areas. Over large times the total slip on neighboring segments is necessarily equal, although in models such as this, significant short-term disequilibrium allows repeated rupture on a single segment; frictional asymmetry promotes this behavior.

The observed temporal instability of recurrence times in hierarchical seismicity may also be significant in our interpretation of the failure of predictions based on more idealized recurrence behavior. Our hierarchical model predicts that periodic recurrence behavior, though being a fundamental property of some fault segments, is temporally unstable; high-dimensional self-organized critical interactions that are inherently unpredictable apply random local fluctuations on the deterministic far field stress (*24*). Recent sequences of seismicity in California appear to support the hypothesis that such local fluctuations can significantly alter recurrence predictions based on deterministic strain accumulation. For example, King and others (*25*) show that the occurrence of the Landers earthquake (magnitude $M = 7.4$) may have been advanced by as much as one to three centuries by small changes in Coulomb stress ($\approx$1 bar) as a result of preceding moderate magnitude events at Galway Lake, Homestead Valley, North Palm Springs, and Joshua Tree. They further argue that the Landers earthquake increased the Coulomb stress at Big Bear by 2 to 3 bars, triggering the $M = 6.5$ Big Bear event.

It appears that natural seismicity may exhibit sensitivity to small stress changes which is similar to this model. If these observations are generally reflected in real seismicity, then it will not be possible to use recurrence intervals, no matter how well-defined, in the long-term prediction of earthquakes.

REFERENCES AND NOTES

1. W. H. Bakun and T. V. McEvilly, *J. Geophys. Res.* **89**, 3051 (1984).
2. K. E. Sieh, *Bull. Seismol. Soc. Am.* **68**, 1731 (1978).
3. T. R. Toppozada, C. R. Real, D. L. Parke, *Calif. Div. Mines Geol. Open File Rep. 81-11* (1981).
4. J. J. Walsh and J. Waterson, *J. Struct. Geol.* **10**, 329 (1988).
5. C. Childs, J. J. Walsh, J. Waterson, in *North Sea Oil and Gas Reservoirs II* (Graham and Trottman, London, 1990), pp. 309–318.
6. P. Bak, C. Tang, K. Weisenfeld, *Phys. Rev. A* **38**, 364 (1988).
7. P. Bak and C. Tang, *J. Geophys. Res.* **94**, 15635 (1989).
8. A. Sornette and D. Sornette, *Europhys. Lett.* **9**, 197 (1989).
9. Defined as a group of systems which share the same power law exponent, see for example S. K. Ma, *Modern Theory of Critical Phenomena* (Benjamin, Reading, MA, 1975).
10. S. R. Brown, C. H. Scholz, J. B. Rundle, *Geophys. Res. Lett.* **18**, 215 (1991).
11. M. Wyss and R. O. Burford, *Nature* **329**, 323 (1987).
12. C. H. Scholz, *ibid.* **348**, 197 (1990).
13. ______, *The Mechanics of Earthquakes and Faulting* (Cambridge Univ. Press, New York, 1990).
14. J. F. Pacheco, C. H. Scholz, L. R. Sykes, *Nature* **355**, 71 (1992).
15. I. G. Main, *ibid.* **357**, 27 (1992).
16. K. E. Sieh, M. Stuiver, D. Brillinger, *J. Geophys. Res.* **94**, 603 (1989).
17. For the sake of brevity, precise mathematical details of the model are not included here but have been published elsewhere [J. McCloskey, C. J. Bean, B. O'Reilly, *Geophys. Res. Lett.* **20**, 1403 (1993); J. McCloskey, *Geophys. J. Int.* **115**, 538 (1993)]. Parameter values for the results presented here are given in Fig. 3.
18. J. Huang and D. L. Turcotte, *Geophys. Res. Lett.* **17**, 223 (1990).
19. ______, *Nature* **348**, 234 (1990).
20. G. Sugihara and R. M. May, *ibid.* **344**, 734 (1990).
21. Y_1 and Y_2 are the lengths of the springs connecting blocks 1 and 2 to the driver. See Fig. 1, the caption to Fig. 3, and (*20*) for details.
22. L. R. Sykes and S. P. Nishenko, *J. Geophys. Res.* **89**, 5905 (1984).
23. W. R. McCann, S. P. Nishenko, L. R. Sykes, J. Krause, *Pure Appl. Geophys.* **117**, 1082 (1979).
24. See for comparison D. Sornette and J. Virieux, *Nature* **357**, 401 (1992).
25. G. C. P. King, R. Stein, J. Lin, *Bull. Seismol. Soc. Am.* **84**, 935 (1994).

26. J. McC. would like to acknowledge financial support from the Leverhulme Trust. We both thank B. O'Kane for help in coding the model and our colleagues who read and commented on the manuscript.

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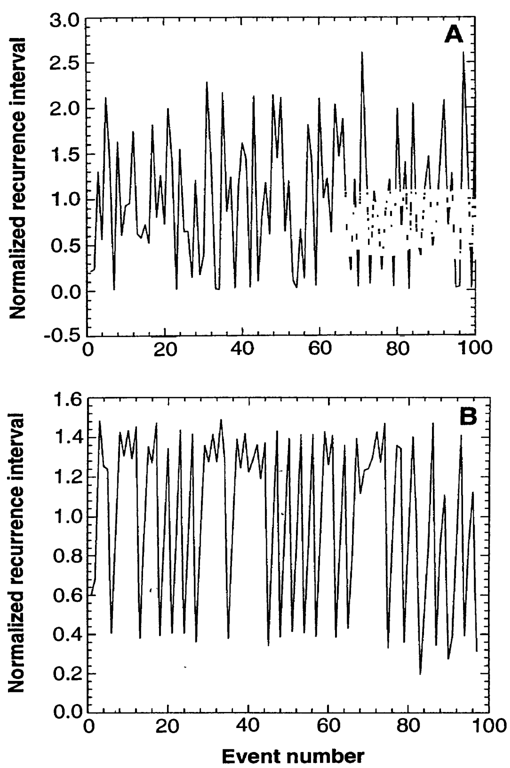

Fig. 4. Temporal variation in normalized recurrence interval for events on the stiffer block. (**A**) Events above model magnitude 4. (**B**) Characteristic events above model magnitude 6. In each case data are normalized to the mean recurrence time of the weak block. Although the low-magnitude events show absolutely no tendency toward uniform recurrence time, high-magnitude events tend to recur at about 1.4T. However, this recurrence interval is unstable over time, showing windows of time-unpredictable behavior.

Paleomagnetic Record of a Geomagnetic Field Reversal from Late Miocene Mafic Intrusions, Southern Nevada

Catherine D. Ratcliff, John W. Geissman, Frank V. Perry, Bruce M. Crowe, Peter K. Zeitler

Late Miocene (about 8.65 million years ago) mafic intrusions and lava flows along with remagnetized host rocks from Paiute Ridge, southern Nevada, provide a high-quality paleomagnetic record of a geomagnetic field reversal. These rocks yield thermoremanent magnetizations with declinations of 227° to 310° and inclinations of −7° to 49°, defining a reasonably continuous virtual geomagnetic pole path over west-central Pacific longitudes. Conductive cooling estimates for the intrusions suggest that this field transition, and mafic magmatism, lasted only a few hundred years. Because this record comes principally from intrusive rocks, rather than sediments or lavas, it is important in demonstrating the longitudinal confinement of the geomagnetic field during a reversal.

The record of marine magnetic anomalies and terrestrial magnetostratigraphy demonstrates that geomagnetic field reversals have occurred frequently throughout geologic time. Detailed paleomagnetic records are needed to determine the behavior of the transitional field during reversals in order to evaluate whether dipolar or strong low-order nondipolar fields define transitions and thus the processes responsible for polarity reversals (*1–4*). However, because field reversals are short-lived phenomena (*5*), they are by no means always well-recorded. Several high-quality, partial to essentially com-

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plete records of polarity transitions have been obtained, mostly from young sediments and lava flows (*6, 7*). These records have implied that virtual geomagnetic poles (VGPs) may be confined to certain longitudes (*8–11*) or clustered in preferred positions (*12–14*) during reversals.

The interpretation of individual field reversal records, however, is often complicated by artifacts of the recording process, and the reliability of many of the data used to define transitions has been challenged (*15, 16*). In principle, intrusive rocks should provide more accurate records of field reversals than sedimentary rocks or lava flows because magnetization acquisition may be more continuous and of high fidelity (*17*). We have obtained paleomagnetic results from late Miocene mafic intrusions, associated lava flows, and remagnetized host rocks at Paiute Ridge, southern Nevada, that provide a high-fidelity record of a geomagnetic field reversal.

The Paiute Ridge subvolcanic center is located in the northern Halfpint Range, on the eastern part of the Nevada test site (Fig. 1). This center is part of episodic, postcaldera mafic volcanism that succeeded volcanic activity of the Timber Mountain–Oasis Valley caldera complex (*18*). This activity consisted of small volume (<1 km^3), spatially scattered basaltic centers of predominantly hawaiitic composition (*19*). The Paiute Ridge center exposes a complex network of mafic dikes, sills, lopoliths, and lavas erupted about 8.6 million years ago (Ma) (Fig. 1).

The intrusions cut mid-Miocene ash-flow tuffs and lower Paleozoic carbonate strata. The intrusions were emplaced within the floor of a north-northwest–trending graben, along associated normal faults and, to a lesser extent, in adjacent horst blocks. Dikes are steeply dipping to the vertical and are generally less than 3 m wide. Larger intrusions range from a few meters to about 20 m in thickness, are discordant, and have sharp contacts with host rocks. Ash-flow tuffs are generally fused within about 2 to 3 m of the intrusions but are poorly indurated at greater distances. A prominent feature of this center is the Paiute Ridge lopolith, which is about 1 km across and estimated to be about 150 m thick. This lopolith contains several syenitic-to-monzonitic pods, up to about 10 m across, that differentiated in situ. Local scoria layers, lava flows, and a conduit plug with radial dikes indicate that surface eruptions accompanied magma emplacement. We estimate that the intrusions were emplaced within about 300 m from the paleosurface, on the basis of the maximum thicknesses of tuff. Minor postmagmatic faulting and erosion of the poorly indurated tuffs have resulted in excellent three-dimensional exposure of the intrusions.

We collected samples (*20*) from 57 sites in intrusions and lava flows and in host carbonate strata and ash-flow tuffs. The number of independent samples collected at a site ranged from 7 to 57, depending on the features exposed. Of the 57 sites, demagnetization was fully completed (*21*) on samples from 48 of them. Data from 12 sites were rejected because of contamination by lightning. Four sites, either detailed contact tests or full traverses across small intrusions, yielded internally complex results (*22*) consistent with rapid directional variations during a reversal. The data from the remaining 32 sites provide a high-fidelity paleomagnetic record of a geomagnetic field reversal.

Rocks from these 32 sites yielded characteristic remanent magnetizations (ChRMs) that we interpret to be primary thermoremanent magnetizations (TRMs). The ChRMs were isolated over moderate to high alternating fields (20 to 125 mT) and laboratory unblocking temperatures (300° to 680°C). Orthogonal demagnetization diagrams show linear trajectories toward the origin at high alternating fields and laboratory unblocking temperatures (Fig. 2) (*23*). Magnetizations were carried primarily by magnetite, but hematite commonly carried a fraction of remanence, especially in fused tuffs and syenites. These observations are supported by isothermal remanent magnetization acquisition experiments and by hysteresis data (*24*). Mean directions (Fig. 3, A and B) for mafic intrusions and remagnetized host rocks at Paiute Ridge deviate by more than 40° from expected, late Miocene reverse or normal polarity directions, and because of their overall distribution, we considered them to reflect transitional field behavior (*25*).

To evaluate whether the Paiute Ridge

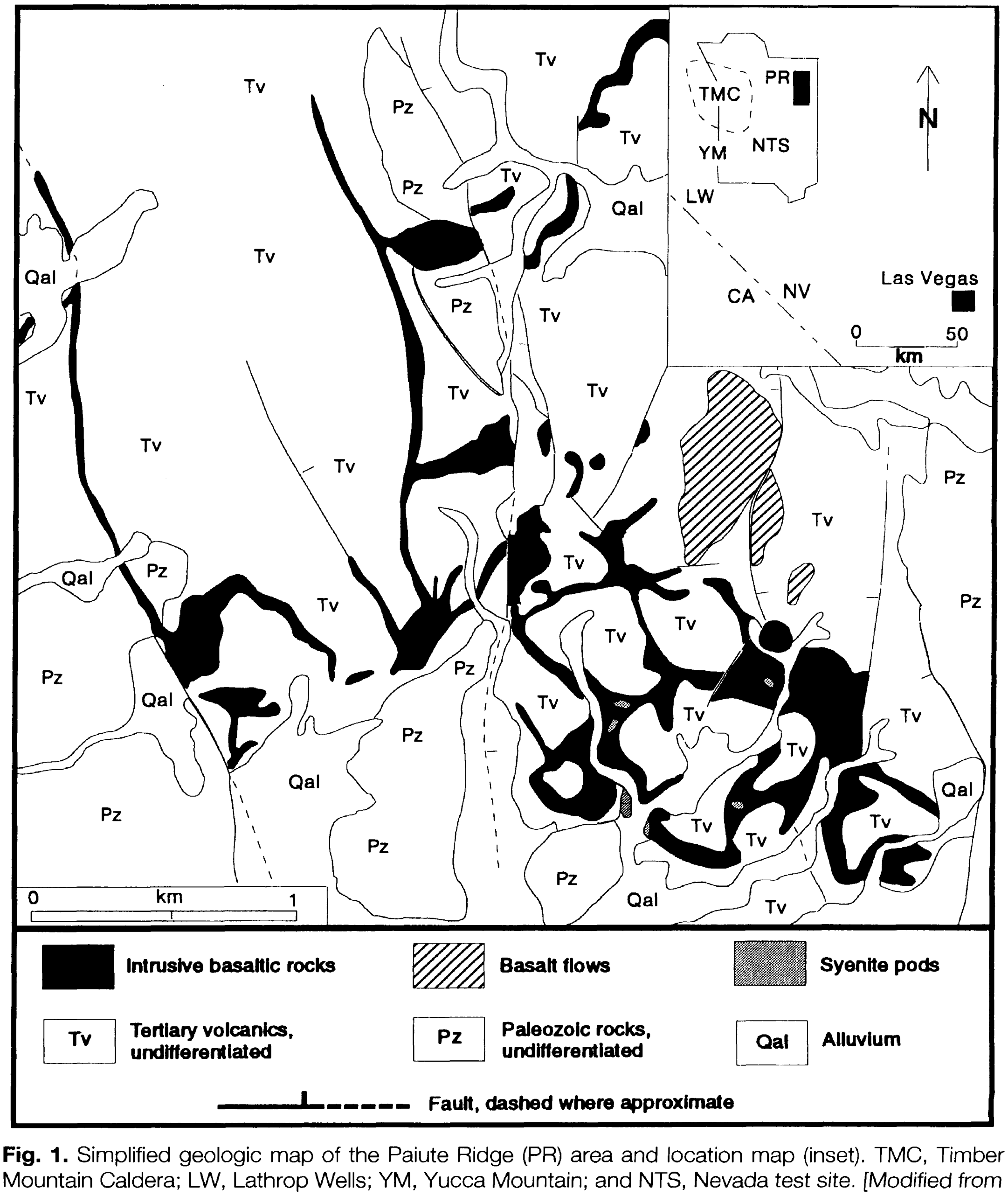

Fig. 1. Simplified geologic map of the Paiute Ridge (PR) area and location map (inset). TMC, Timber Mountain Caldera; LW, Lathrop Wells; YM, Yucca Mountain; and NTS, Nevada test site. [*Modified from* Byers and Barnes (*45*)]

directions are primary TRMs acquired during a geomagnetic field reversal, we conducted contact tests (*26*) and TRM acquisition experiments. For contact tests, we sampled host rocks at distances from contacts ranging from about 1 cm to 40 m (*27*). Intrusions and host rocks commonly yielded statistically distinct magnetizations, yet both materials recorded transitional directions. For example, site PR45 (Fig. 3, A and B) was collected from baked ash-flow tuff within 1 m of the upper contact of the Paiute Ridge lopolith and had a site mean of declination $D = 226.7°$, inclination $I = -6.8°$ [$\alpha_{95} = 3.7°$, $k = 137$, 12 of 12 samples (*28*)]. Site PR44 (Fig. 3, A and B) was collected from the lopolith, within 6 m of site PR45, and had a mean of $D = 245.6°$, $I = -30.3°$ ($\alpha_{95} = 9.8°$, $k = 29$, 8 of 9 samples). The ChRMs for rocks from both sites were isolated over the same range of laboratory unblocking temperatures (>500°C), but the site means were distinct at the 99% confidence level (*29*). Other, more detailed, contact tests showed significant changes in remanence direction with distance from the contact (Fig. 4). We interpret these data to reflect rapid directional variation during cooling through magnetization blocking temperatures. For example, Coe and Prevot (*30*) estimated that the direction of the field may vary by 0.5° to 3° per year during a reversal. It is possible, then, that rocks cooling at slightly different times could record different directions, despite their proximity. We consider the contact tests to be positive because both the intrusions and the host rocks acquired transitional field directions (Fig. 3, A and B).

The TRM acquisition experiments showed that rocks from Paiute Ridge are capable of faithfully recording the ambient geomagnetic field and that the unusual magnetizations observed are not an artifact of rock magnetic behavior (*31, 32*). In alternating field demagnetization of the acquired TRM, all samples exhibited magnetizations within 5° of the applied field, indicating that they had reliably recorded the ambient magnetic field. Alternating field demagnetization of the anhysteretic remanent magnetization before and after these experiments did not demonstrate any significant changes in magnetic mineralogy.

Field observations preclude the possibility that the Paiute Ridge magnetizations are the result of post–late Miocene tilting or vertical axis rotation or of remagnetization. Contemporaneous lava flows of the complex are horizontal, and dikes and conduits are nearly vertical. The ash-flow tuffs do not dip by more than about 20°, but the tilting of these rocks is considered to pre-

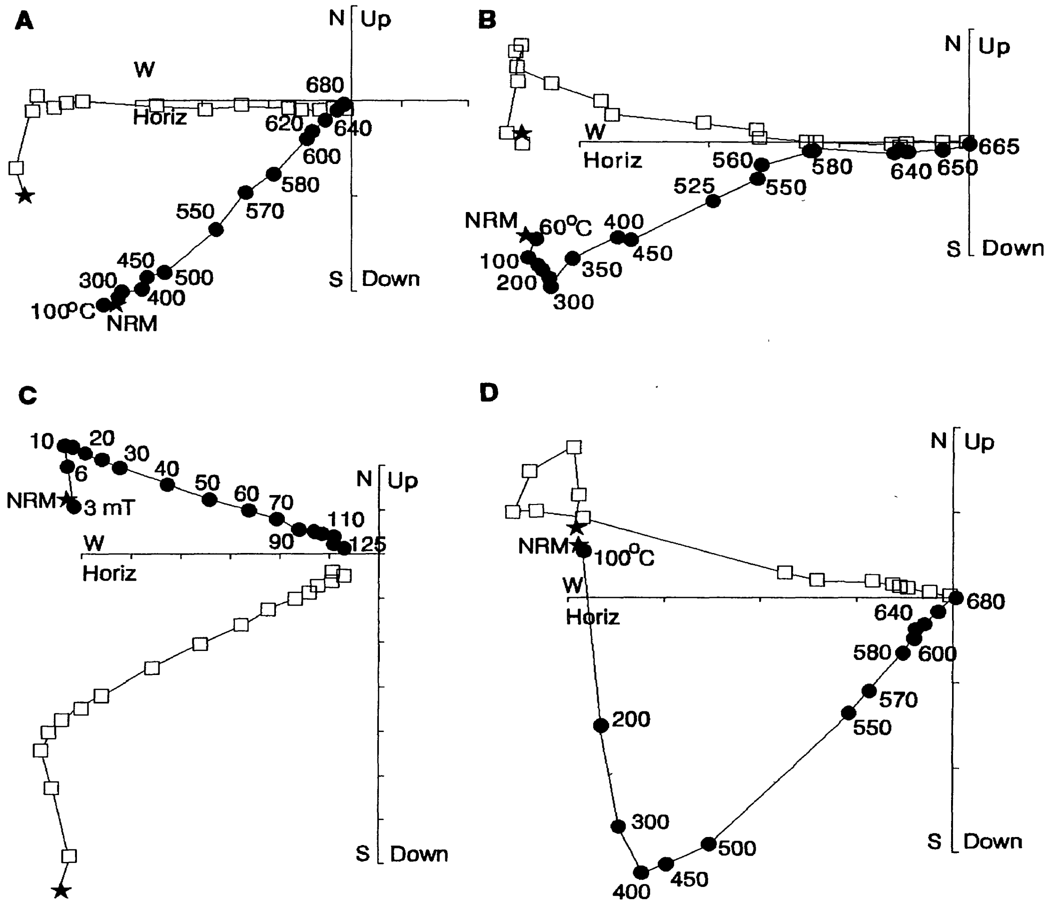

Fig. 2. Orthogonal demagnetization diagrams (geographic coordinates) for selected samples. Open squares represent projections onto the true vertical plane (inclination); closed circles represent projections onto the horizontal plane (declination). One division equals 0.1 A/m. NRM refers to the natural remanent magnetization. (**A**) Site 55, lopolith interior; (**B**) site 30, syenite pod; (**C**) site 50, lava flow; and (**D**) site 45, fused tuff.

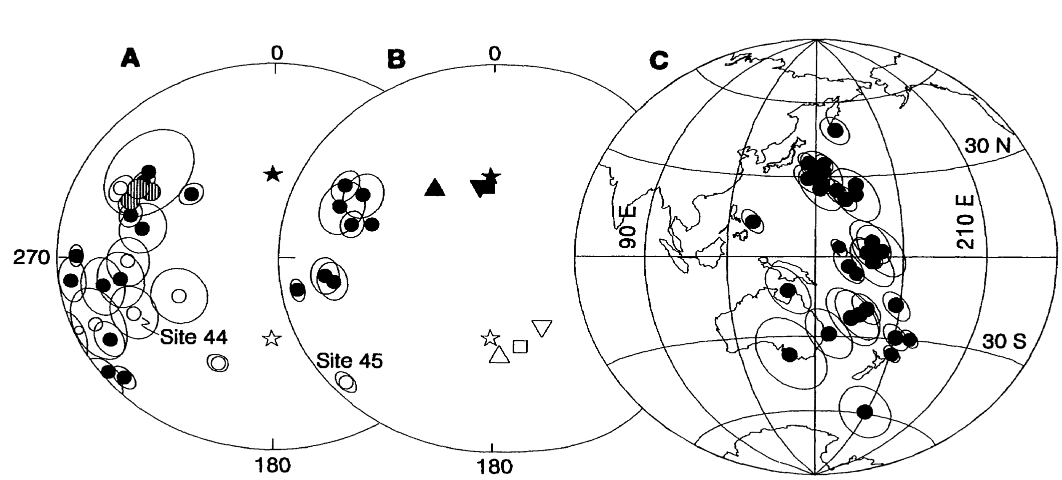

Fig. 3. (**A** and **B**) Equal area projections of site mean directions (geographic coordinates), with cones of 95% confidence, from Paiute Ridge, and (**C**) orthographic global projection of VGPs. Open (filled) symbols refer to upper (lower) hemisphere projections. Lined circles (A) are site means from the three lava flows sampled. Stars (A and B) represent late Miocene axial geocentric dipole direction. Filled square is the Grand Mean direction for the Ammonia Tanks ash-flow tuff; filled inverted triangle is the geographic mean direction for our site 54, which is in this ash-flow tuff; filled upright triangle is the tilt-corrected mean direction for this site. Open square is the Grand Mean direction for the Rainier Mesa ash-flow tuff; open inverted triangle is the mean direction for our site 56, which is in this ash-flow tuff; open upright triangle is the tilt-corrected mean direction for this site. Grand Mean paleomagnetic data from these ash-flow tuffs are from Hudson (*34*).

date mafic magmatism (33). Although we believe that correction of the data for tilt of the ash-flow tuffs is inappropriate, this exercise does not affect the overall pattern of this record, other than shallowing the observed inclinations and moving the VGP path west. On a more regional scale, comparison of the Paiute Ridge magnetizations with data from nonremagnetized host rocks of mid-Miocene age (Fig. 3B) shows that the intermediate directions are not the result of later, widespread remagnetization or of vertical axis rotation. Previous regional paleomagnetic studies (34–36) demonstrate that there has been little vertical axis rotation in the Nevada test site area, even during periods of peak extension.

We obtained $^{40}Ar/^{39}Ar$ isotopic age spectrum data to define (37) the age of the reversal recorded by the Paiute Ridge intrusions and to determine if it could be correlated with a known polarity reversal. A preferred age for the reversal is about 8.6 Ma, and thus, it is possibly associated with chrons C4An (38), C4AR-1, or C4AR-2 (39).

Although the reversal record is not defined by a single intrusion, when considered as an ensemble of random samplings of the geomagnetic field over a short time, the record as defined by VGPs appears to be virtually continuous, especially at low to intermediate latitudes (Fig. 3C). Unfortunately, the data from Paiute Ridge do not allow us to determine unequivocally the chronology of directional changes, and thus, the sense of reversal. The site means for the three lava flows sampled (Fig. 3A) were statistically indistinguishable. Furthermore, we have been unable to find any cross-cutting relations among intrusions. For some sites, progressive demagnetization trajectories are uniform among samples (40); if these reflect a change in field direction with magnetization blocking, we find these results consistent with a normal-to-reverse polarity reversal. Some results from detailed contact tests (Fig. 4), although complex, appear consistent with this sense of reversal.

Most VGPs for Paiute Ridge are at least 45° from the expected axial geocentric dipole position for the late Miocene (Fig. 3C). Centered over about 165°E, the VGP path is confined to west-central Pacific longitudes, resembling VGP paths reported from other localities (8–10) and in particular the Cobb Mountain subchron (11). Whether these preferred paths reflect long-term core-mantle processes or are an artifact of sampling location or recording material is controversial. Because the Paiute Ridge record comes from young, undeformed, intrusive rocks, rather than just lava flows or sediments, it provides independent support for the existence of a preferred VGP path during a reversal. Conversely, several Paiute Ridge VGPs fall close to Hoffman's (12, 13) western Australia subequatorial pole cluster; perhaps the data set identifies a transition record before or after a transient dipolar field state is established. From a single transition record, the nature of the geomagnetic field during a reversal (that is, dipolar versus nondipolar) cannot be determined (6, 41), but the Paiute Ridge data provide a high-quality record showing the recurrence of a preferred path in the late Miocene.

Because the cooling behavior of shallow mafic intrusions is fairly well understood, approximate cooling times imply that the transitional field recorded at Paiute Ridge may have been of a few hundred years duration. For conductive cooling (42), a shallow intrusion with dimensions resembling those of the Paiute Ridge lopolith could cool from emplacement temperatures to about 500°C within 200 to 300 years (43). Smaller intrusions could acquire TRMs in considerably less time. Results from some contact tests [for example, site 53 (Fig. 4)] support rapid field variations during the short time required for the transfer of heat from intrusions. From a physical volcanology standpoint, the paleomagnetic data from Paiute Ridge demonstrate that it is possible for centers of mafic magmatism of these dimensions to have a short emplacement and cooling history. Despite the complex nature of the subvolcanic intrusion geometry at Paiute Ridge, surface products of magmatism at Paiute Ridge were essentially monogenetic in character, consistent with observations of large volume cinder cones of mafic composition (44).

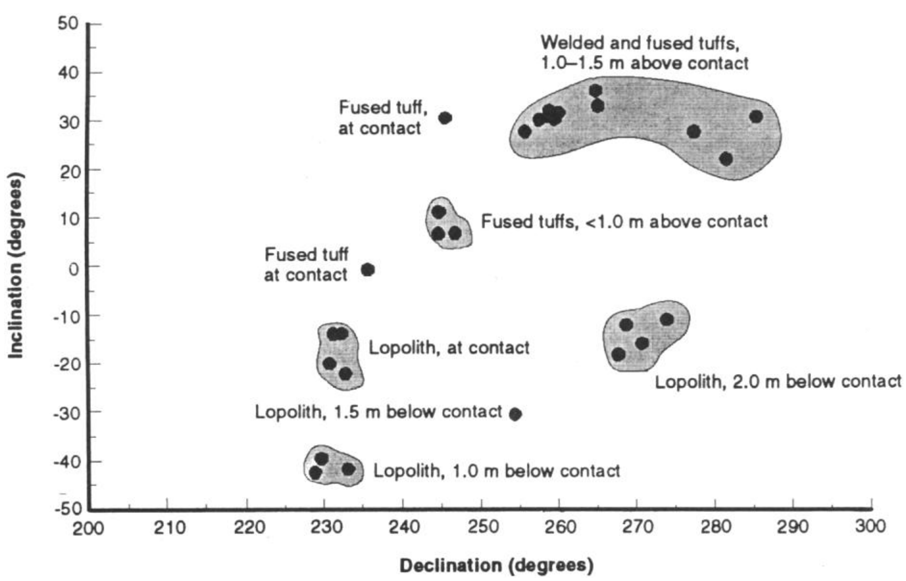

Fig. 4. Plot of direction data from individual samples from site PR53, a west-dipping (25°) contact between the Paiute Ridge lopolith and fused ash-flow tuffs. Each magnetization plotted was isolated by alternating field demagnetization to 125 mT, followed by thermal demagnetization to about 400°C, where over 99% of the magnetization had been removed. Assuming purely conductive cooling, thermally remagnetized host rocks farthest from the contact would be the first to cool through the appropriate range of magnetization blocking temperatures. At this site, these rocks yield magnetizations of moderate positive inclination and west-to-northwest declination (closest to normal polarity); those closer to and at the contact yield magnetizations of shallow inclination and west-southwest declination.

REFERENCES AND NOTES

1. S. W. Bogue, *Nature* **351**, 445 (1991).
2. V. Courtillot, J.-P. Valet, G. Hulot, L.-L. LeMouel, *Eos* **73** (fall suppl.), 337 (1992).
3. K. A. Hoffman, *ibid.* **74** (fall suppl.), 97 (1993).
4. D. Gubbins, *Rev. Geophys.* **32**, 61 (1994).
5. Estimates of reversal duration based on sedimentary records range from about 10,000 to about 5000 years [B. M. Clement and D. V. Kent, *Nature* **310**, 488 (1984); C. Laj, S. Guitton, C. Kissel, A. Mazaud, *J. Geophys. Res.* **93**, 11655 (1988)].
6. S. W. Bogue and R. T. Merrill, *Annu. Rev. Earth Planet. Sci.* **20**, 181 (1992).
7. K. A. Hoffman, *Sci. Am.* **256** (no. 5), 76 (May 1988).
8. B. M. Clement, *Earth Planet. Sci. Lett.* **104**, 48 (1991).
9. E. Tric *et al.*, *Phys. Earth Planet. Inter.* **65**, 319 (1991).
10. C. Laj, A. Mazaud, R. Weeks, M. Fuller, E. Herrero-Bervera, *Nature* **351**, 447 (1991).
11. B. M. Clement and D. G. Martinson, *J. Geophys. Res.* **97**, 1735 (1992).
12. K. A. Hoffman, *Nature* **354**, 273 (1991).
13. ——, *ibid.* **359**, 789 (1992).
14. L. Brown, J. Pickens, B. Singer, *Geology* **22**, 299 (1994).
15. P. Rochette, *Earth Planet. Sci. Lett.* **98**, 33 (1990).
16. C. G. Langereis, A. A. M. Van Hoof, P. Rochette, *Nature* **358**, 226 (1992).
17. However, the combination of a potentially complex, often slow cooling history, distributed blocking temperature spectra for the TRM-carrying mineralogy, and subsequent alteration makes most intrusions inappropriate recorders of field reversals. Exceptions include the reversal recorded by the mid-Miocene Tatoosh granodiorite reported by J. R. Dunn, M. Fuller, H. Ito, and V. A. Schmidt [*Science* **172**, 840 (1971)] and R. Dodson *et al.* [*Geophys. J. R. Astron. Soc.* **53**, 373 (1978)] and the late Miocene Laurel Hill granodiorite reported by H. Ito and M. Fuller [*Palaeogeophysics*, S. K. Runcorn, Ed. (Academic Press, London, 1967), pp. 133–138]. In total, both intrusions give confined VGP paths over western Pacific longitudes.

18. B. M. Crowe, *Am. Nucl. Soc. Proc. High-Level Rad. Waste Manage. Conf.* **1**, 65 (1990).
19. D. T. Vaniman, B. M. Crowe, E. S. Gladney, *Contrib. Mineral. Petrol.* **80**, 341 (1982).
20. All samples were collected as cores with a portable drill and nonmagnetic drill bits. Sample azimuths were obtained with the use of solar compass readings. Samples were cut into standard 2.5 cm by 2.2 cm right-cylinder specimens
21. A three-axis superconducting rock magnetometer (2G Enterprises Model 760R) was used for all remanence measurements. Progressive alternating field and thermal demagnetization was done with commercial 2G Enterprises and Schonstedt instruments, respectively.
22. C. D. Ratcliff, thesis, University of New Mexico, Albuquerque (1993); C. D. Ratcliff, J. W. Geissman, F. Perry, in preparation.
23. We used principal component analysis on discrete trajectories to determine the direction of the best-fit line; lines (always unanchored) with maximum angular deviations greater than 15° were rejected. Where two discrete components of magnetization, one with unblocking temperatures greater than 580°C carried by hematite, were identified in demagnetization diagrams, we always used the magnetite-dominated magnetization isolated below 580°C as that characteristic of the site. Site means were determined by calculating the Fisherian mean of characteristic linear segments from accepted, individual samples. At least 60% of the samples from each site were used in the determination, and site means with α_{95}'s (*28*) greater than 15° were rejected.
24. Isothermal remanent magnetization acquisition experiments show essentially complete saturation by 150 to 250 mT. Hysteresis data from fresh, fine-grained intrusions show that these rocks are characterized by coercivities between 18 and 26 mT, ratios of saturation remanence to saturation magnetization between 0.17 and 0.24, and ratios of coercivity of remanence to coercivity between 2.2 and 2.9, consistent with abundant fine magnetite as the principal remanence carrier.
25. N. D. Watkins, *Geotimes* **4**, 18 (1976).
26. C. W. F. Everitt and J. A. Clegg, *Geophys. J. R. Astron. Soc.* **6**, 312 (1962). Paleomagnetic contact tests are considered positive if, at high statistical confidence, both the intrusion and adjacent host rock have essentially the same remanence direction, yet more distant host rocks retain a distinct preintrusion remanence. Because the magnetic mineralogy usually differs from that of the remagnetized host, agreement of ChRMs in a contact test suggests a primary magnetization for the intrusion.
27. Host ash-flow tuffs and associated deposits in the Paiute Ridge area are poorly welded or poorly indurated, or both. It was difficult to sample these rocks where they had not been baked by the intrusions.
28. [illegible] the cone of 95% [illegible] ean direction; *k* is the concentration parameter.
29. P. L. McFadden and F. Lowes, *Geophys. J. R. Astron. Soc.* **67**, 19 (1981).
30. R. S. Coe and M. Prevot, *Earth Planet. Sci. Lett.* **92**, 292 (1989).
31. A. Stephenson, S. Sadikun, D. K. Potter, *Geophys. J. R. Astron. Soc.* **84**, 185 (1986).
32. R. B. Hargraves, D. Johnson, C. Y. Chan, *Geophys. Res. Lett.* **18**, 2193 (1991).
33. W. J. Carr, *Geol. Soc. Am. Mem.* **176**, 283 (1990).
34. M. R. Hudson, *Geol. Soc. Am. Bull.* **104**, 581 (1992).
35. J. G. Rosenbaum, M. R. Hudson, R. B. Scott, *J. Geophys. Res.* **96**, 1963 (1991).
36. M. R., Hudson, D. A. Sawyer, R. G. Warren, *Tectonics* **13**, 258 (1994).
37. A whole-rock K-Ar age of 8.5 ± 0.3 Ma was reported by B. M. Crowe, S. Self, D. Vaniman, R. Amos, and F. Perry [*J. Geol.* **91**, 259 (1983)]. For our determinations, samples from three sites include sanidine from a fused ash-flow tuff from within 1 m of the upper contact with the Paiute Ridge lopolith, orthoclase from a 4-m-wide pod of coarse-grained syenite, and sanidine from a fused ash-flow tuff within 1 m of the lower contact with a large lopolith. For the two ash-flow tuff sanidine separates, step-heating apparent ages increase progressively with the amount of gas released. The minimum ages are 8.65 (±0.10) and 8.66 (±0.18) Ma (all uncertainties are 2σ). We interpret these dates to be maximum estimates of the age of partial outgassing because each age spectrum dropped until the trapped components clouded the signal. An Arrhenius plot for the sanidine data indicates that there were no distinct small domains, which would result in a well-resolved low-temperature plateau. The orthoclase separate from the syenite pod gave an integrated step-heating date of 8.59 ± 0.07 Ma. The age spectrum data do not define a plateau; the integrated age is based on steps 2 to 14 of the age spectrum, with 12 of the 13 dates in this range falling within the uncertainty.
38. S. C. Cande and D. V. Kent [*J. Geophys. Res.* **97**, 13917 (1992)] give the age of chron C4An as 8.861 to 8.529 Ma.
39. W. B. Harland, A. V. Cox, P. G. Llewellyn, A. G. Smith, R. Walters [*A Geologic Time Scale 1989* (Cambridge Univ. Press, Cambridge, 1990, p. 148)] give the age of chron C4Ar-1 as 8.36 to 8.42 Ma and that of chron C4Ar-2 as 8.66 to 8.71 Ma.
40. For example, at site 43 (results not included in Fig. 3), all samples of remagnetized ash-flow tuffs collected within 2 m of a vertical mafic dike have natural remanent magnetization directions of about $D = 230°$, $I = -5°$. With demagnetization, magnetizations carried by magnetite define great circle trajectories, with over 50° of arc, to values of about $D = 290°$, $I = +35°$.
41. D. Gubbins and G. Sarson, *Nature* **368**, 51 (1994).
42. G. A. Valentine, B. M. Crowe, F. V. Perry, *Am. Nucl. Soc. Proc. High-Level Rad. Waste Manage. Conf.* **2**, 2344 (1992).
43. Models incorporating more complex, convective cooling behavior give higher cooling rates and therefore shorter time periods for magnetization blocking.
44. C. A. Wood, *J. Volcanol. Geotherm. Res.* **8**, 315 (1980).
45. F. M. Byers Jr. and H. Barnes, *U.S. Geol. Surv. Map GQ 552* (1967).
46. Research supported in part by the Yucca Mountain Project Office as part of the Civilian Radioactive Waste Management Program. Additional support provided by the Student Research Allocations Committee and the Department of Earth and Planetary Sciences at the University of New Mexico and by the Geological Society of America. We thank C. Hunt and J. Marvin for assistance with hysteresis measurements.

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Marked Post–18th Century Environmental Change in High-Arctic Ecosystems

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Paleolimnological data from three high-arctic ponds on Cape Herschel, Ellesmere Island, Canada, show that diatom assemblages were relatively stable over the last few millennia but then experienced unparalleled changes beginning in the 19th century. The environmental factors causing these assemblage shifts may be related to recent climatic warming. Regardless of the cause, the biota of these isolated and seemingly pristine ponds have changed dramatically in the recent past and any hopes of cataloging natural assemblages may already be fruitless.

Anthropogenic impacts such as acid haze (*1*), acid snow (*2*), and other pollutants (*3*, *4*) continue to encroach on the high Arctic, and the effects of global changes, such as the predicted greenhouse warming, are expected to be amplified in polar regions (*5*). Because of the absence of long-term monitoring data, it is not directly possible to determine background variability or to track the trajectories of past environmental changes.

In consideration of the paucity of long-term monitoring data for the Arctic (*6*), indirect proxy methods must be used to infer past environmental conditions. The abundance of lakes and ponds in high-arctic regions makes paleolimnological approaches powerful tools to assist interpretations of environmental change (*7*). In this report, we analyze diatom assemblages preserved in high-arctic sediments to document pond ontogeny in this extreme environment.

Diatoms are the most widely used group of biological indicators in paleolimnological research, and they are rapidly becoming a primary indicator group for several large-scale and long-term biomonitoring programs of environmental change (*8*). Diatoms are abundant, ecologically diverse, and are known to respond, in a quantifiable manner, to environmental changes. Moreover, the siliceous cell walls (frustules) of diatoms are usually well preserved in lake and pond sediments.

Ellesmere Island is the northernmost island in the Canadian Arctic archipelago (Fig. 1). Cape Herschel (78°37'N, 74°42'W), located on the east-central coast of the island facing Smith Sound, is a rugged peninsula (about 2 km by 5 km) of high relief (0 to 285 m above sea level) composed of granitic bedrock overlain by small patches of calcareous till (*9*). No glaciers now occupy the cape, but small patches of snow persist throughout the summer, and glaciers are present to the immediate north and south. As in other high-arctic locations, vegetation is scant, consisting mainly of mosses, grasses,

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