Journal of Paleolimnology **27:** 1–7, 2002.

© 2002 *Kluwer Academic Publishers. Printed in the Netherlands.*

Rapid communication

A ~6100 ^{14}C yr record of El Niño activity from the Galápagos Islands

Melanie A. Riedinger[1], Miriam Steinitz-Kannan[2], William M. Last[3] & Mark Brenner[4]
[1]*Department of Biology, Northeastern Illinois University, Chicago, IL 60625-4699, USA*
(E-mail: M-Riedinger@neiu.edu)
[2]*Department of Biological Sciences, Northern Kentucky University, Highland Heights, KY 41099-0400, USA*
(E-mail: kannan@nku.edu)
[3]*Department of Geological Sciences, University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada*
(E-mail: WM_Last@UManitoba.ca)
[4]*Department of Geological Sciences, University of Florida, Gainesville, FL 32611-2120, USA*
(E-mail: brenner@ufl.edu)

Received 23 July 2001; accepted 19 September 2001

Key words: El Niño, ENSO, Galápagos Islands, hypersaline lake, laminations, mid-Holocene climate

Abstract

Lithostratigrahic and mineralogic analyses of sediments from hypersaline Bainbridge Crater Lake, Galápagos Islands, provide evidence of past El Niño frequency and intensity. Laminated sediments indicate that at least 435 moderate to very strong El Niño events have occurred since 6100 ^{14}C yr BP (~7130 cal yr BP), and that frequency and intensity of events increased at about 3000 ^{14}C yr BP (~3100 cal yr BP). El Niño activity was present between 6100 and 4000 ^{14}C yr BP (~4600 cal yr BP) but infrequent. The Bainbridge record indicates that there has been considerable millennial-scale variability in El Niño since the middle Holocene.

Introduction

Our understanding of Holocene climate variability in the tropics is constrained by the limited number of high-resolution climate records from this region that extend back beyond the last few centuries (Thompson et al., 1992; Dunbar et al., 1994; Rodbell et al., 1999). Within the neotropics, long-term records are crucial for examining historical changes in the linked oceanic-atmospheric processes that regulate the El Niño/Southern Oscillation (ENSO) phenomenon and impact global climate. Since the 1982–1983 El Niño event, a wealth of biological, geological, and archaeological data has been used to document historical ENSO activity (Thompson et al., 1984; DeVries, 1987; Wells, 1987; Cook, 1992; Martin et al., 1993; Sandweiss et al., 1996). The varying nature and resolution of these diverse records have generated much debate regarding the timing of onset and Holocene periodicity of ENSO (Ortlieb et al., 1993; DeVries et al., 1997; Wells & Noller, 1997; Sandweiss et al., 1998). A common shortcoming of some data sets is that the postulated ENSO signal might result from both ENSO and non-ENSO events, and a clear cause-and-effect relationship to ENSO activity is not established. This becomes more problematic for records derived from outside the core region of ENSO activity in the equatorial Pacific, or from areas subject to considerable environmental or climatic fluctuations.

The Galápagos Islands, located within the core ENSO region, consistently experience positive precipitation and sea surface temperature (SST) anomalies during El Niño events, and possess a number of hypersaline lakes that experience reduced salinity during these periods (Tupiza, 1985). Galápagos lake sediment deposits archive the history of salinity fluctuations, and thus provide a record of ENSO activity. We present here a ~6100 ^{14}C yr high-resolution record of El Niño frequency and intensity based on lithostratigraphic and mineralogic analyses of a laminated core from hypersaline Bainbridge Crater Lake, in central Galápagos. We compare our record to other paleoclimate data sets, primarily from mainland South America, that document ENSO variability.

Study site

Bainbridge Crater Lake is located on the largest islet (<0.2 km^2) in the Bainbridge Rocks (Figure 1), a series of small islands produced by phreatic and littoral eruptions that lie along the southeastern coast of Santiago Island. The lake is ~200 m in diameter, shallow (Z_{max} = 3.3 m), and just above sea level. During our December 1991 field season, the lake was hypersaline (~100‰ TDS), conductivity was 145 mS/cm, pH was 8.1, and ionic composition was dominated by Na^+ (2.25 m; 4.7 × 10^4 mg L^{-1}) and Cl^- (1.43 m; 4.6 × 10^4 mg L^{-1}). The lake was not chemically stratified and was only weakly thermally stratified at the time of sampling.

Materials and methods

A ~4.2 m-long sediment core was collected in December, 1991 using a modified Livingstone piston sampler (Livingstone, 1955). The core sections were returned intact to the laboratory and stored at 4°C. Core sections were split longitudinally, described, and photographed (visible and x-radiography). Bulk mineralogy, detailed carbonate and evaporite mineralogy, moisture, organic matter content, and total carbonate contents were analyzed on subsamples taken at 2-cm intervals using standard x-ray diffraction and ignition techniques (Heiri et al., 2001; Last, 2001). Radiocarbon dates were obtained on the organic fraction of 49 subsamples following pretreatment with HCl. Forty-eight dates were obtained by AMS (National Ocean Sciences AMS Facility, Woods Hole Oceanographic Institution & The University of Arizona AMS Facility) and one date was obtained by standard count (Beta Analytic, Miami, Florida). Radiocarbon ages were calibrated using the program CALIB 4.0 and applying the Southern Hemisphere correction (Stuiver & Reimer, 1993). A short core obtained to document El Niño events within the last century failed to yield measurable ^{210}Pb activity.

Results

Bainbridge basal sediments date to 6170 ± 55 ^{14}C BP (7130 +45/–216 cal yr BP; AA-9074), and most of the 49 dates are in stratigraphic order. The sedimentation rate has been relatively constant for much of the past 6

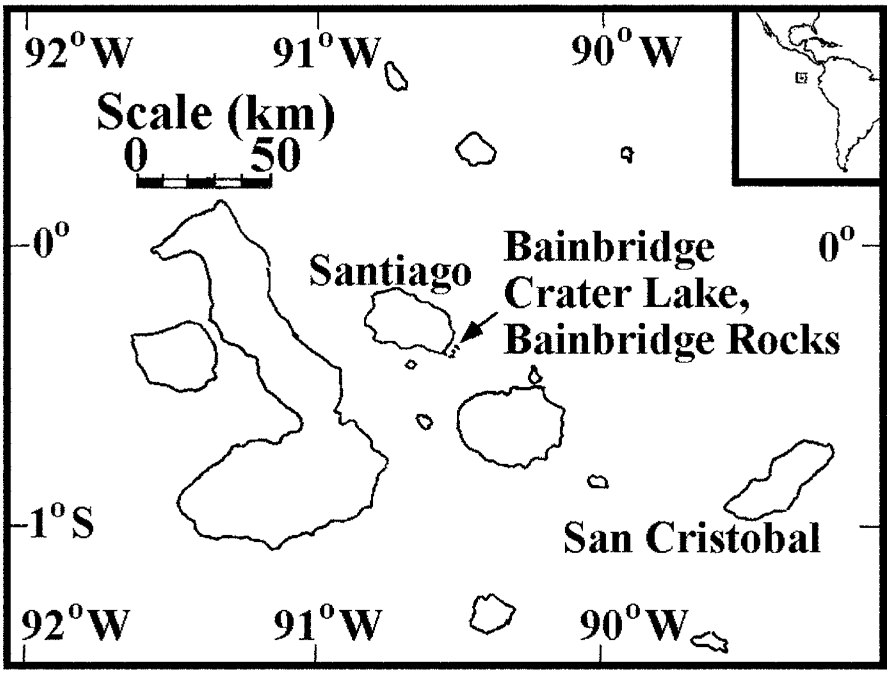


Figure 1. Location of Bainbridge Crater Lake, Bainbridge Rocks, Galápagos Islands. San Cristóbal, site of El Junco Lake, also is shown.

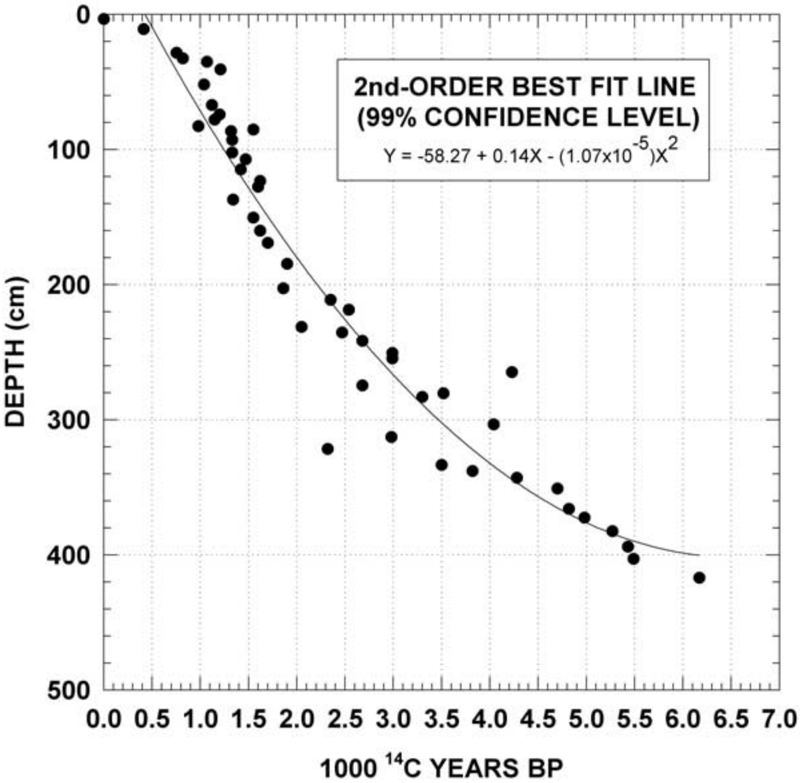


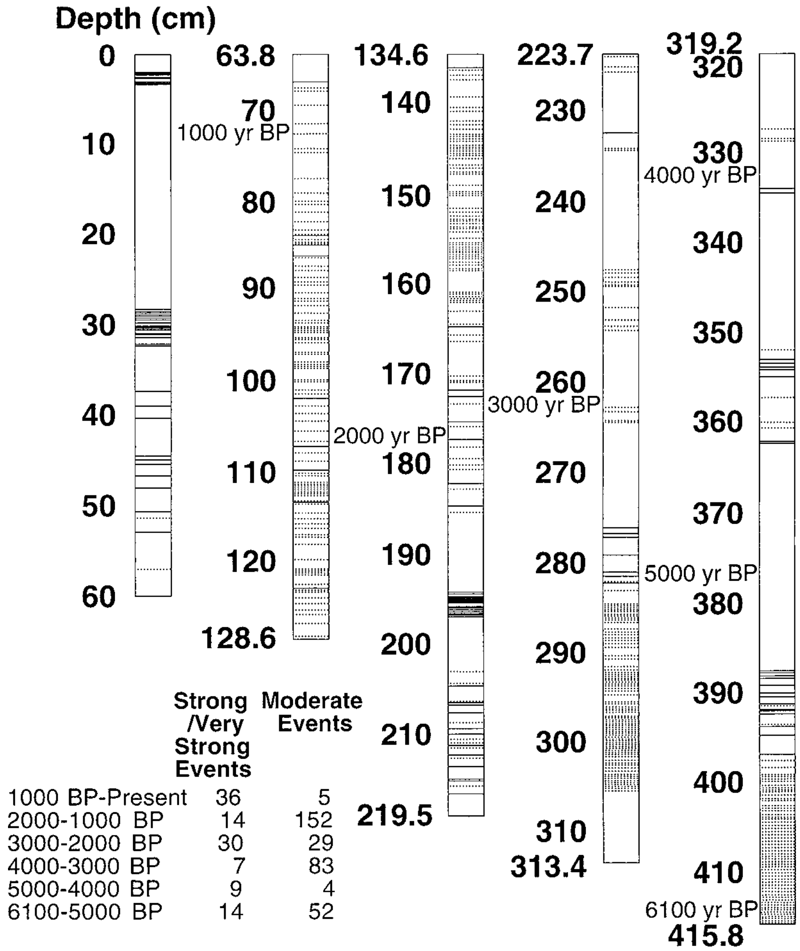
Figure 2. Depth versus time plot for the Bainbridge Crater Lake sediment core. Forty-eight AMS radiocarbon and 1 standard date were used to establish the core chronology. The increased sedimentation in the upper ~200 cm of the core most likely reflects increased catchment erosion and corresponds to the interval containing the majority of the siliciclastic and more than half of the carbonate laminae in the record.

millennia, but increases somewhat in the upper 200 cm of the core (Figure 2).

The stratigraphic sequence consists almost entirely of poorly indurated, massive to finely laminated, organic-rich endogenic and authigenic salts, with only minor siliciclastic detritus. Overall, halite and sulfate salts dominate the sequence, with carbonate minerals comprising generally less than 20% of the inorganic fraction. The sulfate minerals are mainly gypsum, although various Mg and Na sulfates, such as bloedite and thenardite, occur throughout the core. Carbonate mineral composition is considerably more diverse. Aragonite, dolomite and Mg-calcite dominate the carbonate fraction, but huntite, kutnohorite, northupite, hydromagnesite, monohydrocalcite, calcite and nahcolite also occur. The phosphate mineral brushite is common, and pyrite is found in relatively high abundance in the upper half of the core. In contrast to the complex endogenic and authigenic mineral assemblage, the minor amount of allogenic sediment is composed of a relatively simple mixture of feldspar minerals (mainly potassic feldspars), quartz, and clay minerals.

Organic content averages 25% and exhibits no systematic variation with depth. Sediment deposited prior to 4200 ^{14}C yr BP (~4800 cal yr BP) is characterized by relatively high siliciclastic and carbonate mineral contents. Laminated aragonite dominates the carbonate fraction. Sharply overlying this is about a meter of organic-rich gypsite characterized by very low carbonate, halite, and siliciclastic contents. A sharp contact at ~2400 ^{14}C yr BP (~2300 cal yr BP) separates this gypsite from the overlying pyrite-rich, halite-dominated laminated muds deposited during the last several millennia.

The Bainbridge core contains two distinct types of laminae, most concentrated within the last 2400 ^{14}C years of the record (Figure 3). Approximately 325 irregularly-spaced carbonate laminae and thin beds are present and range in thickness from <1–12 mm. There are 110 distinct siliciclastic laminae that are also present and are generally <4 mm thick. These laminae are composed almost entirely of finely-crystalline carbonate minerals or fine-grained siliciclastics, and they exhibit no obvious rhythmicity or spacing cyclicity. Carbonate



	Strong /Very Strong Events	Moderate Events
1000 BP-Present	36	5
2000-1000 BP	14	152
3000-2000 BP	30	29
4000-3000 BP	7	83
5000-4000 BP	9	4
6100-5000 BP	14	52

Figure 3. The laminae record of El Niño activity. Siliciclastic laminae (strong/very strong intensity events) are represented by solid lines; carbonate laminae (moderate intensity events) are indicated by dashed lines. Boundary ages of 1000–6100 ^{14}C yr BP were assigned using Figure 2. Each column represents a separate drive. Sediment intervals between 60–63.8, 128.6–134.6, 219.5–223.7, and 313.4–319.2 cm were collected into the cutting shoe used to penetrate the sediments during coring, and disturbed during core recovery. Laminae were not preserved as a result, and therefore these intervals were omitted from the diagram.

laminae are more prominent at the base of the record (6100-5000 ^{14}C yr BP; 7100–5900 cal yr BP), and from 4000-3000 ^{14}C yr BP (~4600–3100 cal yr BP) and 2000-1000 ^{14}C yr BP (~1900–900 cal yr BP). Siliciclastic laminae are more abundant after 3000 ^{14}C yr BP, though they occur throughout the core. This sequence has not yet been subjected to a time-series statistical analysis.

Discussion

We postulate that the preservation of both types of laminae results from a chemically stratified water column produced during El Niño activity, and that the laminae can be used as a measure of El Niño frequency. The relatively high abundance of pyrite in the upper half of the core provides further evidence of stratification for much of the last 2400 ^{14}C years, as its preservation requires strongly reducing conditions. Chemical stratification, or meromixis, could be generated here by a number of mechanisms. A ‘fresher’, low salinity surface layer in the water column could result from an increased influx of rain water within the catchment basin, which would occur during El Niño events. Alternately, surface freshening could develop if there is an influx of sea water into the system. A portion of the crater wall is ~3 m above sea level, and likely is breached during the periods of large waves or higher sea levels (Hayes, 1985) that are characteristic of El Niño. Marine diatoms are absent from the diatom record suggesting that, although ocean water occasionally might have breached the basin wall, it was not the primary cause of meromixis.

Siliciclastic and carbonate laminae might be the product of different El Niño intensities, and thus might provide an index of past ENSO strength. We suggest that the siliciclastic laminae reflect strong to very strong events, when high levels of rainfall promote erosion of the crater walls, resulting in significant clastic influx. The steep sides of the crater are sparsely vegetated with salt- and drought-tolerant herbs and grasses, and although the increased El Niño rainfall often induces luxuriant growth in the arid zones of the archipelago, this growth might not be adequate to stabilize the slopes. The more numerous carbonate laminae likely result from events of moderate intensity, when the El Niño precipitation is substantial enough to lower lake salinity to a level that promotes carbonate precipitation, but not sufficient to generate much catchment erosion (Figure 3). Weak events might not bring sufficient rainfall to this site to generate meromixis and laminae preservation, and are likely absent from our record.

Using laminae as an index of both El Niño frequency and intensity, the Bainbridge record indicates that there have been at least 435 moderate to very strong El Niño events since ~6100 ^{14}C yr BP (Figure 3). Our data suggest that mid-Holocene El Niño activity was infrequent, with 23 strong to very strong, and 56 moderate events occurring between ~6100 and ~4000 ^{14}C yr BP. El Niño frequency increased between ~4000 and ~3000 ^{14}C yr BP (seven strong/very strong and 83 moderate events). The last 3000 ^{14}C years are characterized by increases in the frequency (266) and intensity (80 strong/very strong) of events. El Niño events of the 1990s are absent from our record because the Bainbridge core was collected in 1991.

The lake-level record from El Junco Lake, San Cristóbal Island, Galápagos (Colinvaux, 1972) provides supporting evidence for minimal El Niño activity in Galápagos during the middle Holocene and for a late-Holocene increase in El Niño frequency and intensity. Between 6200 and 3000 ^{14}C yr BP, El Junco, which today is ~6 m deep, was a shallow system with fluctuating lake levels, suggesting dry conditions with little El Niño activity. Modern lake levels were established by 3000 ^{14}C yr BP, indicating that wetter conditions prevailed during the late Holocene, probably because of increased El Niño frequency and/or intensity. High lake levels between 8000 and 6200 ^{14}C yr BP provide evidence that El Niño activity might have occurred in Galápagos during the early Holocene.

A late-Holocene increase in El Niño activity in the Galápagos Islands is consistent with ENSO records from western South America. Faunal remains from archaeological middens in coastal Peru suggest that the loss of two temperature-sensitive mollusk species and their replacement by a cosmopolitan species at ~2800 cal yr BP was caused by increased El Niño frequency (Sandweiss et al., 2001). Flood deposits in coastal Peru also indicate a late-Holocene increase, with 13 out of 18 Holocene flood sediments attributed to El Niño activity deposited in the last 3200 cal years (Wells, 1990). Low-resolution vegetation and lake-level records from Chile and Argentina document significant increases in moisture during the late Holocene that might reflect increased El Niño frequency (McGlone et al., 1992).

A considerable body of evidence suggests that the modern El Niño phenomenon was established during the middle Holocene (Sandweiss et al., 1999). Molluscan faunal remains from Peruvian archaeological sites north of 10°S indicate that a shift from tropical to temperate species occurred at about 5000 ^{14}C yr BP, and this shift has been linked to the onset of El Niño (Sandweiss et al., 1996). Pollen records from tropical northern Australia document a decrease in effective precipitation and increased climate variability beginning around 4000 ^{14}C yr BP that might reflect the development of the modern ENSO-dominated climate (Shulmeister & Lees, 1995). Laminated sediments from an Andean lake in southwestern Ecuador suggest that the 2–8.5-yr periodicity of modern El Niños was established around 5000 cal yr BP (Rodbell et al., 1999). This record provides evidence that El Niño events occurred during the late Pleistocene and early Holocene but at a longer (≥15 yr) periodicity. Our data from Bainbridge Crater Lake document mid-Holocene El Niño activity, though at a lesser frequency and intensity than in the late Holocene. A similar pattern has been described from sedimentary deposits in the coastal desert of southern Peru, where low-energy, organic-rich layers and the absence of high-energy debris flows during the middle Holocene have been used as evidence of reduced El Niño strength and frequency (Fontugne et al., 1999). Bainbridge and Peruvian evidence are consistent with recent atmosphere and coupled atmosphere-ocean general circulation models for the equatorial Pacific that suggest a prevalence of La Niña rather than El Niño conditions during the middle Holocene (Bush, 1999).

The limited number of high-resolution records has made it difficult to assess long-term variability in El Niño intensity. Flood deposits in Peru since 7000 cal yr BP suggest that there has been an average of one strong event every 1000 years (Wells, 1990). Beach-ridge data from coastal Brazil record seven strong El Niño-like events between 5100 and 3900 ^{14}C yr BP, and three between 2500 ^{14}C yr BP and present (Martin et al., 1993). Historical documents and instrumental records suggest that at least 44 strong to very strong and approximately 75 moderate events might have occurred in the last 450 years (Quinn et al., 1987; Quinn, 1993). Re-evaluation of some of these references confirms only 15 strong to very strong events between 1525 and 1891 AD (Ortlieb & Macharé, 1993). The laminae record from Bainbridge Crater Lake documents eight strong to very strong events in the last 400 ^{14}C years (~500 cal yrs), and a minimum of 110 strong to very strong and 325 moderate intensity events since 6100 ^{14}C yr BP. Our data also demonstrate that there has been much variability in the occurrence of moderate intensity events, with increased frequency characterizing 6100–5000, 4000–3000, and 2000–1000 ^{14}C yr BP. The Bainbridge record shows that although strong to very strong event frequency has increased during the late Holocene, there has been considerable millennial-scale variability in El Niño activity during the last 6100 ^{14}C years.

Acknowledgments

This research was supported by funding from NOAA (grant NA 56GP0188), NSF (grant ATM-9106284), The National Geographic Society, the Natural Sciences and Engineering Research Council of Canada, a Northeastern Illinois University research award, and the University of Manitoba Research Board. We thank Michael Miller, Ramamurthi Kannan, Geetha Kannan, and Linda Carrasco for field assistance, and the Charles Darwin Research Station and crew of the Beagle III for logistical support. Vicki Martin-Kier, Paula Rockwell, Ryan Belsham and Steve Pooler provided laboratory assistance. Tom Whitmore helped with editing and graphics. We also thank Walter Dean and Donald Rodbell for their helpful comments on the manuscript.

References

Bush, A. G. B., 1999. Assessing the impact of mid-Holocene insolation on the atmosphere-ocean system. Geophys. Res. Lett. 26: 99–102.

Colinvaux, P. A., 1972. Climate and the Galapagos Islands. Nature 240: 17–20.

Cook, E., 1992. Using tree rings to study past El Niño/Southern Oscillation influences on climate. In: Diaz, H. F. & Markgraf, V. (eds), El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation. Cambridge University Press, Cambridge: 203–214.

DeVries, T. J., 1987. A review of geological evidence for ancient El Nino activity in Peru. J. Geophys. Res. 92: 14, 471–14, 479.

DeVries, T. J., L. Ortlieb, A. Diaz, L. Wells & Cl. Hillaire-Marcel, 1997. Determining the early history of El Niño. Science 276: 965–966.

Dunbar, R. B., G. M. Wellington, M. W. Colgan & P. W. Glynn, 1994. Eastern Pacific sea surface temperature since 1600 A.D.: The δ^{18}O record of climate variability in Galápagos corals. Paleoceanography 9: 291–315.

Fontugne, M., P. Usselmann, M. Lavallée, M. Julien & C. Hatté, 1999. El Niño variability in the coastal desert of southern Peru during the mid-Holocene. Quat. Res. 52: 171–179.

Hayes, S. T., 1985. Sea level and near surface temperature variability at the Galápagos Islands, 1979–1983. In: Robinson, G. & del Pino, E. M. (eds), El Niño in the Galápagos Islands: the 1982–1983 Event. Charles Darwin Foundation for the Galápagos Islands, Quito: 49–81.

Heiri, O., A. F. Lotter & G. Lemcke, 2001. Loss-on-ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. J. Paleolim. 25: 101–110.

Last, W. M., 2001. Mineralogical analysis of lake sediments. In: Last, W. M. & Smol, J. P. (eds), Tracking Environmental Change using Lake Sediments. Vol. 2: Physical and Chemical Techniques. Kluwer Academic Publishers, Dordrecht, in press.

Livingstone, D. A., 1955. A lightweight piston sampler for coring lake deposits. Ecology 36: 137–139.

Martin, L., M. Fournier, P. Mourguiart, A. Sifeddine, B. Turcq, M. L. Absy & J. M. Flexor, 1993. Southern Oscillation signal in South American palaeoclimatic data of the last 7000 years. Quat. Res. 39: 338–346.

McGlone, M. S., A. P. Kershaw & V. Markgraf, 1992. El Niño/Southern Oscillation climatic variability in Australasian and South American paleoenvironmental records. In: Diaz, H. F. & Markgraf, V. (eds), El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation. Cambridge University Press, Cambridge: 435–462.

Ortlieb, L. & J. Macharé, 1993. Former El Niño events: records from western South America. Glob. Planet. Change 7: 181–202.

Quinn, W. H., 1993. The large-scale ENSO event, the El Niño and other important regional features. Bull. Inst. fr. études andines 22: 13–34.

Quinn, W. H., V. T. Neal & S. E. Antunez de Mayola, 1987. El Niño occurrences over the past four and a half centuries. J. Geophys. Res. 92: 14, 449–14, 461.

Rodbell, D. T., G. O. Seltzer, D. M. Anderson, M. B. Abbott, D. B. Enfield & J. H. Newman, 1999. An ~15,000-year record of El Niño-driven alluviation in southwestern Ecuador. Science 283: 516–520.

Sandweiss, D. H., J. B. Richardson III, E. J. Reitz, H. B. Rollins & K. A. Maasch, 1996. Geoarchaeological evidence from Peru for a 5000 years B.P. onset of El Niño. Science 273: 1531–1533.

Sandweiss, D. H., K. A. Maasch, D. F. Belknap, J. B. Richardson III & H. B. Rollins, 1998. Discussion of: Lisa E. Wells, 1996. The Santa Beach ridge complex, Journal of Coastal Research 12 (1), 1–17. J. Coast. Res. 14: 367–373.

Sandweiss, D. H., K. A. Maasch & D. G. Anderson, 1999. Transitions in the mid-Holocene. Science 283: 499–500.

Sandweiss, D. H., K. A. Maasch, R. L. Burger, J. B. Richardson, H. B. Rollins & A. C. Clement, 2001. Variation in Holocene El Niño frequencies: climate records and cultural consequences in ancient Peru. Geology 29: 603–606.

Shulmeister, J. & B. G. Lees, 1995. Pollen evidence from tropical Australia for the onset of an ENSO-dominated climate at *c.* 4000 BP. Holocene 5: 10–18.

Stuiver, M. & P. J. Reimer, 1993. Extended ^{14}C database and revised CALIB radiocarbon calibration program. Radiocarbon 35: 215–230.

Thompson, L. G., E. Mosley-Thompson & B. M. Arnao, 1984. El Niño-Southern Oscillation events recorded in the stratigraphy of the tropical Quelccaya ice cap, Peru. Science 226: 50–53.

Thompson, L. G., E. Mosley-Thompson & P. A. Thompson, 1992. Reconstructing interannual climate variability from tropical and subtropical ice-core records. In: Diaz, H. F. & Markgraf, V. (eds), El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation. Cambridge University Press, Cambridge: 295–322.

Tupiza, A., 1985. Cambios en la laguna del Cementerio y en Puerto Villamil, Isla Isabela, causados por el fenómeno 'El Niño' en 1982–83. In: Robinson, G. & del Pino, E. M. (eds), El Niño in the Galápagos Islands: the 1982–1983 Event. Charles Darwin Foundation for the Galápagos Islands, Quito: 273–278.

Wells, L. E., 1987. An alluvial record of El Niño events from northern coastal Peru. J. Geophys. Res. 92: 14, 463–14, 470.

Wells, L. E., 1990. Holocene history of the El Niño phenomenon as recorded in flood deposits of northern coastal Peru. Geology 18: 1134–1137.

Wells, L. E. & J. S. Noller, 1997. Determining the early history of El Niño. Science 276: 965–966.