iments, V. M. Bryant, Jr., and R. G. Holloway, Eds. (American Association of Stratigraphic Palynologists, Calgary, Ontario, 1985), pp. 39–70.
6. T. C. Atkinson, K. R. Briffa, G. R. Coope, *Nature* **325**, 587 (1987).
7. A. L. Washburn, *Earth Sci. Rev.* **15**, 327 (1979)
8. U. Siegenthaler, U Eicher, H Oeschger, *Ann Glaciol.* **5**, 149 (1984).
9. T. E. Cerling, *Earth Planet. Sci. Lett.* **71**, 229 (1984).
10. H. P. Schwarcz, in *Handbook of Environmental Isotope Geochemistry*, P. Fritz and J. Ch. Fontes, Eds. (Elsevier, Amsterdam, 1986), vol. 2, pp. 271–303.
11. C. J. Yapp and S. Epstein, *Earth Planet. Sci Lett.* **34**, 333 (1977).
12. K. Rozanski, *Chem. Geol.* **52**, 349 (1985)
13. S. Oana, *J. Earth Sci. Nagoya Univ.* **5**, 103 (1957).
14. R. Sugisaki, *Am. J. Sci.* **259**, 144 (1961).
15. E. Mazor, *Geochim. Cosmochim. Acta* **36**, 1321 (1972).
16. J. N. Andrews and D. J. Lee, *J. Hydrol.* **41**, 233 (1979).
17. J. Rudolph, H. K Rath, C. Sonntag, in *Isotope Hydrology* (International Atomic Energy Agency, Vienna, 1984), pp. 467–477.
18. M. Stute and J. Deák, *Radiocarbon* **31**, 902 (1989).
19. T. H. E. Heaton, A. S. Talma, J. C Vogel, *Quat. Res.* **25**, 79 (1986).
20. S. H. Hamlin, *Rep. 175* (Bureau of Economic Geology, Austin, TX, 1988).
21. F. J. Pearson and D. E. White, *Water Resour. Res.* **3**, 251 (1967).
22. J. E. Brinkman, thesis, University of Arizona, Tucson (1981).
23. G. Marquardt and E. Rodriguez, Jr., "Groundwater resources of the Carrizo aquifer in the Winter Garden area of Texas" (*Rep. 210*, vol 2, Texas Water Development Board, Austin, 1977)
24. M. Stute, thesis, University of Heidelberg (1985) (in German).
25. During its underground passage, ground water accumulates nonatmospheric noble gases that are produced in the soil matrix by nuclear processes or diffused from deeper layers of the earth's crust or mantle. Excesses of Ne, Ar, Kr, and Xe due to these processes are rarely detected and can easily be separated from the atmospheric noble gases owing to their different isotopic composition. However, He may show concentrations several orders of magnitude above the solubility equilibrium level and the amount of atmospheric He cannot be isolated. Also, the solubility of He is relatively insensitive to temperature. Therefore, He cannot be used in paleotemperature studies. The other process contributing to the concentrations of all noble gases is excess air formation due to dissolution of small air bubbles caused by fluctuations of the ground-water table [T. H. E. Heaton and J. C. Vogel, *J. Hydrol.* **50**, 201 (1981)]. In most cases this process can be easily corrected for, because the noble gas concentration ratio of the excess air component equals that of air, whereas the solubility equilibrium component is fractionated with respect to air as a result of the different solubilities of the single noble gases. For the data set from the Carrizo aquifer described below, excess air contributes on average (numbers in parentheses. maximum) 22(34)% to the Ne, 8(13)% to the Ar, 4(8)% to the Kr, and 3(5)% to the Xe concentration of the water sample. Because solubility and its temperature dependence increase with atomic mass, the Ne concentrations are most sensitive to the addition of excess air whereas the Xe concentrations are mainly controlled by temperature. To separate the two unknowns, two noble gas concentrations, ideally Ne and Xe, are needed.
26. The Ar concentrations appear to be on the average 2% too low to be consistent with the other noble gases. The reason is probably an incomplete removal of chemically active gases from the gas sample, these gases influence the sorption characteristics of the charcoal trap used to separate the individual noble gases. If the Ar value is used for calculation of the noble gas temperatures, error bars become slightly larger and the noble gas temperatures are shifted to lower values, on average by 0.37°C This shift would not affect our conclusions.
27. M Stute and C. Sonntag, in *Isotopes of Noble Gases as Tracers in Environmental Studies* (International Atomic Energy Agency, Vienna, in press)
28. G D. Smith, F. Newhall, L H Robinson, D. Swanson, *U S Dep. Agric Soil Conserv Serv. Rep. SCS-TP-144* (1964)
29. *Climates of the States* (National Oceanic and Atmospheric Administration, Washington, DC, 1978), vol 2.
30. J Hansen and S. Lebedeff, *J. Geophys Res.* **92**, 13345 (1987)
31. Dating of ground water by ^{14}C is complicated by the complex hydrochemistry of C in the groundwater system We applied several recent ^{14}C correction models [see F M Phillips, M. K. Tansey, L. A. Peeters, S Cheng, A Long, *Water Resour. Res.* **25**, 2259 (1989) for a summary] to Pearson and White's data (*21*) and obtained a standard deviation of ±2000 years, which may serve as an estimate of the uncertainty in ^{14}C ages due to C hydrochemistry.
32. F M. Phillips, thesis, University of Arizona, Tucson (1981)
33. R F Weiss, *J. Chem Eng. Data* **16**, 235 (1971)
34. ______, *Deep-Sea Res.* **17**, 721 (1970)
35. H L Clever, Ed., *Krypton, Xenon, and Radon—Gas Solubilities*, Solubility Data Series 2 (International Union of Pure and Applied Chemistry, Pergamon, Oxford, 1979)
36. We thank F M. Phillips, F J. Pearson, Jr , R. Raabe, L Love, L N Plummer, C Sonntag, M Groning, A Suckow, K. Osenbruck, K. Pitz, H Jacob, and Texas farmers for their valuable contributions to this work This project was supported by NSF contract ATM 91-05538, the Lamont-Doherty Center for Climate Research, and the Alexander V Humboldt Foundation Lamont-Doherty Geological Observatory contribution 4928

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Geothermal Evidence from Canada for a Cold Period Before Recent Climatic Warming

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Three deep boreholes in a small area in Quebec, each having two high-accuracy temperature logs separated by 22 years, allow reliable determination of the ground surface temperature history during the past few centuries. The temperature logs show that the recent climatic warming was preceded by a cold period near the end of the 19th century in this area. The presence of such a cold period is also suggested by borehole temperature data from other areas in Canada.

Whether the climatic warming during the past hundred years is caused entirely by human activities is uncertain. Early instrumental observations indicate that surface air temperatures were low near the end of the 19th century (*1*, *2*), but the scarcity of meteorological stations before 1880 precludes a meaningful global analysis (*3*). However, the presence of a cold period in various parts of the world at that time has also been suggested by some but not all studies using proxy methods (*4–6*). These data suggest that the recent warming might be partially or mostly a return from a cold period. In this report, we describe geothermal evidence from Quebec and other areas in Canada for the presence of a cold period before warming near the end of the 19th century. The estimation of ground surface temperature (GST) histories from precise borehole temperature measurements was first attempted in 1969 (*7*) and 1971 (*8*), but its importance had not been widely appreciated until Lachenbruch and Marshall (9) provided evidence from the Alaskan Arctic for climatic warming during the past several decades. Recent developments include the use of a model that realistically simulates lithologic layers in the crust and flexible inversion methods (*10–12*) and estimation of GST over a vast area (*13*). Compared to proxy methods, this technique involves simple physics (heat conduction) and is not subject to uncertainties related to calibration. However, the estimated GST history is necessarily a highly smoothed version of the real one and provides an interesting contrast with temperature records that are based on proxies.

In 1990, we relogged 12 boreholes that had been logged in 1968 as part of a detailed geothermal study (*14*) near Lac Dufault, Quebec (Fig. 1), in an Archean volcanic belt of the Superior Province of the Canadian Shield. Repeat temperature logs, especially those separated by more than 20 years, are desirable for three reasons. (i) They better constrain the GST estimation because not only the curvatures in each temperature profile, but also the temperature changes with time at given depths, contain information on the past GST. (ii) They help to identify transients in subsurface temperatures that are due to climatic changes as opposed to curvatures in the temperature profiles caused by terrain effects and conductivity variations. (iii) They allow accurate identification of disturbances by water flow. Three of the 12

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holes, 022, 024, and 389 (Fig. 2), were free of water flow disturbance and were used for GST estimation. The temperature measurement, typically at an interval of 10 m in 1968 and 3 m in 1990, has an absolute inaccuracy of <0.026 K and a relative inaccuracy of <0.006 K. Thermal conductivities were measured on core samples (disks) with a divided bar at about every 30 m in each borehole. The samples were water-saturated after vacuum removal of trapped air before measurement, and measurement of individual disks to an uncertainty of 5% is expected.

We used a spectrum inverse method (*12*) for the simultaneous inversion of the two temperature logs from each borehole. The rock medium is assumed to have a laterally homogeneous layered structure, so that heat conduction is vertical. Given measured temperature-depth profiles, we estimated the spectra of the unknown GST using a Bayesian type generalized least squares theory (*15*). The determination of GST from subsurface temperatures is an ill-posed inverse problem, and proper constraints are required for a stable and unique solution. Constraints on the GST, thermal properties, and borehole data are given in the form of a priori Gaussian probabilities. Basic constraints on the unknown GST are its smoothness and boundedness. We introduced these constraints probabilistically by regarding the a priori GST time series as a stationary Gaussian process with a Hamming autocovariance function. There are two important parameters in the autocovariance function: the time domain standard deviation (SD) and the cut-off period P_c. The GST at any time falls within 1 SD of the a priori GST, a constant with time, with a probability of about 68%. The SD was set to 1.58 K in our calculations, reflecting our a priori estimate of the magnitude of the GST variation during the past several thousand years. Using a different SD will change the amplitude of the estimated GST history only slightly. The cut-off period determines the smoothness of the GST and filters out any GST variation with shorter periods. We used a cut-off period of 100 years. A smaller P_c enhances the resolution of the recent GST and reduces the resolution back in time but does not affect the overall shape of the GST, which is constrained by two temperature logs 22 years apart.

The a priori conductivity value used for each layer was the average of the measurements across the layer; the SD, due to measurement inaccuracy and the scattering of the values around the average, is 0.2 W m^{-1} K^{-1}. The a priori values of thermal diffusivity $\alpha = \lambda/\rho c$ that we used are derived from conductivity (λ) and are based on a thermal capacity (ρc) of 2.3 MJ m^{-3} K^{-1}, a value typical of continental rocks, where ρ is the density and c is the specific heat. The estimated GST is sensitive to the uncertainties in conductivities but much less sensitive to those of the diffusivities (*12*). To account for the possible small-scale variation of thermal conductivity not described by the layered model, we have assigned a standard deviation of 0.01 K to the temperature data, which is larger than the relative inaccuracy of the temperature measurements. The differences between the measured borehole temperatures and those calculated from the estimated GSTs are in general much smaller than this SD. Radioactive heat generation of rocks at Lac Dufault is on the order of 0.2 $\mu W\ m^{-3}$ and can be safely ignored.

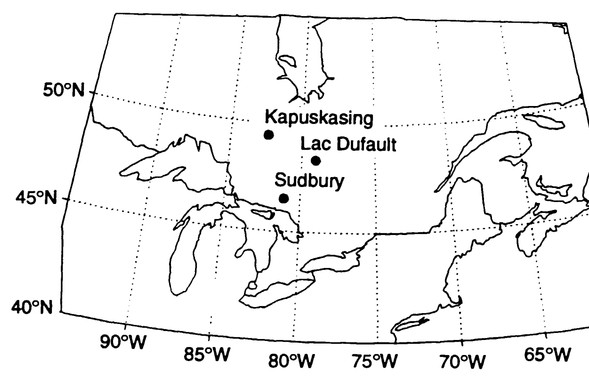

Fig. 1. Map of eastern Canada showing borehole sites.

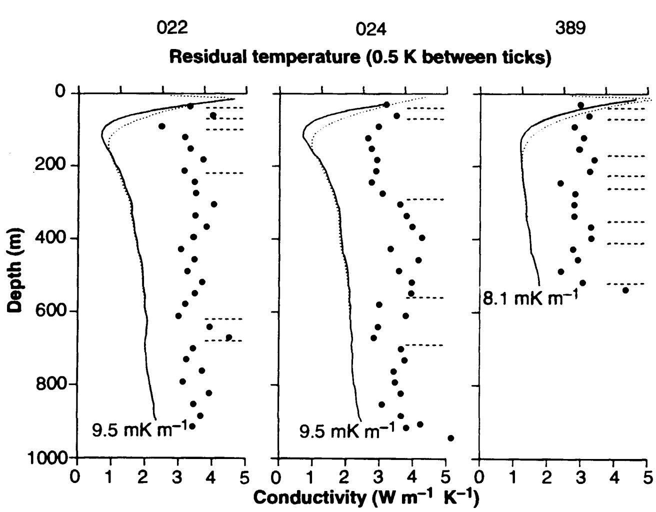

Fig. 2. Temperature and thermal conductivity data (solid circles) from three boreholes at Lac Dufault, Quebec. Temperatures are shown as residuals to allow an expanded scale to be used. The residuals were obtained by arbitrarily removing a constant gradient (shown at the bottom of each curve) from the measured temperatures. Solid curves: June 1968; dotted curves: May 1990. The layered structure used in the inversion of data is also shown by dashed lines.

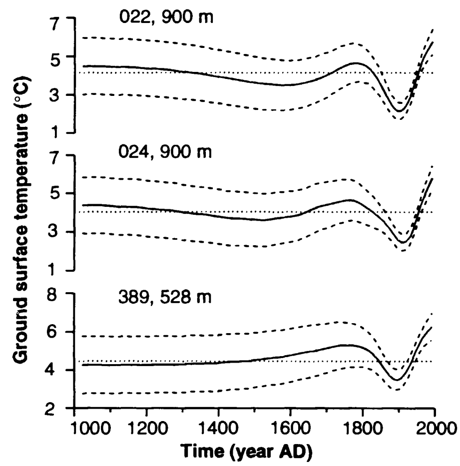

Fig. 3. Ground surface temperature histories estimated from three boreholes at Lac Dufault. The dashed lines represent 1 SD. The site number on each curve is followed by the borehole depth in meters. The estimated mean surface temperature is shown by a dotted line. The SDs for the mean surface temperatures are typically 0.2 K.

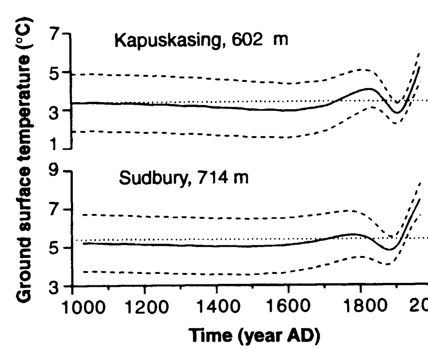

Fig. 4. Ground surface temperature histories estimated from two boreholes in Ontario as shown in Fig. 1. For explanation, see legend to Fig. 3.

The estimated GSTs from all the boreholes are similar (Fig. 3). The record of the GSTs of the most recent hundred years agrees with the trend of the average surface air temperatures of the Northern Hemisphere (3) and that of central Ontario (*16*), the nearest region where century-long reliable meteorological data are available. All three holes show a cold period near the end of the 19th century, which is in agreement with tree-ring data from the United States and southwestern Canada (5). Tree-ring data from the high-latitude area of Canada and Alaska (*17–19*) also suggest such a cold period but with a temperature minimum about 50 years earlier. The two deeper holes, 022 and 024, show a less well resolved older cold period ~400 years ago, which agrees with what has been identified by historical and glacial studies as the Little Ice Age (*20, 21*). Because of the limitation imposed by borehole depths (shown on each curve) and the nature of heat diffusion, GST variations before A.D. 1500 cannot be resolved with confidence.

The land where the boreholes were drilled is low and flat in the south and higher and more rugged in the north, with an average difference in elevation of about 70 m. Boreholes 022 and 024 are located in the flat low area; therefore, the topographic effect on the geothermal gradient is negligible. Hole 389 is at a higher elevation and on a south-facing slope. Stronger solar radiation on the slope causes the upper part of the temperature profile to be "bent" toward the warm side, which results in a higher mean surface temperature and an apparent slight warming trend in the GST. Because the sites that were investigated are covered by snow in winter, the annual mean GST is higher than that of the surface air temperature.

The Lac Dufault paleotemperature results are considered the most reliable that are available because of the unmatched quality of the thermal data. We have also studied deep borehole data from another 19 sites in Canada. Although conditions are not as favorable at any of these sites as at Lac Dufault, GST estimates from most of them do show a cold period before the recent climatic warming. Five of the sites yield results nearly identical to those of Lac Dufault for the last 200 years. The GSTs from the two sites nearest Lac Dufault (Fig. 4) substantiate the Lac Dufault results, although their uncertainties are larger.

In order to determine whether the recent warming has been caused by human activities, we need to know whether the current temperature and the current rate of temperature increase are significantly above normal, that is, the average temperature and the average rate of temperature increase during the centuries or millennia before industrialization. Because of the decrease in the resolution of GST back in time, we cannot assess the rate of increase. However, the long-term mean GST can be estimated, and this can be compared with the current temperatures. The deeper the borehole, the better is the mean GST that is determined, but our test using a 3-km hole shows that this value is robust if the borehole is deeper than 600 m. By a comparison of temperatures only (Figs. 3 and 4), the recent warming has indeed resulted in a temperature that is 1° to 2°C higher than average, but the warming is partially a recovery from a cold period.

REFERENCES AND NOTES

1. P. D. Jones *et al.*, *J. Clim. Appl Meteorol* **25**, 1213 (1986)
2. H. W. Ellsaesser, M. C. MacCracken, J. J. Walton, S. L. Grotch, *Rev. Geophys* **24**, 745 (1986).
3. J. Hansen and S. Lebedeff, *J. Geophys. Res.* **92**, 13345 (1987).
4. L. M. Libby, in *Climate History, Periodicity, and Predictability*, M. Rampino, J. Sanders, W. Newman, L. Konigsson, Eds. (Van Nostrand Reinhold, New York, 1987).
5. H. C. Fritts and J. M. Lough, *Clim Change* **7**, 203 (1985).
6. E. Cook *et al.*, *Science* **253**, 1266 (1991)
7. A. E. Beck and A. Judge, *Geophys. J. R. Astron Soc.* **18**, 145 (1969)
8. V. Cermak, *Palaeogeogr Palaeoclimatol Palaeoecol* **10**, 1 (1971)
9. A. H. Lachenbruch and B. V. Marshall, *Science* **234**, 689 (1986).
10. S. B. Nielsen and A. E. Beck, *Tectonophysics* **164**, 345 (1989)
11. P. Y. Shen and A. E. Beck, *J. Geophys. Res* **96**, 19965 (1991).
12. K. Wang, *ibid* **97**, 2095 (1992).
13. H. Beltrami and J. C. Mareschal, *Geophys Res Lett* **4**, 605 (1991)
14. T. J. Lewis and A. E. Beck, *Tectonophysics* **41**, 41 (1977)
15. A. Tarantola and B. Valette, *Rev Geophys Space Phys* **20**, 219 (1982)
16. R. W. Longley, in *Proceedings of Toronto Meteorological Conference* (Royal Meteorological Society, London, 1953).
17. G. C. Jacoby and E. R. Cook, *Arct Alp. Res.* **13**, 409 (1981)
18. ——, L. D. Ulan, *Quat Res. (NY)* **23**, 18 (1985).
19. G. C. Jacoby and R. D'Arrigo, *Clim Change* **14**, 39 (1989)
20. H. H. Lamb, *Climate Present, Past and Future* (Methuen, London, 1977), vol. 2.
21. J. M. Grove, *The Little Ice Age* (Methuen, London, 1988)

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Stress Diffusion Along the San Andreas Fault at Parkfield, California

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Beginning in January 1990, the epicenters of microearthquakes associated with a 12-month increase in seismicity near Parkfield, California, moved northwest to southeast along the San Andreas fault. During this sequence of events, the locally variable rate of cumulative seismic moment increased. This increase implies a local increase in fault slip. These data suggest that a southeastwardly diffusing stress front propagated along the San Andreas fault at a speed of 30 to 50 kilometers per year. Evidently, this front did not load the Parkfield asperities fast enough to produce a moderate earthquake; however, a future front might do so.

Since mid-1987, the microearthquake activity of the San Andreas fault near Parkfield, California, has been monitored by the use of a ten-station network of borehole seismographs (Fig. 1, A and B). This region has the potential for moderate earthquakes at some time in the next few years (*1–3*). On the basis of magnitude-distance statistics, the distribution of earthquakes detected by the network is complete to roughly magnitude $M = 0$ near the center of the network and $M = 0.25$ overall (4). By the beginning of 1989, we had identified two seismically quiet patches of fault on which the future earthquakes might take place (4). The hypocentral locations of earthquakes observed since 1989 have not filled in the two aseismic patches we found then. Instead, they have begun to define clusters of intense activity, particularly north of the network.

Before 1990, the cumulative moments (effectively the sum of the fault areas times their slips) in the regions around the patches increased at roughly constant rates, with one exception, a large step in the cumulative moment produced by an $M \sim 4$ earthquake in May 1989, midway between Middle Mountain and Gold Hill. After the beginning of 1990, the cumulative moment rates in the Parkfield area began changing as a function of both time and location. Between January 1990 and May 1991, we observed a rapid increase in the cumulative moment

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