be stable and will not generate earthquakes. The value of L at the stability transition, L_t, depends on the assumed value of $(a-b)$, the parameter defining the slip velocity dependence of friction[4], and is $\sim 10^{-1}$ m (see Fig. 1). The result indicates that a stability transition will occur at a depth of ~2.5 km, which is additional to that expected from the action of fault gouge in changing the sign of $(a-b)$[13].

This effect may be estimated in a different way, from an expression for the maximum size of a stable fault patch, which is also a function of L and p. Combining equation (3) with equation (14) of ref. 14, we obtain

$$r_c = \frac{0.37E^3\kappa}{p^3(b-a)} \qquad (4)$$

The transition will occur at a depth equal to this maximum stable dimension. Assuming a representative value of $(b-a) = 0.005$, equation (4) indicates that this depth is ~3.5 km, in reasonable agreement with our first estimate.

Previous modelling studies have assumed a constant value of L. Here we show that it must decrease with depth. This will result in a degree of fault instability that increases with depth, which will enhance the tendency for large earthquakes to nucleate near the base of the seismogenic region[15]. An earthquake nucleation model[14] based on this type of friction law indicates that during nucleation there will be a precursory slip, $u_n \approx 5L$, on a patch of radius $r_n \approx 10^5 L$. From the values of L estimated here, $5 > u_n > 0.5$ cm and $1 > r_n > 0.1$ km, with the smaller values obtaining at greater depth, where large earthquakes tend to nucleate. This will make more difficult the problem of detecting, with surface measurements, precursory phenomena resulting from nucleation.

This work was supported by the US Geological Survey. I thank N. Yoshioka for early discussions of this problem, and F. Chester, K. Evans, A. Lerner-Lam and J. Dieterich for helpful reviews.

Received 16 August; accepted 7 November 1988.

1. Dieterich, J. H. *J. geophys. Res.* **84**, 2161-2168 (1979).
2. Ruina, A. L. *J. geophys. Res.* **88**, 10359-10370 (1983).
3. Tse, S. T. & Rice, J. R. *J. geophys. Res.* **91**, 9452-9472 (1986).
4. Stuart, W. D. *PAGEOPH* **126**, 619-641 (1988).
5. Brown, S. R. & Scholz, C. H. *J. geophys. Res.* **90**, 12575-12582 (1985).
6. Scholz, C. H. & Aviles, C. A. in *Earthquake Source Mechanics* (eds Das, S., Boatwright, J. & Scholz, C.) 147-155, (Am. Geophys. Un. Washington, DC, 1986).
7. Rabinowicz, E. *J. appl. Phys.* **22**, 1373-1379 (1951); *J. appl. Phys.* **27**, 131-135 (1956); *Proc. phys. Soc. Lond.* **71**, 668-675 (1958).
8. Okubo, P. G. & Dieterich, J. H. *J. geophys. Res.* **89**, 5817-5827 (1984).
9. Walsh, J. B. *J. geophys. Res.* **70**, 381-389 (1965).
10. Brown, S. R. & Scholz, C. H. *J. geophys. Res.* **90**, 5531-5545 (1985).
11. Mandelbrot, B. B. *The Fractal Geometry of Nature* 236 (Freeman, San Francisco, 1983).
12. Power, W. L., Tullis, T. E. & Weeks, J. D. *J. geophys. Res.* **93** (in the press).
13. Marone, C. & Scholz, C. H. *Geophys. Res. Lett.* **15**, 621-624 (1988).
14. Dieterich, J. H. in *Earthquarke Source Mechanics* (eds Das, S., Boatwright, J. & Scholz, C.) 37-47 (Am. Geophys. Un. Washington, DC, 1986).
15. Das, S. & Scholz, C. H. *Nature* **305**, 621-623 (1983).

Pre-Incan agricultural activity recorded in dust layers in two tropical ice cores

L. G. Thompson, M. E. Davis, E. Mosley-Thompson & K-b. Liu*

Byrd Polar Research Center, 125 South Oval Mall, Ohio State University, Columbus, Ohio 43210, USA
* Department of Geography and Anthropology, Louisiana State University, Baton Rouge, Louisiana 70803, USA

In South America, no documentary records survive from before the incursion of the Spaniards in the mid-sixteenth century. Knowledge of pre-Hispanic civilizations in this region comes largely from archaeological excavations, which may now be supplemented by information recorded in two ice cores drilled in the Quelccaya ice cap in southern Peru (Fig. 1)[1,2]. A 1,500-year record of particle concentrations and conductivity in these cores shows two major dust episodes, each lasting about 130 years, centred at AD 920 and 600. Here we examine these dust events in the light of oxygen isotope and net accumulation records, and suggest a correlation with pre-Incan agricultural activity. The annual net accumulation record for AD 1915–1984 compares well with annual changes in Lake Titicaca water levels and with annual precipitation at El Alto (LaPaz, Bolivia), suggesting that the 1,500-year net accumulation record from Quelccaya may serve as a proxy for water level changes in Lake Titicaca. The ice-core record suggests that climatic variability, reflected in lake level changes, has strongly influenced fluctuations in agricultural activity in southern Peru.

The ice-core timescales were reconstructed from a combination of stratigraphic, microparticle concentration (MPC), liquid conductivity (C), and oxygen isotopic (δ^{18}O) data[2]. As the annual layers thin toward the bottom, the timescales become less precise[1]. The records derived from the Quelccaya ice cores show naturally occurring events—marked by increased MPC—such as droughts, the Little Ice Age and volcanic eruptions[1,2]. Here we concentrate on two unusually intense dust peaks occurring before AD 1000 and explore a possible relationship to pre-Incan cultural activity.

Figure 2 illustrates the decadal averages from AD 470 to 1980 for total MPC, C, δ^{18}O and net accumulation (metres of ice-equivalent). From AD 1000 to 1980 the decadal averages for both cores are combined to produce a composite record. From AD 470 to 1000 only core 1 is used, as the summit core contains a discontinuity at 153.68 m (corresponding to AD 745)[1]. The most significant climatic event in the past 1500 years is the Little Ice Age, dated here as AD 1500-1900[2]. Nevertheless, the dust events of the sixth and tenth centuries, recorded by insoluble (MPC) and soluble (C) particles dominate all other features (Fig. 2). These peaks exhibit the greatest intensities around AD 920 and 600 and each lasts ~130 yr. The tenth century dust event is equally prominent in both cores.

Little evidence is available to determine the cause of these events, as no written records exist from pre-Hispanic times.

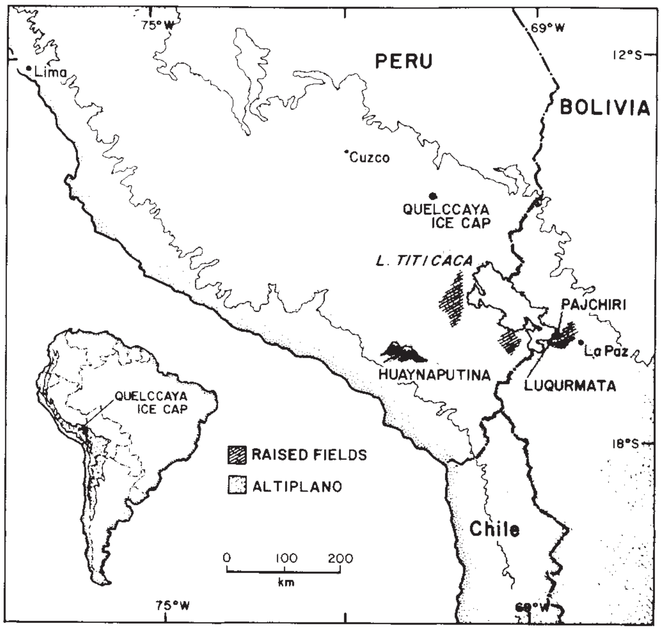

Fig. 1 Map showing the Quelccaya ice cap on the altiplano of Southern Peru ($13^{0}56^{1}$ S, $70^{0}50^{1}$ W, 5,670 m elevation) relative to Lake Titicaca and the raised fields.

© 1988 Nature Publishing Group

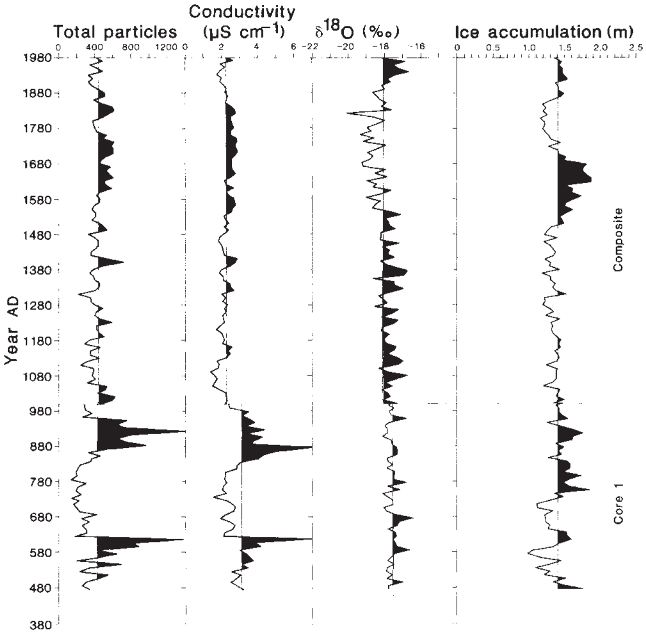

Fig. 2 Profiles of decadal averages from AD 470 to 1980 of total particles (≥0.63 to ≤16.0 μm in diameter per ml of sample × 10^3), conductivity, $\delta^{18}O$ and net accumulation (metres of ice equivalent). The dust events of AD 920 and 600 are dominant in the microparticle and conductivity profiles.

Therefore, we investigated first the natural causes of perturbations, as characterized by increased MPC and C, observed in the more recent portions of the Quelccaya records.

Water samples from the two dust peaks and from intervening sections in the pre-AD 1000 section of core 1 were examined by light microscopy and scanning electron microscopy (SEM). The particles appear to derive from wind-blown dust, with minor amounts of diatoms and volcanic particles also present. Volcanic activity, however, was not the primary source for these events. Although several active volcanoes are located in southern Peru, the dominant easterly flow inhibits deposition on Quelccaya. Only the eruption of Huaynaputina in AD 1600 (Fig. 1) is distinctly observed in the MPC and C records of the ice cores[2].

In more recent portions of the core, prolonged droughts produced high soluble- and insoluble-particle concentrations[3]. But the accumulation profiles demonstrate, when examined on an annual basis, that the peak influx of dust for both events (AD 600 and AD 920) coincided with higher-than-average accumulation. Similarly, the corresponding oxygen isotope record shows no evidence of brief cold episodes during those periods. This behaviour is not characteristic of the neoglacial period—the 'Little Ice Age', AD 1490-1900 (Fig. 2)—during which the increase in dust was associated with the cooler temperatures inferred from lower $\delta^{18}O$ (ref. 2).

These two earlier dust events do not appear to be attributable directly to natural sources (such as drought or volcanic activity), and we therefore consider the possibility of cultural impact on the environment as a major factor in the production of these events.

The Lake Titicaca region, ~200 km south-east of Quelccaya, was once a major centre of pre-Incan cultural and agricultural activity. The altiplano is a cold, wind-swept environment subject to a marked alternation between dry (April-October) and wet (November-March) seasons. The high plateau ranges in elevation from 3,500 m to over 4,000 m and exhibits substantial diurnal temperature variation. During the growing season, frosts and sporadic hailstorms may cause extensive crop damage[4]. The topography, elevation and attendant cold climate of the altiplano severely constrain agriculture in the Titicaca basin. For example, only hardy tubers such as potato, oca, olluco and mashwa, and the unique cold-adapted chenopod grains, quinoa and caniwa, can be readily cultivated. These crops, cultivated extensively in pre-Hispanic times, continue to play a prominent role in the diet of the modern inhabitants of the altiplano[5,6].

Around the edges of Lake Titicaca, ridged fields with distinctive patterns have been observed since 1966 (Fig. 1). In pre-Hispanic time, they covered at least 202,800 acres over the Western lake plain at elevations of 3,800-3,850 m (ref. 7) making them the most extensive of their kind in South America[8]. Studies[9,10] of human activities at Luqurmata and Pajchiri sites on the southern end of Lake Titicaca demonstrate that the peak of raised field construction and maintenance of Tiwanaku V occurred mainly between AD 400 and 900, and that most of the fields were abandoned from AD 900 to 1100. There is no consistent archeological picture, however, of when other sites around the Lake Titicaca basin were occupied. The finer particle sizes in the ice cores from the AD 920 and 600 dust events suggest a lake sediment source.

Under current conditions crops are grown in the rainy season (November-April), when the easterly winds dominate. The crops are harvested during the dry season and the winds come from the south to north-west off the dry altiplano when the fields are bare. The annual dust layers on Quelccaya currently form during the dry season[11]. Water levels in Lake Titicaca, measured monthly from 1914 to present, show a low water level during each year's dry season[12]. In the past, the combination of extensive use of fields and the exposure of large areas of silty sediment as a result of low water levels in regional lakes (including Lake Titicaca) could have produced an important dust source in this region. Located upwind of the ice cap, these fields would increase dust deposition in the snowfall.

The size distributions of these dust peaks were measured in 14 ranges from 0.63 to 16.0 μm in diameter. The volume per cent distributions are bimodal, with peaks in both fine (0.63-1.6 μm) and coarse (8-16 μm) fractions, but with the former dominating. In contrast, the distributions in most other sections of the core are generally skewed towards the coarser sizes. SEM and light microscopy observations confirm these analyses. The finer particle sizes in the ice cores from the AD 920 and AD 600 dust events therefore suggest a lake sediment source. Furthermore, during expanded use of agricultural fields, pastures would be forced to higher elevations and may have served as dust sources when overgrazing occurred.

Table 1 Coefficients of determination (R^2) for the AD 1915-1961 records of net accumulation from Quelccaya, changes in Lake Titicaca water levels, and precipitation measured at El Alto, Bolivia

	Net accumulation (3-yr r.m.)*	Net accumulation†	Lake T‡	Lake T(+1)§	Lake T(+2)‖
El Alto¶	0.124	0.116	0.325	0.235	0.022
Net accumulation (3-yr r.m.)*		0.172	0.302	0.324	0.230
Net accumulation†			0.160	0.138	0.014

* Three-year running mean. † Quelccaya net accumulation (standard deviations). ‡ Lake Titicaca annual water level (mm) changes. § Lake T with one-yr lag. ‖ Lake T with 2-yr lag. ¶ Annual precipitation (mm), El Alto (La Paz, Bolivia).

© 1988 Nature Publishing Group

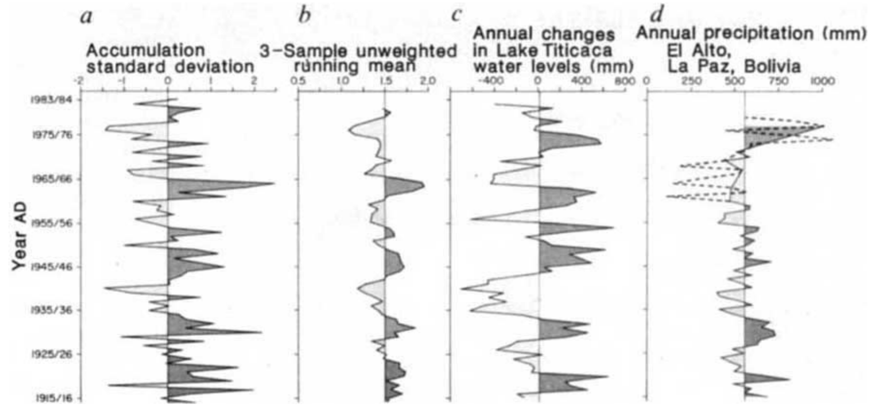

Fig. 3 Quelccaya accumulation record (mm ice equivalent) for AD 1915-1984, presented as standard deviations of annual values (*a*) and the three-year running mean (*b*), is compared with annual changes in Lake Titicaca water levels (mm) (*c*) and annual precipitation (mm) (*d*) at El Alto (La Paz, Bolivia). Dashed line in (*d*) represents years with incomplete data.

The Quelccaya accumulation record for AD 1915-1984 is compared with the annual changes in Lake Titicaca water level in Fig. 3. The coefficient of determination ($R^2 = 0.32$) between annual precipitation at El Alto (La Paz, Bolivia) and Lake Titicaca level changes is similar to that ($R^2 = 0.30$) between the three-year running mean of accumulation from Quelccaya and the Lake Titicaca level changes. The coefficients of determination (Table 1) are highest between annual changes in Lake Titicaca water levels (for both the current year and a one-year lag), the Quelccaya three-year average of net accumulation, and annual precipitation at El Alto. Thus, for the period of comparison, the accumulation record from Quelccaya ice cores provides a reasonably accurate record of regional precipitation, suggesting that the 1500-yr Quelccaya net balance record can be used as a proxy for lake-level changes in Lake Titicaca. The relatively low correlations between changes in the annual water levels in Lake Titicaca, the measured precipitation at El Alto, and the Quelccaya net balance record probably result because the lake level is determined not only by regional precipitation but also by evaporation, surface discharge from the lake, and groundwater flowing into and out of the lake[13].

The ice-core record reveals two periods of possible agricultural activity in the period from AD 470 to 1000. The characteristics of the two dust events, however, differ greatly. The AD 490-620 event (Fig. 2) shows a gradual increase in dust which peaks in AD 610-620 and then drops abruptly. As inferred from the Quelccaya accumulation and $\delta^{18}O$ records, climatic conditions at the onset were dry and warm, whereas warm and wet conditions prevailed from AD 580 to 640, with maximum snow accumulation and dust deposition from AD 610 to 620.

In contrast, the AD 830-960 dust event is quite different. The steady increase in dust deposition peaks in AD 920 and gradually decreases until AD 1060. Also, the accumulation remains high throughout, with maximum snow accumulation coinciding with maximum dust influx from AD 910 to 920.

Low-latitude, high-altitude glaciers offer a tremendous potential for high-temporal-resolution pollen studies, as they are located in close proximity to abundant plant life. Quelccaya ice-core samples typically contain several hundred to over a thousand grains of pollen and spores per litre of water, which is two orders of magnitude higher than that found in the Devon ice cap in the Canadian Arctic[14]. In these determinations, water samples from the ice cores were filtered through 7-μm Nitex cloth; the residues were treated with hydroflouric acid, acetolysed, stained and mounted on one slide per sample. One tablet of exotic *Eucalyptus* was added to each water sample before processing for estimating pollen concentration. Except in a few samples, 35-124 fossil grains and 1100-3600 *Eucalyptus* tracers were counted per sample.

Specific pollen samples collected from the AD 920 dust event show no conclusive evidence of agricultural activities. Although pollen concentrations are relatively high (~1,600 grains per litre), the percentages of major pollen taxa (Gramineae, Compositae, *Plantago*, *Alnus*) are not significantly different from those of adjacent samples. Unfortunately, most of the plants cultivated on the altiplano do not produce wind-blown pollen, and thus pollen cannot be used in this case to identify specific crops grown in the raised fields.

The ice cores from the Quelccaya ice cap contain a 1,500-yr record of the climatic variability that affected human activities in southern Peru. The dust peaks from before AD 1000 may reflect agricultural and grazing activity, climatic change, or most probably a combination of the two. Information recovered from ice cores provides a valuable supplement to the archaeological record and may help investigators uncover the patterns and timing of some pre-Hispanic cultural activities in South America. Additional ice-core and archaeological studies must be conducted in the tropical Andes to determine whether or not these two dust events are local and unique to the altiplano of Southern Peru or whether they reflect a larger-scale regional occurrence of an as yet unknown cause.

This work was supported by NSF Division of Atmospheric Sciences and the Division of Polar Programs. We thank Professor W. Dansgaard and Dr P. Grootes for the oxygen isotope analyses of summit core and core 1, and Dr Santiago E. Antunez de Mayolo for water level changes in Lake Titicaca. We thank numerous scientists, engineers and technicians from Electroperu for scientific and logistical assistance and the Inter-American Geodesic Survey office in Lima for logistical support. Many people have participated in the ten field seasons and their efforts are gratefully acknowledged.

Received 12 August; accepted 10 November 1988.

1. Thompson, L. G., Mosley-Thompson, E., Bolzan, J. F. & Koci, B. R. *Science* **229,** 971 (1985).
2. Thompson, L. G., Mosley-Thompson, E., Dansgaard, W. & Grootes, P. M. *Science* **234,** 361 (1986).
3. Thompson, L. G. & Mosley-Thompson, E. in *Abrupt Climatic Change: Evidence and Implications* (eds Berger, W. H. & Labeyrie, L. D.) 99-110 (NATO ASI Series, 1987).
4. Kolata, A. L. *Am. Antiquity* **51,** 748-762 (1986).
5. Bastien, J. W. *Am. Ethnological Soc. Monogr.* **64,** (1978).
6. Cardich, A. in *Advances in World Archeology* (eds Wendorf, F. & Close, A. E.) 193-333 (Academic, New York, 1985).
7. Denevan, W. M. *Science* **169,** 647-654 (1970).
8. Smith, C. T., Denevan, W. M. & Hamilton, P. *Geogrl J.* **134,** 354-367 (1968).
9. Kolata, A. L. *Field Museum nat. Hist. Bull.* **53,** 13-28 (1982).
10. Kolata, A. L. in *Ancient South Americans,* (eds Jennings, J. D. & Freeman, W. H.) 241-284 (San Francisco, 1983).
11. Thompson, L. G., Mosley-Thompson, E. & Arnao, B. M. *Science* **226,** 50-53 (1984).
12. Künzel, F. & Kessler, A. *Archs Met. Geophys. Bioclim. Ser. B* **36,** 219-227 (1986).
13. Street-Perrott, F. A. & Harrison, S. P. in *Paleoclimatic Analysis and Modelling* (ed. Hecht, A. D.) 291-340 (Wiley, New York, 1985).
14. McAndrews, J. H. *Quat. Res.* **22,** 68-76 (1984).

© 1988 Nature Publishing Group