excursion [*Negrini and Davis*, 1992] indicate that nonexcursion paleomagnetic directions are recorded very accurately in the Summer Lake sediments.

The discrepancy in the recording fidelity of excursion versus nonexcursion directions is puzzling but we note that the intervals containing the Summer Lake I and II Excursions

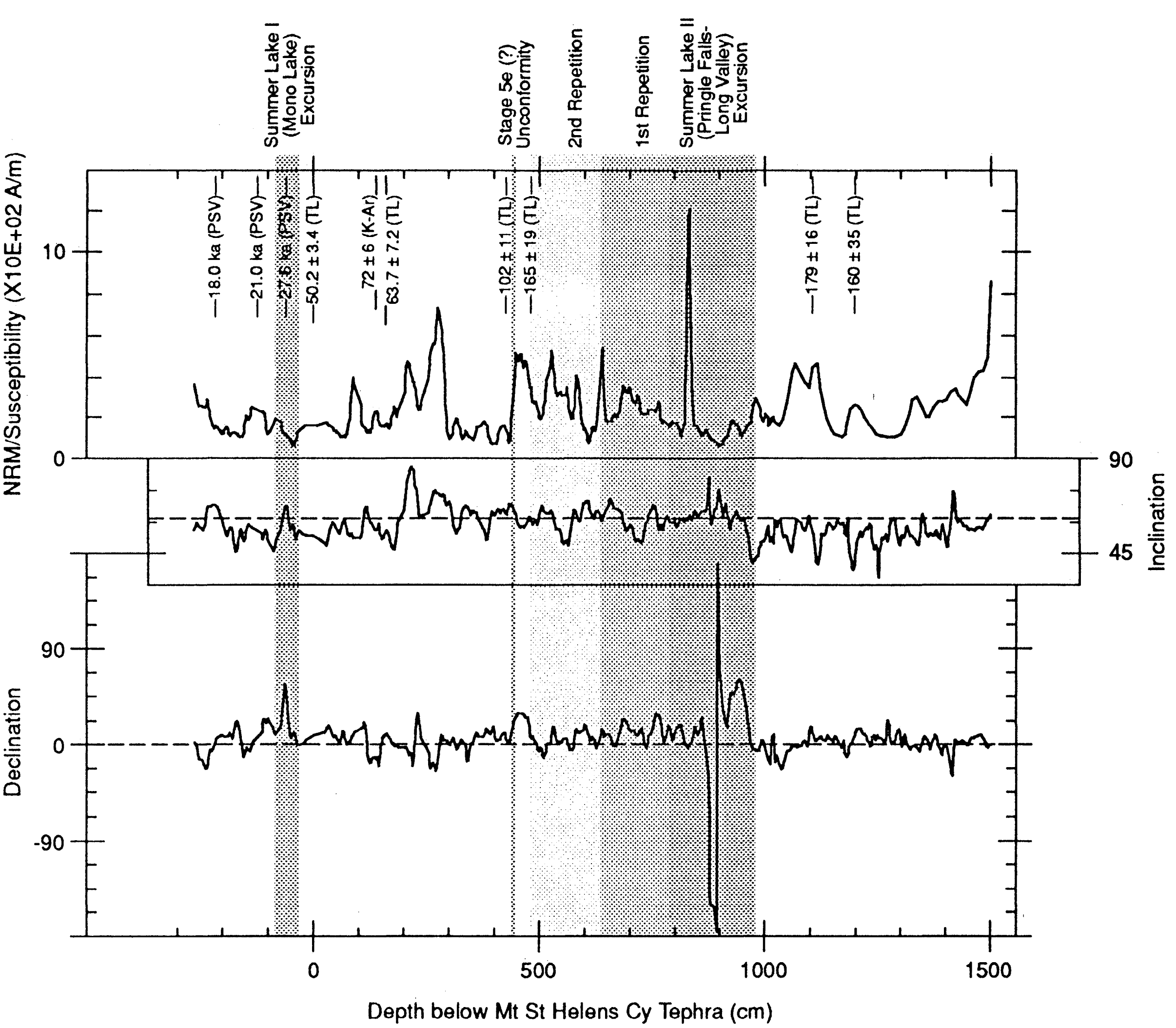

Figure 7. Composite declination, inclination and relative paleointensity (NRM/susceptibility) data for the Lake Chewaucan sediments exposed at various sites in the Ana River Canyon. Selected ages from Table 1 are plotted along with the stratigraphic position of important lithologic and paleomagnetic intervals. Data are vector-smoothed with a seven-point Gaussian algorithm to facilitate comparison.

correspond to the lowest relative paleointensities recorded in the Lake Chewaucan sediments (Figure 7). These observations are consistent with overprinting of magnetic remanence in lake sediments by a subsequent high-intensity field as proposed by *Coe and Liddicoat* [1994]. Using their model, we propose that the anomalous excursion paleomagnetic directions in the interval corresponding to the lowest paleointensities were overprinted by the nonanomalous directions corresponding to the recovered paleofield after the excursion, thereby attenuating the VGP paths of the excursions (e.g., Figure 9).

Excursion-Related Secular Variation and Paleointensity

Negrini et al. [1988] suggested the existence of waveform repetition associated with the Summer Lake II Excursion based solely on a series of eastward declination plateaus separated by westward spikes in the declination. This series of scalar declination features corresponds to the features in the composite record of this study (Figure 7) between the end of the excursion (980 cm) and the stage 5e unconformity (450 cm). Below, we show that these declination features form two cycles of a complex waveform evident from an analysis of the entire paleomagnetic vector (declination, inclination, and paleointensity). Furthermore, the VGP paths of the two repetitions of this waveform are similar in morphology to the VGP path of the excursion itself, as recorded at the Pringle Falls locality.

On inspection of Figure 7, it is not apparent that the waveforms proposed in the original study [*Negrini et al.*, 1988] have corresponding inclination features. However, if pairs of eastward declination plateaus are considered rather than individual plateaus, then they match up well with a coherent inclination feature generally defined by a prominent 10-15° inclination low separated by two inclination highs of

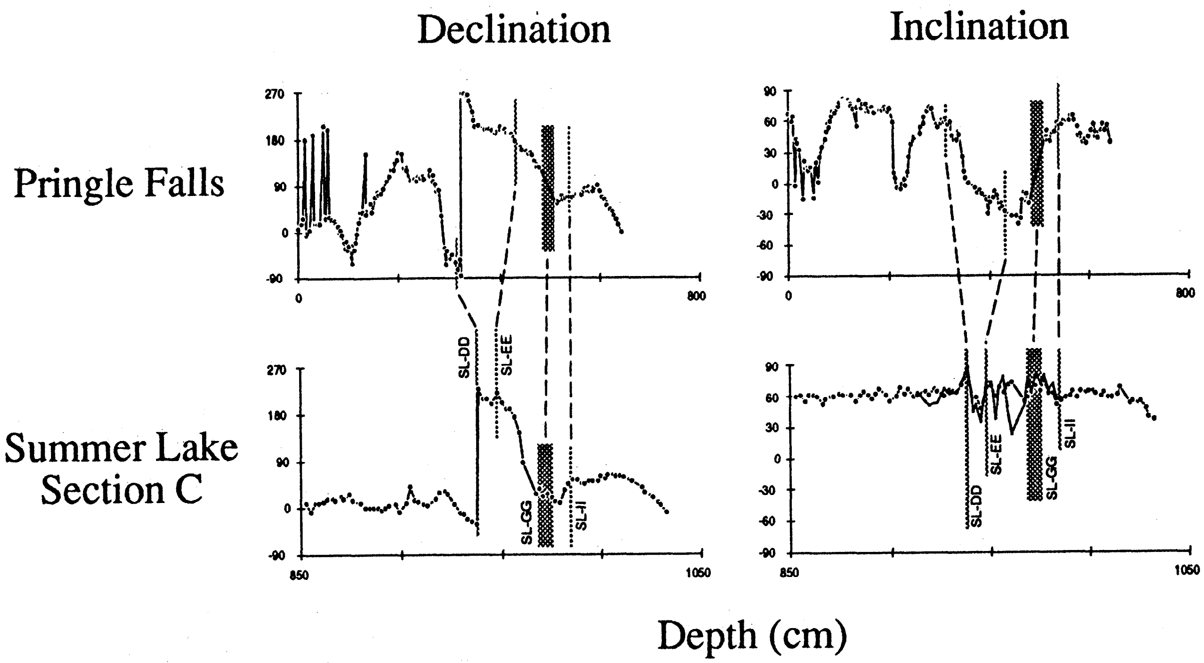

Figure 8. Correlation of declination and inclination records from the AR-C section with the Pringle Falls record of *Herrero-Bervera et al.* [1989]. Stratigraphic positions of the newly correlated tephra layers are plotted along with the paleomagnetic data.

slightly smaller magnitude. Based on this definition, we separated the data subsets into two repetitions of the same waveform (Figure 10). The older and younger cycles are labeled first and second repetition, respectively. There is a convincing correspondence of declination and inclination features from repetition to repetition. The paleointensity features also correlate well. These paleointensity features are also clearly evident in the NRM/ARM and NRM/IRM estimates of paleointensity as presented by *Roberts et al.* [1994].

To facilitate a description of the vector waveform through time, we plotted the two cycles as VGP paths on polar projections (Figure 11). Also plotted in Figure 11 are the excursion data from the Pringle Falls record [*Herrero-Bervera et al.*, 1989]. The record from Pringle Falls was chosen because

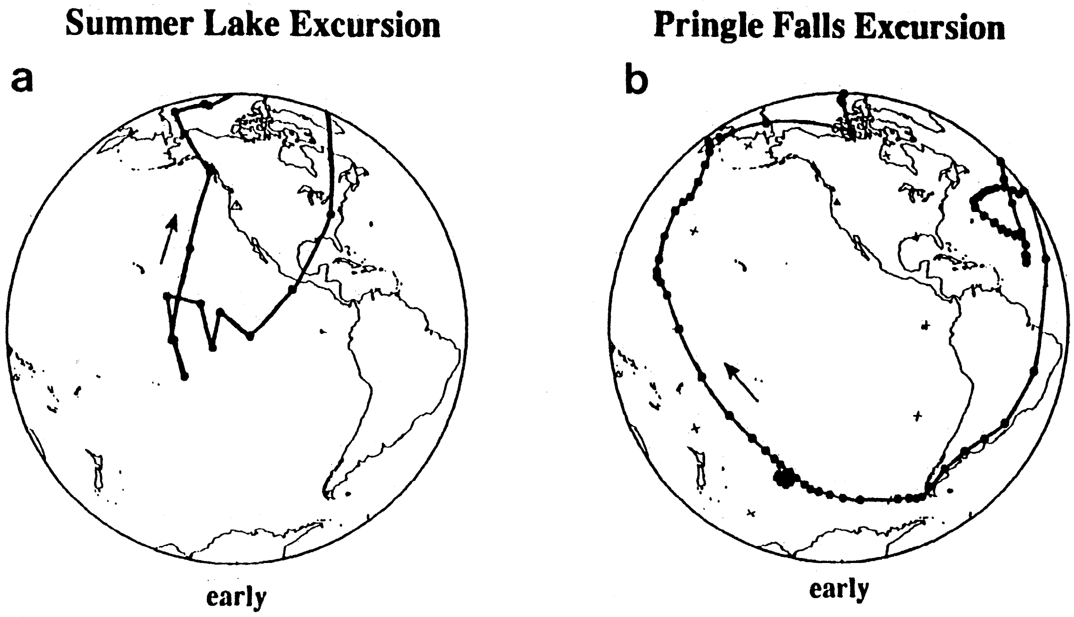

Figure 9. VGP plots of main part of excursion as recorded at (a) Summer Lake, and (b) Pringle Falls. Equal-angle plots are centered at the intersection of the equator and the longitude of the sampling sites.

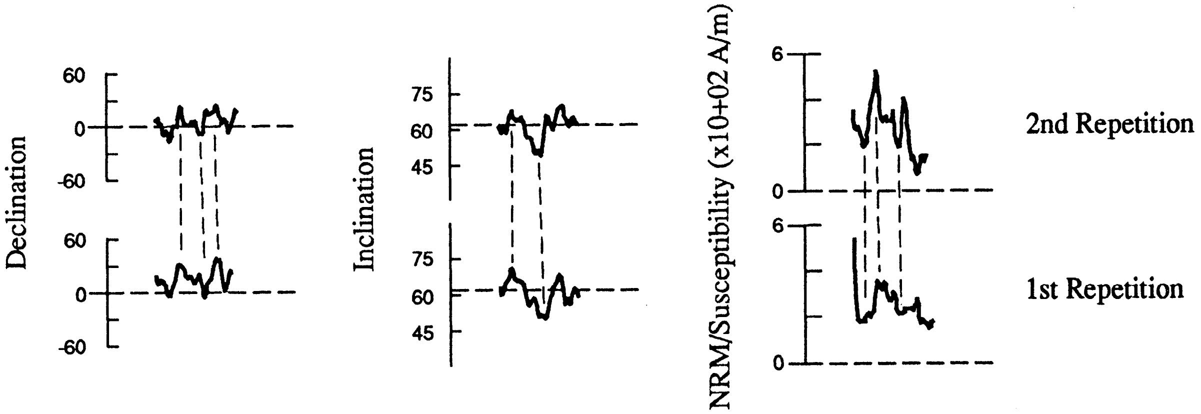

Figure 10. Comparison of declination, inclination, and relative paleointensity versus depth for first (older) and second (younger) repetitions of the excursion waveform. The stratigraphic positions of these intervals are indicated in Figure 7.

it is the most accurate and complete record available for the excursion (E. Herrero-Bervera, written communication, 1993). All data in Figure 11 were smoothed prior to transformation to VGP space. The orthogonal components of the pretransformed paleomagnetic unit vectors were smoothed by passing a seven-point Gaussian window through the data set.

Because the amplitude of the excursion is much larger than that of the first and second Repetitions, the excursion plots extend from the north geographic pole to the equator, whereas the repetition plots extend only to 60°N. Even so, the morphologies of the VGP paths for the early and middle parts of the excursion are distorted because they extend into the southern hemisphere (Figures 11i and 11h). For these segments, we have added VGP plots which are centered on the intersection of the equator and the site longitude (Figure 12). From this perspective, the simple looping nature of these segments is very clear.

The VGP paths for the excursion and the two subsequent cycles define a distinct waveform which clearly repeats itself. This waveform consists of early and middle segments both of which transcribe clockwise (cw), loops confined to longitudes approximately 90° away from a great circle connecting the site location with Earth's spin axis. The early segment is shown for each repetition in Figures 11i, 11f, and 11c. The middle segment is shown in Figure 11h, 11e, and 11b. The poorest example of these is the early segment of the second repetition as recorded in the Summer Lake sediments. We note that this interval also corresponds to a zone of low relative paleointensities (Figures 7 and 10). Thus the record in this interval may have been overprinted during a subsequent interval of higher paleointensity in the same manner as the excursion record from the Summer Lake sediments (see above). The final segment of the waveform consists of a distinct ccw-cw-ccw looping sequence (Figures 11g, 11d, and 11a).

Note that in the two repetitions, the waveform is rotated 180° about Earth's spin axis. For this reason, the VGP plots for the repetitions (Figures 11a-11f) are oriented so that the site longitudes are at the top of the plot, whereas the plots for the excursion itself are oriented in the more conventional manner with the site longitudes at the bottom (Figures 11g-11i).

Secular Variation From Elsewhere in the Sequence

All of the remaining directional data are plotted as VGPs in Figures 13 and 14, except for those data from the part of the section containing notable unconformities. Figures 13 and 14 are centered on the spin axis and range outward to 60°N. The data in Figure 13 are from the bottom of the section up to a level immediately below the Summer Lake II Excursion. The data in Figure 14 are from the part of the sequence from the prominent zone of unconformities up to the Summer Lake 12 (Mount St. Helens Cy) tephra.

It is immediately apparent from inspection of Figures 13 and 14 that the above described excursion waveform is not present in any part of the record except for that which immediately follows the Summer Lake II Excursion. Furthermore, the VGP paths in Figures 13 and 14 are characterized by a lack of consistency both in the shape and sense of looping. Rarely does the shape or sense of looping remain constant for more than two cycles and only in one case do two well-developed, large amplitude (10°-20°) loops appear in succession (Figures 14d-14e). In particular, the lack of consistent, linear VGP paths argue against oscillating, standing, radial dipoles as important sources for secular variation as proposed previously for the Quaternary magnetic field of North America [*Evans* et al., 1989; *Gillen and Evans*, 1989; *Hedlin and Evans*, 1987; *Evans*, 1984].

Implications for Excursions and Secular Variation as Related Field Behavior

Based on the above observations, a clear case can now be made to support the occurrence of a repeating waveform initiated by the Summer Lake II/Pringle Falls/Long Valley Excursion that continues after the excursion for at least two cycles. The VGP path traced out during each repetition is strikingly similar to that traced out by the excursion itself, except for a 180° rotation of the reference frame about Earth's spin axis (Figure 11). A relative paleointensity signature of the waveform is also clearly evident for the two repetitions (Figures 7 and 10).

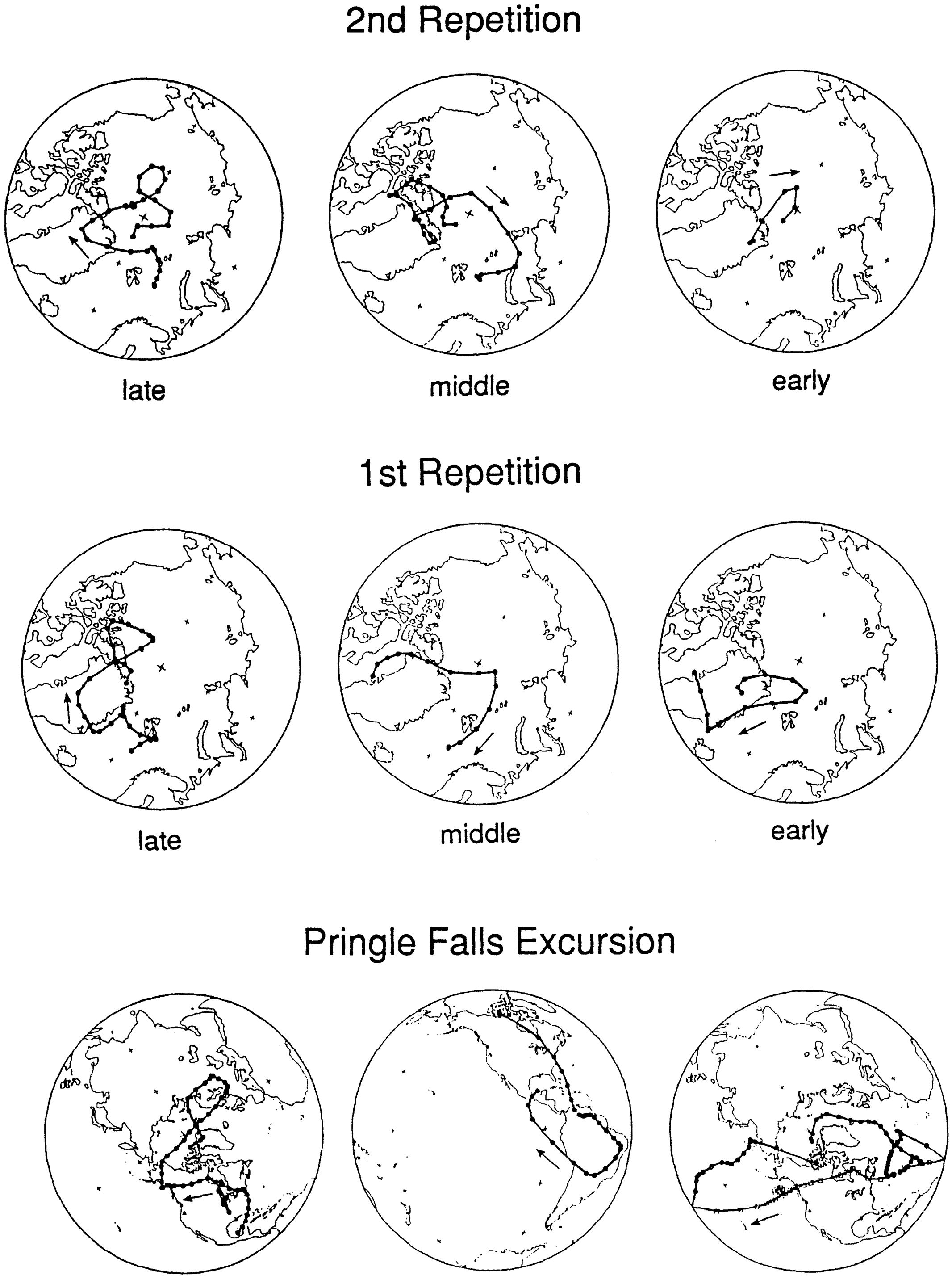

Figure 11. VGP plots of the excursion waveform (Figures 11g-11i) and the two repetitions (Figures 11d-11f and 11a-11c). Plots are centered on the geographic north pole. For the excursion, the entire northern hemisphere is plotted and the site latitudes are at the bottom. For the repetitions, the plots range in latitude from the geographic north pole to 60°N. Data for the repetitions correspond to those plotted in Figure 10 as declination and inclination data.

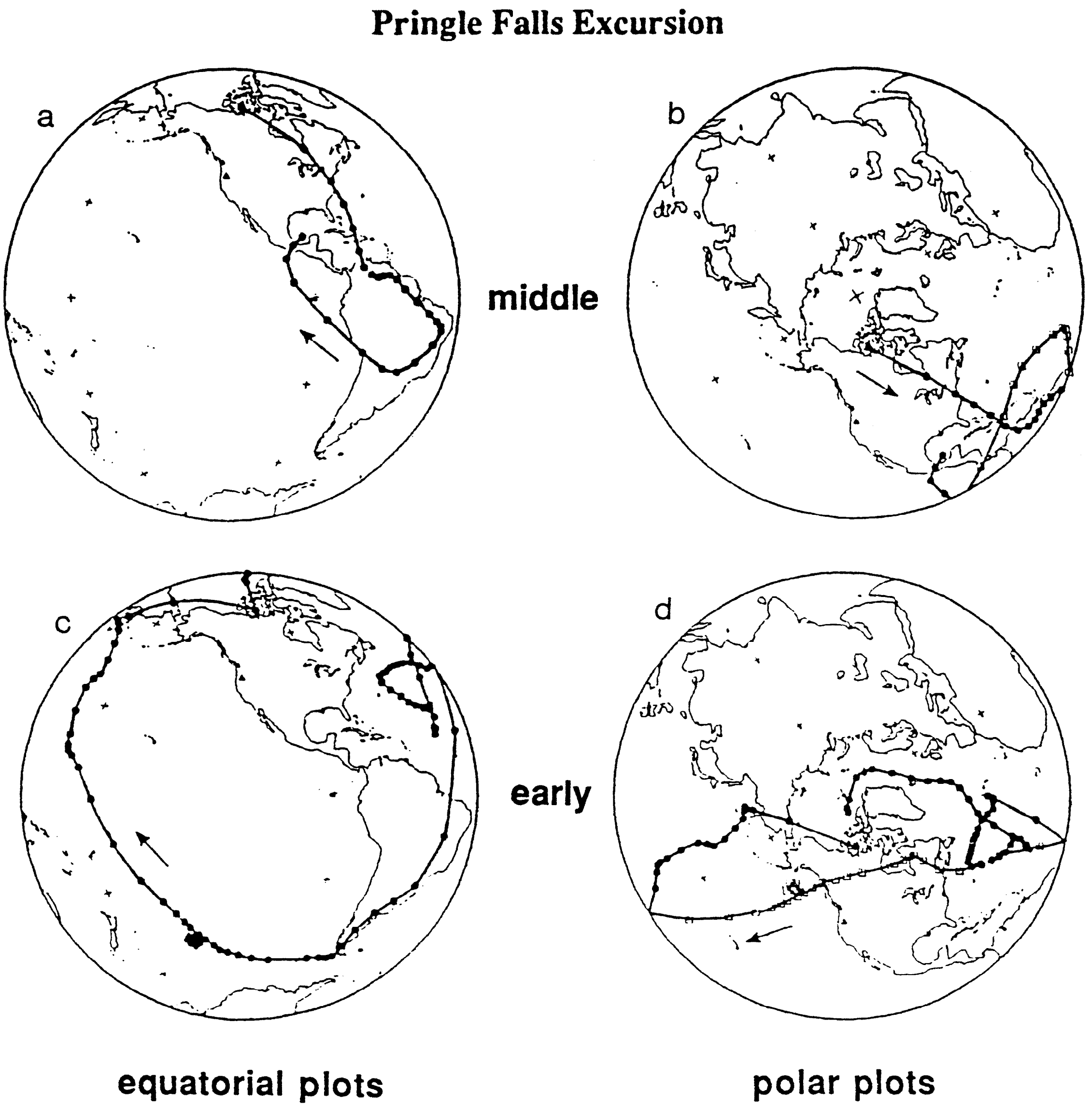

Figure 12. Pole-centered VGP plots for the early and middle parts of the excursion (Figures 12b and 12d) plotted alongside plots of the same data centered on the intersection of the equator and the site longitude (Figures 12a and 12c). The new perspective offered by the equatorial plots more clearly illustrates the simple looping nature of the early and middle parts of the excursion.

Analysis of the secular variation from elsewhere in the section suggests that the excursion had an abrupt onset and that the repetitions of the excursion waveform are restricted to the time interval immediately after the excursion. Furthermore, the paleointensity of the field during the two repetitions was moderately high relative to the extremely low intensity during the excursion interval (Figure 7). Therefore it does not appear that the repetitions of this particular waveform were due to a prolonged period of diminished dipole moment as suggested by *Levi and Karlin* [1989] for the recurrences of the waveform recorded in their 54-20 ka record. In contrast, the geomagnetic behavior exhibited by the Pringle Falls/Long Valley/Summer Lake II Excursion indicates that secular variation, when initiated by an excursion, can occur even after the field fully recovers from low intensities during the excursion. If this implication is confirmed by additional, total vector records of excursions and subsequent secular variations, then it would force important constraints on theoretical models. Excursion models would then be required to allow damped oscillations after the main excursion event is over. Also, these models must allow the 180° rotation of reference frame about Earth's spin axis between the excursion waveform and its repetitions, as observed here.

The excursion studied here has been compared to full polarity transitions by *Tric et al.* [1991] based on similarities in the morphologies of the VGP paths. If this excursion is closely related to full polarity transitions then one would also expect to observe recurrences of characteristic waveforms in the secular variation after reversals of the magnetic field.

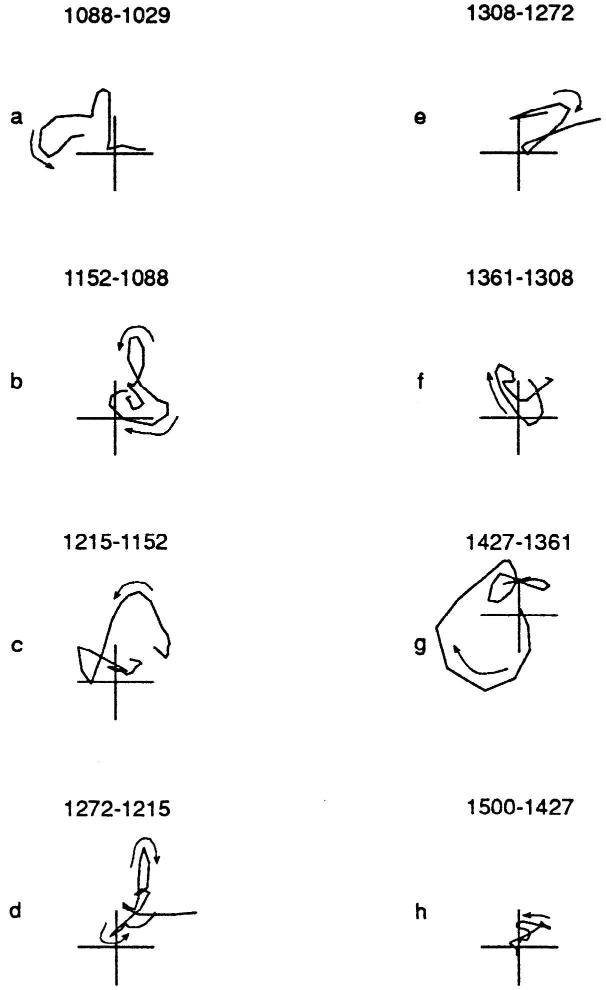

Figure 13. Polar VGP plots of the secular variation below the excursion. The large central cross of each plot extends outward from the geographic north pole to 80°N. The site longitude is at the bottom of each plot. The depth range for each segment of data is indicated above each plot. These depths correspond to the depth scale on Figure 7.

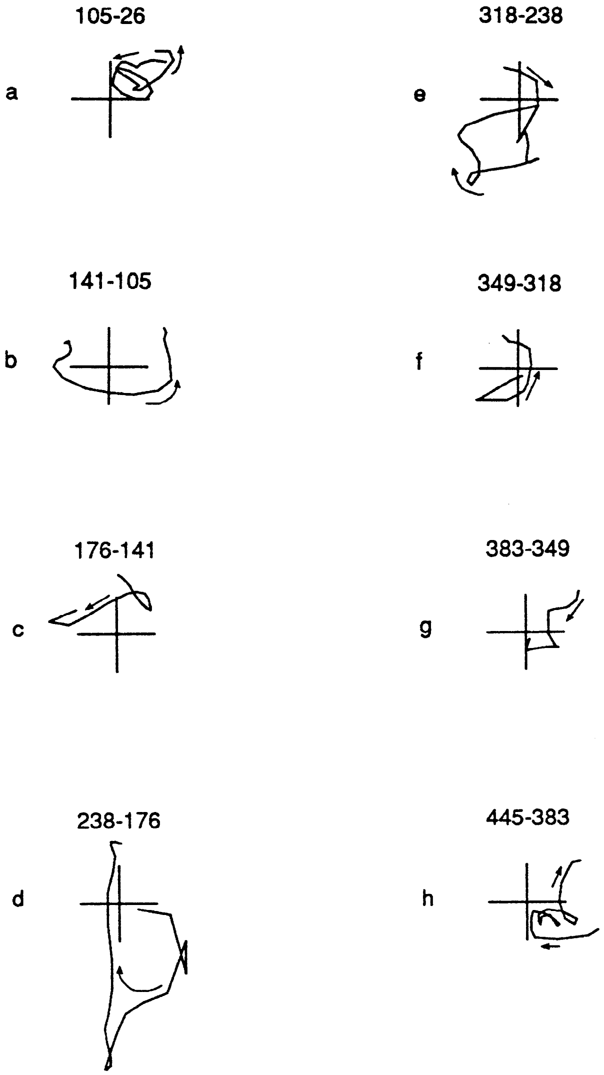

Figure 14. Pole-centered VGP plots of the secular variation above the excursion. The plots are configured identically to those of Figure 13.

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