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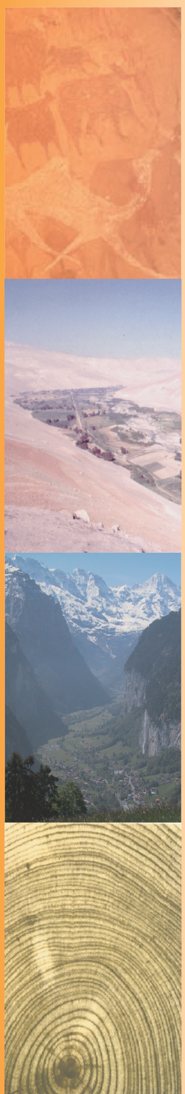

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PAGES News
PAST GLOBAL CHANGES

Valerie Hall and Brent Alloway, Guest Editors
Christoph Kull and Leah Christen, Editors

VOL.12, N°3 – DECEMBER 2004

Tephra

Above: *Tephra plume - 1996 eruption of Ruapehu Volcano, Central North Island, New Zealand (Photo: V. Manville, Institute of Geological & Nuclear Sciences - GNS).*
Below: *View towards Ngauruhoe Volcano (Mt Doom in the movie "Lord of the Rings") in Tongariro National Park, Central North Island, New Zealand. Late Pleistocene Ruapehu and Tongariro tephra beds are clearly visible in the road exposure (Photo: B.V. Alloway).*

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Editorial: Tephra

Tephra are the widest ranging direct hazard from a volcano and are capable of extending over areas as large as continents. The importance of tephra in establishing a chronological framework for volcanic and sedimentary successions can be not over-emphasized. Once a recognizable tephra layer has been dated, it provides a time horizon wherever it is located and is, therefore, pivotal in correlating equivalent-aged successions in a wide variety of terrestrial and marine settings. Traditional efforts have focused on the mapping and geochemical characterization of macroscopically visible (mm- to cm-thick) tephra beds in order to facilitate regional and inter-regional correlation, as well as erect tephrostratigraphic frameworks that underpin volcanic hazard studies and paleoenvironmental reconstructions. Consequently, many tephra records tend to be biased towards macroscopic tephra beds that represent the products of moderate to large magnitude eruptive events. Numerous other tephra representing small to moderate eruptive events are seldom noted since the combined effects of distance and bioturbation in the terrestrial (soil-forming) and deep-sea environments mean that they are not preserved as macroscopic layers.

Over the last decade, however, analyses of a wide range of Late Quaternary deposits have shown that very many contain well-defined layers composed of minute traces of microscopic volcanic ash (cryptotephra) not visible to the naked eye. It is with this material, rather than the larger products of volcanism, that future advances in distal tephrochronology will occur. The papers presented in this special issue of *PAGES News* report recent tephrochronological research from places separated by great distances. The result of these new studies has been to develop new methodologies capable of coaxing extremely small amounts from the most obdurate deposits, so that time frames and site-linkage techniques for past environmental studies have improved greatly in precision. Much of the success of the relatively new science of Quaternary distal tephrochronology is due to inexpensive and standard techniques that allow deposits to be searched quickly to determine if tephra is present, even if only represented by very few tephra shards. Additionally, the recent expansion of tephra studies has utilized analytical systems that can determine the precise geochemistry of single shards of volcanic glass. Certainly, continuing advances in single grain trace element geochemistry, as determined by the laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) technique, will make it possible in the future to establish more correlation tie-lines with a more complete spectrum of tephra events than is currently possible using only the macroscopic tephra record.

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Inside PAGES

The past six months have seen some major activities within the PAGES program—PAGES launched an open search for a new Executive Director, and submitted a grant proposal for further support to the US National Science Foundation.

New PAGES Executive Director:

We are pleased to welcome **Thorsten Kiefer** as the new Executive Director of PAGES.

Thorsten is leaving the Department of Earth Sciences at the University of Cambridge and was previously part of the Institute for Geosciences at the University of Kiel. His recent research has focused on rapid centennial-scale climate changes of the late Pleistocene and Holocene. His academic interests are diverse, incorporating research themes such as understanding the ramifications of global change on regional climates, assessing past human-climate interactions, and determining the role of surface- and deep-ocean circulation on modulating climate. To this end, he has developed and integrated paleoceanographic records with ice core data, climate model simulations and archeological evidence, and has studied a number of areas in the Indian, Pacific, and North Atlantic Oceans. He has been involved in a number of international collaborative projects and has been active in PAGES-related programs including IMAGES (International Marine Global Change Studies) and MARGO (Multiproxy Approach for the Reconstruction of the Glacial Ocean surface). He looks forward to serving the wider paleoclimate community through PAGES. Thorsten has already started working part-time remotely from Cambridge. He will move to Bern and start working full-time in April 2005.
Contact: kiefer@pages.unibe.ch.

New PAGES Proposal Submitted to US-NSF:

Following on from the last successful grant period, PAGES has submitted an application to the US-NSF for further support of its activities for the coming four years. Based on an open call for feedback earlier this year, and discussions within the PAGES SSC and the IGBP network, we were able to propose future activities, adapted to the new demands of paleoenvironmental science. Of course, we continue to welcome your feedback and comments (www.pages-igbp.org/about/feedback.html). A fitting opportunity to demonstrate the vitality and new direction of PAGES will be the 2nd PAGES OSM in Beijing, China (10-12 August 2005; www.pages2005.org).

PAGES Products:

The PAGES online Product Database contains a collection of paired pictures. These demonstrate visually the environmental changes that have taken place between two time points at a single location. However, to make this a truly useful resource, we need additional photos. Please send your contributions or any questions to Christoph Kull (kull@pages.unibe.ch).

The next newsletter issue will be thematically open. If you would like to contribute with a science highlight or a workshop report, please check the guidelines at www.pages-igbp.org/products/newsletters/instructions.html and then send your submission to Christoph Kull (kull@pages.unibe.ch). The deadline is 31 December 2004.

New on the PAGES Bookshelf:

High Latitude Eurasian Palaeoenvironments

Keith Alverson and Olga Solomina, eds.,
Palaeo3 Special Issue, Vol. **209**, Issues 1-4, 2004

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Eastern Europe - From the White and Black Seas
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Southern Siberia - Lakes Baikal and Hvsgol and the Altai Mountains
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The Far East - Kamchatka, Kurile Islands, Bering Sea and Sea of Okhhotsk
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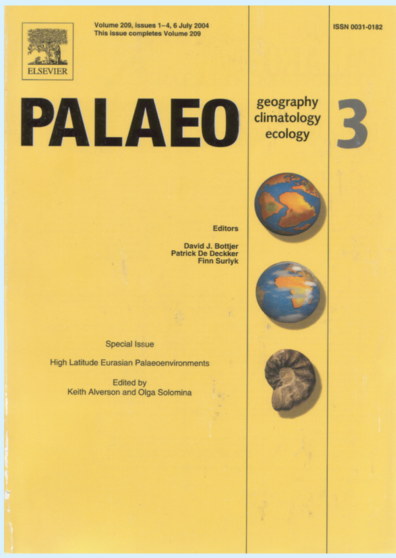

The complete content and introduction are available via the PAGES product database under special issues: www.pages-igbp.org/products/products.html

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Kenya

Paleoscientists are welcome!

Kenya is a country with diverse geology, physiography, ecosystems and climate, whose present-day characteristics are closely associated with the regional tectonic evolution. This diversity offers the paleoscientist a number of natural archives for study. These archives include the following: i) Freshwater lakes (such as Lake Naivasha, Lake Victoria), ii) Saline alkaline lakes (most of the Kenya Rift lakes such as Lakes Turkana, Bogoria, and hypersaline Lake Magadi), iii) Crater lakes e.g. Sacred Lake and Lake Nkunga on Mount Kenya. iv) Proglacial lakes on Mount Kenya, v) Mires and Swamps in several parts of the country, vi) Ice on Mount Kenya, vii) Corals off the Kenya coast, viii) Riverine sediments, and others.

A National Science Highlight: The Crescent Island Crater Basin, Lake Naivasha

A 6 m core from the Crescent Island Crater (CIC) Basin, Lake Naivasha, Kenya describes the hydrological response of Lake Naivasha to a succession of decade-scale fluctuations in the regional balance of rainfall and evaporation in equatorial East Africa (Figure 1) (Verschuren et al., 2000). There was significantly drier climate than today during the Medieval Warm Period (MWP, ca. AD 1000 to 1270) and a relatively wet climate during the Little Ice Age (LIA, AD 1270 - 1850) which was interrupted by three prolonged dry episodes. The MWP period of inferred African aridity and all three severe drought events of the past 700 years were broadly coeval with phases of high solar radiation, and intervening periods of increased moisture were coeval with phases of low solar radiation (Verschuren et al., 2000). Verschuren et al. (2000) compared their record with the pre-colonial history of east Africa recounted in oral traditions, and found evidence that in the six centuries before AD 1895, there was drought-induced famine, political unrest and large-scale migration of indigenous peoples, temporally matching the three lake-recorded drought periods.

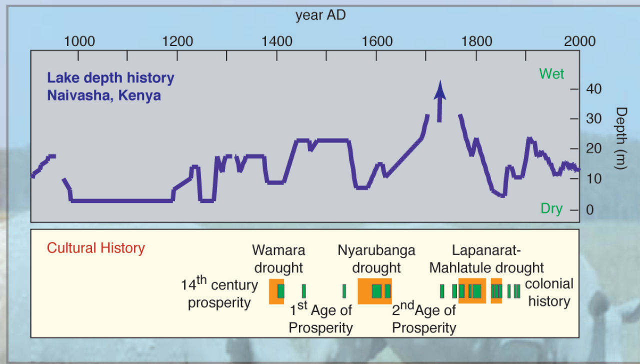

Fig.1: Changing lake level in Lake Naivasha, Kenya as inferred from the sediment record is superimposed with a rough reconstruction, based on oral histories, of societal prosperity in the region (Verschuren et al. 2000).

Reference:
Verschuren D., Kathleen R.L. and Cumming B.F. (2000) Rainfall and drought in equatorial east Africa during the past 1,100 years. *Nature*, **403**: 410-413.

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Funding Sources:

National research funding sources in Kenya are very limited, as is the case for most of sub-saharan Africa. Possible funding is available via the the National Council for Science and Technology or via the PAGES START Africa Secretariat (above).

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Photo: Julie Brigham-Grette

Role of Tephra in Dating Polynesian Settlement and Impact, New Zealand

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Introduction: Heated Debate

Tephrochronology in its original sense is the use of tephra layers as time-stratigraphic marker beds to establish numerical or relative ages (Lowe and Hunt, 2001). Tephra layers have been described and studied in New Zealand for more than 160 years (the German naturalist and surgeon Ernst Dieffenbach described 'recognizable' tephra sections in his 1843 book *Travel in New Zealand*), and the first isopach map, showing fallout from the deadly plinian basaltic eruption of Mt Tarawera on 10 June 1886, was published in 1888 (Lowe, 1990; Lowe et al., 2002). More recently, a wide range of tephra-related paleoenvironmental research has been undertaken (e.g., Lowe and Newnham, 1999; Newnham and Lowe, 1999; Newnham et al., 1999, 2004; Shane, 2000), including new advances in the role of tephra in linking and dating sites containing evidence for abrupt climatic change (e.g., Newnham and Lowe, 2000; Newnham et al., 2003). Here we focus on the use of tephrochronology in dating the arrival and impact of the first humans in New Zealand, a difficult problem for which this technique has proven to be of critical importance.

The timing of initial settlement of New Zealand has been the subject of heated debate. An early but transient contact AD 50 to 150, based on Pacific rat-bone (*Rattus exulans*) dates obtained from natural sites, was proposed by Holdaway (1996) on the premise that the rats, an introduced predator to New Zealand, accompanied the early Polynesians as a food source or as stowaways (Matisoo-Smith, 2002; Matisoo-Smith and Robins, 2004). This proposal seemingly supported Sutton (1987, 1994), who first suggested on the basis of small-scale but short-lived disturbance evident in pollen records that 'archeologically invisible' Polynesian sailors might have reached New Zealand around this time. However, the reliability of the early rat-bone dates has been disputed, especially as aberrant rat-bone dates were reported from several archeological sites (Anderson, 1996, 2000, 2004; Higham and Petchey, 2000; Higham *et al*., 2004), and dates on rat-nibbled land snail shells (*Placostylus ambagiosus*) and rat-nibbled seeds both suggested instead that the Pacific rat became established after AD 1250 (Brook, 2000; Wilmshurst and Higham, 2004). Moreover, the early rat-bone dates at one of Holdaway's (1996) sites in the South Island have not been duplicated (Holdaway et al., 2002; Anderson and Higham, 2004).

Fig.1: Human footprint in basaltic Rangitoto Tephra, erupted c. AD 1400, Auckland, northern North Island (Nichol, 1982). The age of the eruption is derived from multiple radiocarbon, paleomagnetic, thermoluminescence, and obsidian hydration dates (Lowe et al., 2000). Photo courtesy of Reg Nichol.

Using Tephra Layers to Date Archeological and Paleoenvironmental Sites

Because tephras provide essentially instantaneous chronostratigraphic marker horizons, or *isochrons*, that can be correlated between sites independently of radiometric dating, they provide a way of circumventing the various interpretative difficulties associated with radiocarbon dating very recent (last millennia) archeological and paleoenvironmental (natural) sites. Because tephra deposits are found in both archeological and natural sites, they have the capacity for linking such sites in an unambiguous manner unparalleled by other dating or correlative techniques (Lowe et al., 2000).

Direct links between early Polynesians and their descendants (Maori) and tephras in New Zealand are associated with three different eruptive centers on North Island (Lowe et al., 2002).

(1) Human footprints and other artifacts are buried beneath and within basaltic ash erupted from Rangitoto Island volcano, near Auckland, at AD 1400 (Fig. 1).

(2) The remains of Maori cooking stones (*umu*) aged AD 1450 to 1500 lie sandwiched between tephras on the slopes of the andesitic stratovolcano of Taranaki (Mt Egmont) in western North Island (Fig. 2).

(3) The key event for dating Polynesian settlement in New Zealand was the eruption of Kaharoa Tephra, a geochemically distinctive, rhyolitic tephra layer originating from Mt Tarawera volcano in central North Island near Rotorua

Fig. 2: Early Maori cooking stones (umu) sandwiched between andesitic tephra layers on Taranaki volcano, western North Island. At this site, the stones are overlain directly by Burrell Ash and underlain by Waiweranui Lapilli, dating the umu to c. AD 1500 or a little before (Alloway et al., 1990; Lowe et al., 2000). First recognized by Oliver (1931), the oldest umu on Taranaki is dated at c. AD 1450. Photo courtesy of Brent Alloway.

(Lowe et al., 2000). Widely dispersed over > 30,000 km^2 of northern and eastern North Island, Kaharoa Tephra provides a unique 'settlement layer' (*landnámslag*) (Wastegard et al., 2003; Sveinbjornsdottir et al., 2004) in northern New Zealand. Difficult to date accurately by radiocarbon alone because of wiggles in the calibration curves (Lowe et al., 1998), we derived a wiggle-match date of AD 1314±12 for the Kaharoa Tephra eruption—the main plinian, tephra-fall-producing phase of which occurred in the austral winter (Hogg et al., 2003)—using a carbonized log of *Phyllocladus* spp. We used the Southern Hemisphere calibration curves of Hogg et al. (2002), thus avoiding the interhemispheric offset problem, and confirmed our date's likelihood using Bayesian statistics (Buck et al., 2003).

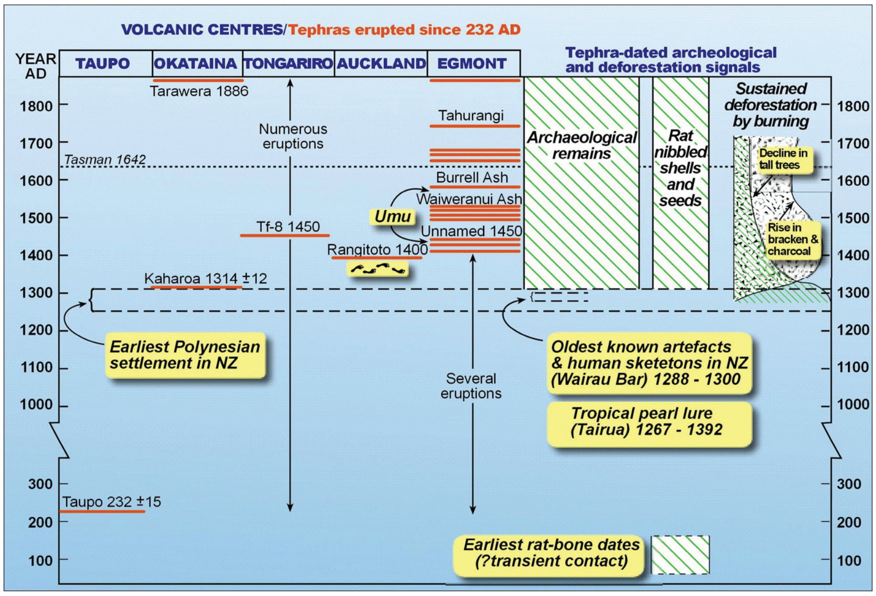

Fig. 4: Summary of stratigraphy and ages of tephras, erupted from five volcanic centers since c. AD 232 (left side of diagram), and their relationship with archeological and deforestation signals in northern and eastern North Island (right) (after Lowe et al., 2000, 2002). The Kaharoa Tephra provides a settlement datum, or landnámslag, for inferred human-induced burning and deforestation in much of northern and eastern North Island (e.g., Newnham et al., 1998; Horrocks et al., 2001). It matches the earliest settlement dates of c. AD 1250–1300 from many sites containing archeological remains (e.g., Anderson, 1991; Higham and Hogg, 1997; McFadgen, 2003; Higham et al., 2004), including the ancient Wairau Bar artifacts and skeletons (Higham et al., 1999) and the tropical pearl lure at Tairua (Schmidt and Higham, 1998) (2 sigma error ranges), the oldest known rat-nibbled snail shells and seeds (Brook, 2000; Wilmshurst and Higham, 2004), and the earliest reliable dates for sustained deforestation elsewhere in the New Zealand archipelago (Ogden et al., 1998; McGlone and Wilmshurst, 1999). The zone depicting possible early transient human contact is based on Holdaway (1996, 1999). Dutchman, Abel Tasman, was probably the first European to visit New Zealand (AD 1642).

Numerous archeological sites in eastern and northern North Island contain the Kaharoa Tephra datum (Fig. 3; Lowe et al., 2000; see also supplementary material), and the absence of artifacts or cultural remains reported beneath it thus far indicates that these sites must be younger than AD 1314. In the same region, nearly 20 pollen profiles obtained from peat or lake deposits contain both Kaharoa Tephra and palynological indicators for the onset of significant deforestation, in the form of both marked and sustained rises in bracken (*Pteridium*) spores and charcoal, and a concomitant decline in tall forest trees (Newnham et al., 1998; Horrocks et al., 2001, 2004; McGlone and Jones, 2004). Unprecedented in the Holocene record, these palynological changes are inferred to be the result of initial and repeated firing by early Maori (Ogden et al., 1998; McGlone and Wilmshurst, 1999; Flenley and Todd, 2001). In a few profiles, the sustained rises in bracken and charcoal occur well after the Kaharoa Tephra datum but in the others, they occur close to the time of its deposition. In four pollen profiles, the earliest sustained rises are recorded in sediments just a few centimeters below the Kaharoa Tephra layer, probably ≤ 50 years before the eruption of AD 1314 (Lowe et al., in press). A similar pattern is evident from independent opal phytolith data in tephra-soil sequences in the Bay of Plenty (Kondo et al., 1994; Sase and Hosono, 1996). Thus, it is likely that the Kaharoa eruption was witnessed by a small number of very early Maori (an argument supported by oral tradition) and that archeological sites containing artifacts just beneath the Kaharoa Tephra may yet be found.

Fig.3: Distal rhyolitic Kaharoa Tephra showing up as a prominent, 5-cm-thick marker layer in shallow peat deposits at Waihi Beach, western Bay of Plenty, eastern North Island. Taupo Tephra (erupted c. AD 232; Sparks et al. 1995; Lowe and de Lange, 2000) occurs also in the section, faintly visible as fine lapilli on the 'corner' in the middle of the photo, a few centimeters above the pale muds near the water table. The peat above Kaharoa datum is darker than below because it contains abundant charcoal from Polynesian burning, which is documented by pollen analysis in this area (Newnham et al., 1995). Cutting tool handle is ~30 cm long. Photo: David Lowe.

Conclusions

Taken together, both the archeological and palynological evidence, constrained by the AD 1314 Kaharoa Tephra datum, suggests that the earliest environmental impacts associated with initial Polynesian settlement in northern New Zealand (North Island) occurred between AD 1250 and 1300. This is coincident with the earliest-known settlement dates from archeological remains on both North and South Islands, with dates obtained from rat-nibbled snail shells and seeds, and with reliably dated deforestation signals (Fig. 4). The fact that the maximum date for the onset of deforestation is similar to dates obtained from the oldest-known archeological sites (e.g., Wairau Bar), implies that the onset of forest burning was more-or-less contemporaneous with initial settlement (Lowe et al., in press). It remains feasible that earlier settlement sites still await discovery beyond the fall-out zone of macroscopic Kaharoa Tephra and that there might have been an earlier transient contact. If such transient contact occurred, it currently remains invisible in the archeological record and is indistinguishable from natural background events in the palynological record (Lowe et al., in press).

Fig. 5: Archeological excavation of an early Maori village (kainga) site on dunes at Papamoa, coastal Bay of Plenty, eastern North Island, with the Kaharoa Tephra (dated at AD 1314±12 by Hogg et al., 2003) forming a prominent white marker layer in peat. Photo: David Lowe.

Acknowledgements

Many colleagues (including those with differing viewpoints) have worked with us over the past decade to help solve the problem of timing of Polynesian settlement and impact in New Zealand and we acknowledge all their contributions. Drs Reg Nichol and Brent Alloway kindly provided photographs, Dr Phil Moore alerted us to the Waihi Beach peat sections, Will Esler told us about Dieffenbach's writings, and Betty-Ann Kamp drafted Figure 2. We especially thank the editors for their encouragement and technical support in preparing our article.

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For full references please consult:
www.pages-igbp.org/products/newsletters/ref2004_3.html

Onshore-Offshore Correlation of Pleistocene Rhyolitic Eruptions from New Zealand: Implications for TVZ Eruptive History and Paleoenvironmental Construction

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Taupo Volcanic Zone (TVZ), in the North Island, New Zealand, is arguably the most active Quaternary rhyolitic system in the world. Numerous and widespread rhyolitic tephra layers, sourced from the TVZ, form valuable chronostratigraphic markers in onshore and offshore sedimentary sequences. In deep-sea cores from Ocean Drilling Program (ODP) Leg 181 Sites 1125, 1124, 1123 and 1122, located east of New Zealand (McCave & Carter, 1997; Hall et al., 2001; Fig. 1), 100 tephra beds have been recognized, post-dating the Plio-Pleistocene boundary at 1.81 Ma. These tephras have been dated by a combination of magnetostratigraphy, orbitally tuned stable-isotope data and isothermal plateau fission track ages. The widespread occurrence of ash offshore to the east of New Zealand is brought about by the small size of New Zealand, the explosivity of the mainly plinian and ignimbritic eruptions and the prevailing westerly wind field (Carter et al., 2003).

Although some tephras can be directly attributed to known TVZ eruptions, there are many more tephras represented within ODP cores that have yet to be recognized in near-source on-land sequences. This is due to proximal source area erosion and/or deep burial, as well as the adverse effect of vapor phase alteration and devitrification within near-source welded ignimbrites. Despite these difficulties, a number of key deep-sea tephras can be reliably correlated to equivalent-aged tephra exposed in uplifted marine back-arc successions of Wanganui Basin (Fig. 1), where an excellent chronology has been developed based on magnetostratigraphy, orbitally calibrated sedimentary cycles and isothermal plateau fission track ages. Significant Pleistocene tephra markers include: the Kawakawa, Omataroa, Rangitawa/Onepuhi, Kaukatea, Kidnappers-B, Potaka, Unit D/Ahuroa, Ongatiti, Rewa, Sub-Rewa, Pakihikura, Ototoka and Table Flat Tephras. Six other tephra layers are correlated between ODP-core sites but have yet to be recognized within onshore records.

The occurrence of fewer than expected equivalent marker beds that can be correlated between Wanganui Basin and the ODP cores is problematic and might be attributed to one or more factors. There is the possibility of narrow and highly directed tephra plumes that restrict the spatial distribution of fallout so that key tephra marker beds might be preserved in one or two cores but not necessarily in cores ideally located downwind from the TVZ and further eastward. Another explanation for the lack of tephras associated with voluminous and widespread eruptive events (e.g., Ongatiti eruption, 1.21 Ma) in Wanganui Basin might be the paleogeographical restriction of riverine sediment distribution systems, which periodically may have favored delivery to the East Coast Basin. Conversely, the products from a number of apparently less-voluminous eruptive events, not identified in the offshore cores, have made their way via fluvial systems to Wanganui Basin.

The lesser number of tephra in the Wanganui Basin may simply reflect the depositional environment. Basinal sediments accumulated in shallow shelfal seas which, judging by the modern shelf off the western North Island, is a high energy setting where the preservation of macroscopic tephra units is not favored, as attested by the paucity of such units in shelf cores. Preservation would have been further disadvantaged by eustatic changes in sea level. Carter et al. (2004), through comparison of eruption history with the $\delta^{18}O$ curve from Site 1123, have shown that the majority of the large rhyolitic eruptions occurred at a time of lower sea level when sub-aerial exposure, fluvial base-level adjustment (downcutting) and subsequent marine transgressions would have eroded any tephra deposit.

An offshore-onshore TVZ eruptive record over the last 2 Ma is summarized in Fig. 2. Some ODP tephra can be attributed to known TVZ eruptions (e.g., the Kawakawa, Omataroa, Rangitawa, Potaka, Unit D/Ahuroa, and Ongatiti tephras). ODP tephra can also be correlated to equivalent-aged tephra beds occurring in marine to near-shore sequences of Wanganui Basin (e.g., the Kaukatea, Kidnappers-B, Pakihikura, Ototoka and Table Flat tephras). However, the source areas of these tephra have yet to be established. Numerous other tephra occurring in ODP cores and Wanganui Basin have yet to be identified in proximal source areas and remain uncorrelated.

Houghton et al. (1995) suggest that major rhyolitic eruptions from the TVZ were related to three main periods of caldera formation: 1.68-1.53 Ma, 1.21-0.68 Ma and 0.34 Ma to present (Fig. 2). However, the ODP records show that major eruptions

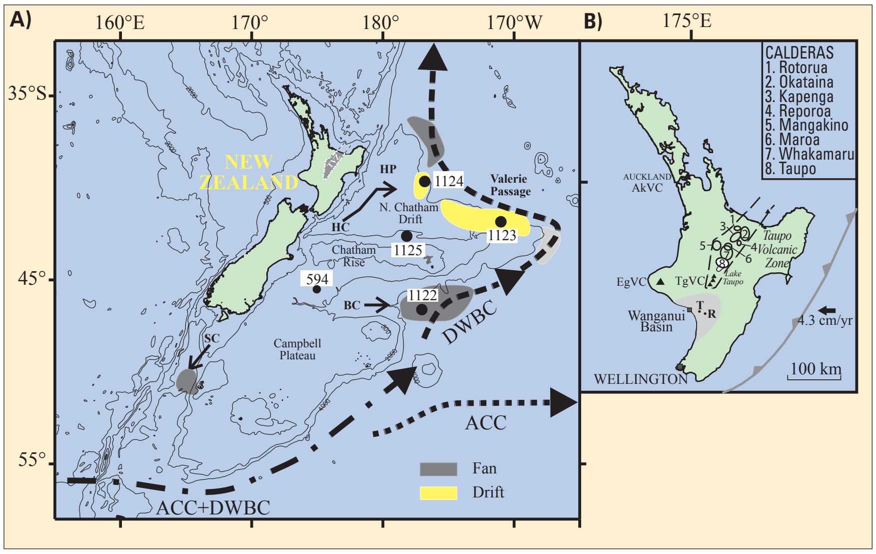

*Fig. 1: (**A**) Location of study area (modified from Hall et al., 2001). Shown is a generalized abyssal circulation scheme and sediment fan drifts, which together make up the major elements of the eastern New Zealand oceanic sedimentary system (Carter et al., 1996; ENZOSS). Contours are at depths of 500, 2000 and 4000 m. Sediment is supplied down the Solander (SC), Bounty (BC) and Hikurangi (HC) channels to abyssal depths and into the path of the deep western boundary current (DWBC), which transports the material along the margin of the Chatham Rise/Hikurangi Plateau, depositing sediment drifts where the flow slows down. The locations of ODP181 Sites 1125, 1124, 1123, 1122 are shown, as well as the location of DSDP-594. ACC, Antarctic Circumpolar Current; TVZ, Taupo Volcanic Zone; HP, Hikurangi Plateau. (**B**) Inset map of the North Island showing location of the Hikurangi Subduction Zone, Taupo Volcanic Zone (TVZ), Wanganui Basin (T, Turakina Section; R, Rangitikei Section) as well as other North Island Volcanic Centers (AkVC, Auckland Volcanic Centre; EgVC, Egmont Volcanic Centre; TgVC, Tongariro Volcanic Centre). TVZ Calderas are numbered 1 through 8.*

also occurred outside those periods, a feature that is confirmed for 1.8-0.6 Ma using data from onshore sites (e.g., Wanganui Basin) distant from the TVZ. The presence of substantial tephra between known periods of caldera formation implies that the ocean received ash from inter-caldera volcanoes or unknown caldera in the TVZ, or from both sources. The ODP record (670-1080 km distance from source) points to more continuous volcanism during the Pleistocene and extending into the Holocene, with a frequency of 1 event per 35 ka (cf. 1 event per c. 50 ka in Wanganui Basin).

Interestingly, the chronology developed for most middle Pleistocene silicic tephra found in distal onshore sites in New Zealand is based on the glass-ITPFT and/or zircon-fission track (FT) techniques. While, FT-age has been pivotal to our understanding of the timing of silicic volcanism and the history of adjacent sedimentary basins, associated age errors range up to 10%. While Ar/Ar tephra ages typically have a lower analytical age error than FT-dates (< 5%), the application of this technique is more restricted due to the sparse occurrence of suitable minerals that can be reliably dated. Certainly, with high resolution records (e.g., tuned stable isotope and light reflectance data, together with paleomagnetic data) like those determined for Site 1123 that can then be graphically correlated to other core sites (e.g., Site 1124), it is possible to derive a tephra age with a precision that is hard to replicate for onshore equivalents dated by either the FT or Ar/Ar techniques.

The identification of previously unrecognized TVZ-sourced deposits in deep ocean records and their correlation to onshore uplifted marine successions (Wanganui Basin) represents a significant refinement of the eruptive record for the TVZ. However, by virtue of distance from the TVZ eruptive source, the Leg 181 ODP records are clearly biased towards macroscopic silicic tephra that represent moderate to large magnitude eruptive events. Tephra from smaller magnitude eruptions, especially those associated with onshore andesitic centers within the TVZ (e.g., Tongariro Volcanic Centre) and/or centers located further west (e.g., Egmont Volcanic Centre), were not noted in the ODP cores. It is un-

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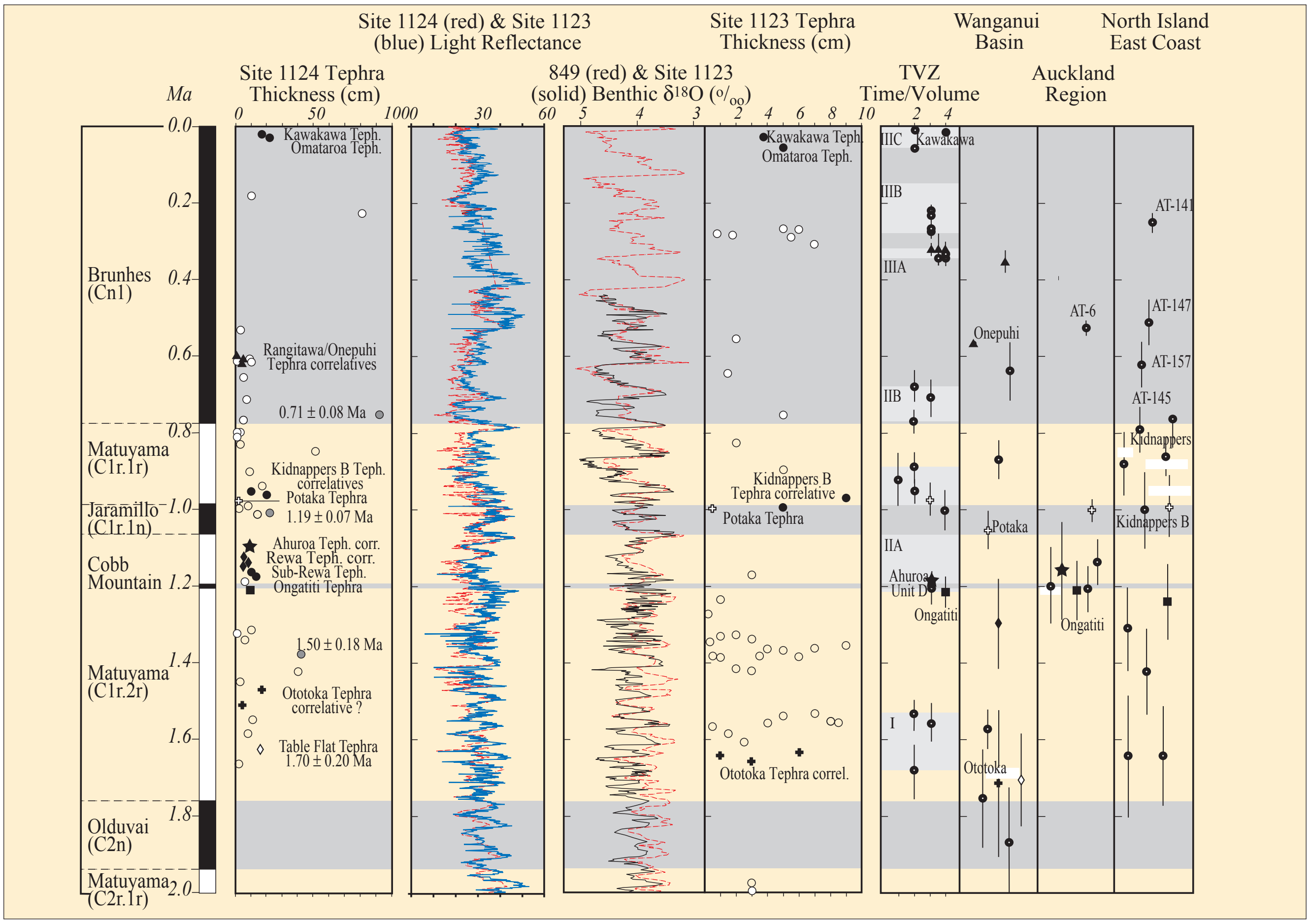

Fig. 2: Summary of 2 Ma record from Sites 1124 and 1123 based on tephra thickness/depth, paleomagnetic polarity, light reflectance and benthic δ^{18}O data. Onshore TVZ record is annotated with periods I-III representing major caldera-related ignimbrite eruptions (shaded light grey). Ages (± 1 SD error) of TVZ eruptive deposits from Wanganui Basin, Auckland region and North Island east coast are also shown.

likely that such eruptives are absent from the marine sites since numerous, dominantly mm-thick (rarely cm-thick) andesitic tephras have been identified within lake sediments on the east coast of the North Island, and in a 35-m-long giant piston core (MD97-2121) retrieved 110 km east of the North Island. At site MD97-2121, the preservation of numerous andesitic tephra has been facilitated by unusually high terrigenous flux extending back to MIS 6 (B. Manighetti and B.V. Alloway, unpublished data). On this basis, it is highly likely that numerous silicic and andesitic *cryptotephra* representing small to moderate eruptive events also occur at ODP181 sites, but that the combined effects of distance and bioturbation in the deep-sea environment prevent their preservation as macroscopic layers. As yet, no direct analysis of cryptotephra has been conducted on the ODP181 cores, although their presence has been inferred from geochemical analysis by Weedon and Hall (in press), who show that anomalous Si/Al, K/Al and Ti/Al values at Site 1123 were associated with tephra-rich sediments.

The identification of Pleistocene TVZ-sourced tephras within the ODP record, and their correlation to Wanganui Basin and other onshore sites, is a significant advance as it provides: (1) an even more detailed history of the TVZ than can be currently achieved from the near-source record, (2) a high-resolution tephrochronologic framework for future onshore-offshore paleoenviromental reconstructions, and (3) an opportunity to critically evaluate the chronostratigraphic framework for onshore Plio-Pleistocene sedimentary sequences through well-dated tephra beds correlated from the offshore ODP sites with astronomically-tuned timescales (e.g., Wanganui Basin, Naish et al., 1998).

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Tracing Volcanic Events in the Greenland Ice Cores

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Although tephrochronology has long been employed as a correlation tool for a broad range of Quaternary sequences, it is only recently that advances in the detection of cryptotephra horizons (tephra horizons that are invisible to the naked eye) have changed the scope and potential of this technique to address paleoclimatic investigations. Identification of distinct cryptotephra horizons in regions not traditionally associated with tephrochronological research has considerably extended the geographical distribution of some tephras, thus emphasizing the potential of using such time-parallel marker horizons for precise correlation of sequences on a continent-wide scale (e.g., Turney et al., 2004). In recent years, investigations in Europe have focused upon the employment of this technique for the improvement of chronological models and for correlative purposes during Termination 1 and the early Holocene (18-9 ^{14}C ka BP)—a period characterized by abrupt and rapid climatic events and plagued by dating uncertainties (Lowe et al., 2001). Indeed, the use of tephrochronology is one of the recommendations made by the INTIMATE and SCOTAV groups for enabling precise correlations of terrestrial, marine and ice core records during this period, with the overall aim of testing hypotheses of synchronous climate change (Turney et al., 2004).

Crucial to this work is a detailed investigation of the tephra record contained within the annually resolved Greenland ice-core records. Chemical signals in the ice, such as sulfate and electrical conductivity measurements (ECM), can be used to construct a detailed volcanic history (Hammer et al., 1981; Zielinski et al., 1996). The origin of such signals remains uncertain however, without the extraction and geochemical analysis of volcanic glass shards contained within the ice. Two important marker horizons of Termination 1 age—the Vedde and Saksunarvatn Tephras—were identified within the GRIP core during the mid 1990s (Grönvold et al., 1995) and represent the only tephras to be traced in terrestrial, marine and ice-core sequences, thus serving as important tie-points. Tephra layers from other periods, such as the Settlement layer and the Ash Zone 2 layer, have also been identified within the GRIP and GISP2 records (Zielinski et al., 1997), but a large proportion of these records remain essentially untouched in terms of tephrochronology and more specifically cryptotephra investigations. Indeed, the detailed Late Quaternary tephrochronology frameworks for the different volcanic regions of Europe (e.g., Haflidason et al., 2000; Davies et al., 2002) accentuate the importance of fully exploring the Greenland tephra records for the presence of tephra horizons.

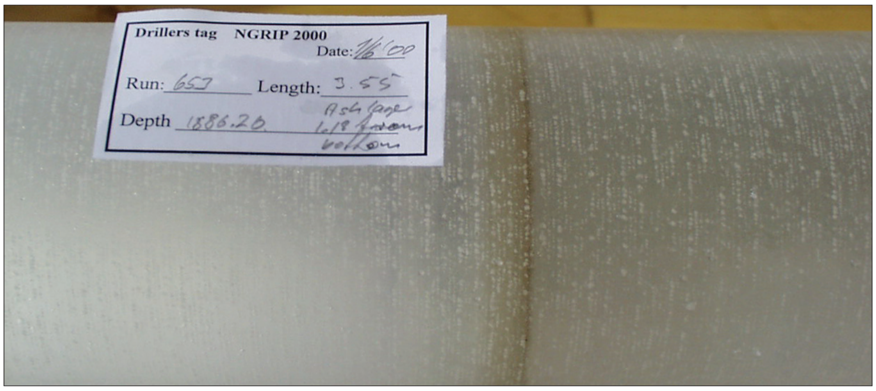

Fig. 1: A 1-cm-thick visible tephra horizon identified within the NGRIP record.

In recent years, teams from the University of Wales Swansea, University of Reykjavik, Queen's University Belfast and Stockholm University, in collaboration with the University of Copenhagen, have begun detailed screening of the GRIP and NGRIP cores for the presence of distinct tephra horizons. Different time periods are currently being investigated by the various teams with the aim of pinpointing key marker horizons that have been previously detected within terrestrial and marine records, as well as examining the detailed volcanic history contained within these records. A portion of this work is undertaken under the remit of the Copenhagen Ice Core Dating Initiative and up until now has focused upon the tephra record spanning the last 30,000 GRIP ice-core yrs BP.

Cryptotephra Extraction

The latest screening of the Greenland ice cores has revealed an abundance of tephra. In some cases, 1-cm-thick tephra horizons have been identified by the naked eye (Fig. 1). In other cases, however, only a few shards, often between 20-40 µm in size and occasionally no more than 5-15 µm (Fig. 2), are present and thus careful extraction and manipulation techniques must be employed to ensure the acquisition of meaningful geochemical results. Tracing the occurrence of cryptotephras therefore relies upon the use of chemical indicators, e.g., sulfate, calcium and ECM data. Often these are useful guides for cryptotephra detection, although in some cases tephra horizons are not accompanied by distinct chemical signatures and vice versa.

Careful subsampling of the archived material is undertaken once a specific horizon has been pinpointed using the high-resolution ice-core chemical data. All particulate material is extracted from the melted sample of ice by centrifugation and is subsequently prepared onto glass slides or SEM stubs. A combination of SEM and light microscopy is used to identify any volcanic particles that may be present and careful thin section preparations are then undertaken to prepare the slide for electron microprobe analysis. Wavelength dispersive spectrometry is utilized to derive the major oxide composition of each tephra. This process is vital for the identification of the source volcano and to ensure accurate correlation with tephras found within other climate records. Precise and standardized geochemical procedures are thus fundamental for the effective use of tephrochronology. Occasionally, geochemical analysis of these tephras can be problematic, particularly as the shard size and the low concentration of shards within some samples can hamper data acquisition. Careful point selection and adequate shard thickness is crucial in these instances.

Ice Core Tephrochronology

Thus far, detailed investigation of the NGRIP sequence has not only revealed the presence of some key marker horizons, e.g., Vedde and Saksunarvatn Tephras, but several previously undiscovered tephras have also been identified. In total, therefore, 12 tephra layers have been identified in the NGRIP record during Termination 1 (Mortensen et al., submitted). Their geochemical compositions point towards Iceland as the most likely volcanic source, although in some cases the major oxide results preclude the precise identification of the source. More distal volcanic regions such as Alaska, the Cascades and Japan must also be considered. Investigations of the GRIP sequence have also revealed the presence of 4 tephra layers that can be correlated with tephras identified within the NGRIP record and as such are important tie-points between the two records that are located 300 km apart. The value of tephrochronology as a correlation tool is clearly demonstrated in this respect. The significance

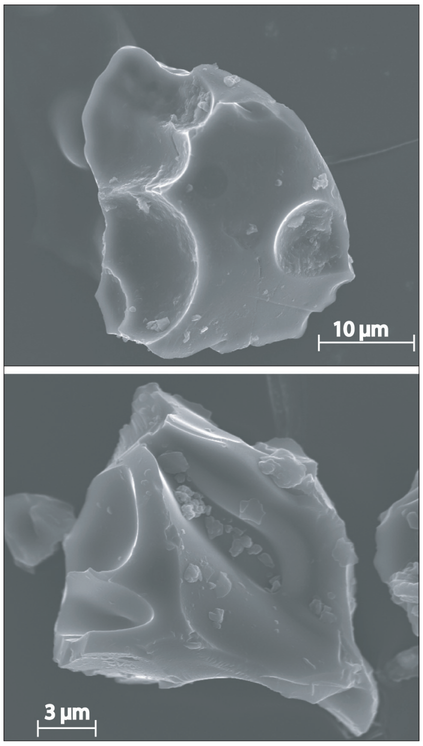

Fig. 2: Scanning electron microscope images of tephra shards extracted from the NGRIP and GRIP records.

and potential of these new tephras as time-parallel marker horizons in the North Atlantic region, however, is uncertain until their presence can be detected elsewhere and the likely distribution pattern identified.

Intense investigations are ongoing to assess whether some of the key Termination 1 marker horizons, e.g., Laacher See (LST) and Borrobol Tephras, that are widely dispersed in other climatic records of Termination 1 age in Europe, occur within the NGRIP and the more-southerly GRIP record. If their position can be pinpointed within these records, this would open up a number of possibilities for correlation with, e.g., annually resolved records in central Europe where the LST is prominent (Litt et al., 2001) and for resolving a number of dating issues that surround the Borrobol Tephra in terrestrial and marine records (Davies et al., 2004).

Future Investigations

Selective screening of the GRIP and NGRIP cores has so far demonstrated that our knowledge of the Icelandic tephrochronology framework is far from complete and the temporal resolution offered by the Greenland records is unmatched for this objective. Consequently, the Greenland tephra record will provide exceptional insight into the eruptive frequency of specific volcanic centers as well as the magnitude and nature of each eruption. The search continues, however, for some of the more well-known marker horizons within the Holocene, Termination 1 and preceding periods that are found within marine and terrestrial records in Europe. Detection of key tie-points between the different records will enable hypotheses of synchronous climate change to be tested, as well as resolving some of the dating uncertainties (e.g., marine reservoir corrections) that hamper paleoclimate investigations during the Late Quaternary.

Acknowledgements

The NGRIP deep drilling project is directed and organized by the Department of Geophysics at the Niels Bohr Institute for Astronomy, Physics and Geophysics, University of Copenhagen. It is supported by funding agencies in Denmark (SNF), Belgium (FNRS-CFB), France (IPEV and INSU/CNRS), Germany (AWI), Iceland (RannIs), Japan (MEXT), Sweden (SPRS), Switzerland (SNF) and the USA (NSF, Office of Polar Programs). The Copenhagen Ice Core Dating Initiative is a 5-year project funded by the Carlsberg Foundation and conducted at the Department of Geophysics, University of Copenhagen. The project involves absolute dating of the NGRIP core and correlation with other paleoclimatic archives using tephra horizons.

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Tephra Geochemistry Confirms the Caldera-forming Eruption of Aniakchak, not Santorini, at 1645 BC

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One of the most powerful volcanic eruptions known to have occurred during the Holocene was the mid-second millennium BC (~3300 ^{14}C yr BP) 'Minoan' eruption of Santorini (or Thera) in the southern Aegean Sea. Much controversy surrounds inferred cultural and environmental impacts attributed to the Santorini eruption; notable among these are mid-second millennium BC climatic variations, as manifested by anomalous tree-ring growth rates and acidity peaks registered in ice-cores from Greenland. One such acidity peak attributed to the Santorini eruption, and recorded in the Dye3 and GRIP ice cores from Greenland, is dated to 1645 BC. In order to link a particular eruption with the ice core record, one must first find and analyze juvenile volcanic materials, then correlate these elemental analyses with known sources. Hammer et al. (2003) claim that glass shards recovered from the GRIP ice core from Greenland confirm a 1645±4 BC age for the Minoan eruption of Santorini. Here we summarize the results of our tephrochronological analyses on Aniakchak (Alaskan) tephra (Pearce et al., 2004) and compare these with the reinterpreted data of Hammer et al. (2003). We propose that the eruption of Aniakchak, not Santorini, can be correlated to the 1645 BC acidity spike.

Hammer et al. (2003) produced major-element data using an analytical scanning electron microscope (ASEM) and trace-element data by ion microprobe (SIMS) to compare the ice-core glass (A1340-7) with the Minoan (Bo-1) glass from Santorini. Despite large analytical errors on their ASEM analyses, and considerable compositional differences in many elements (SiO_2, FeO_t, MgO, Ba, Sr, Rb, Sm, Nb), these samples were considered to be equivalent. Their analyses of Minoan glass

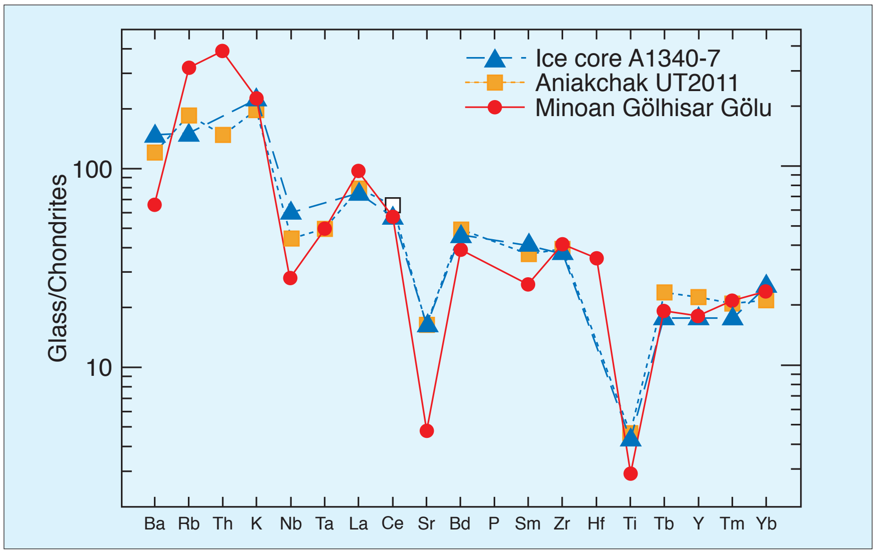

Fig. 1: Chondrite normalized incompatible element spidergram for glass from the GRIP ice core (A1340-7; Hammer et al., 2003), the Minoan tephra deposited at Gölhisar Gölü, SW Turkey (Pearce et al., 2002) and Aniakchak tephra (UT2011; Pearce et al., 2004). (Normalization factors from Thompson (1982)).

(Bo-1) are similar to our analyses of Minoan glass from a sediment core retrieved from Gölhisar Gölü, a small intramontane lake in SW Turkey (Pearce et al., 2002; Eastwood et al., 1999). However, the Turkish data show considerable differences with the ice-core glass. Because of the large number of major-element analyses by Hammer et al. (2003), it was possible to compare directly their ice-core glass composition (by ASEM) with that of other tephras (by EPMA) by recalibrating the ice-core data using the relationship between the Bo-1 data from Hammer et al. (2003) and Minoan glass from Gölhisar Gölü (Eastwood et al., 1999).

We also compared the Hammer et al. (2003) ice-core data with North American eruptions and found that the Aniakchak tephra (UT2011) and the ice core glass (A1340-7) are extremely similar with only minor differences (< 8% relative) for all elements except FeO_t (25% relative difference). In all cases, the 1 σ error on the ASEM analyses of A1340-7 encompasses the analysis of UT2011. The major-element data strongly suggest that the glass in the ice core is derived from Aniakchak; the glass shard data from the other North American sources all have very different compositions.

Hammer et al. (2003) also produced SIMS trace-element analyses of 8 glass shards from the A1340-7 ice core sample and compared these with 3 analyses of glass from the Bo-1 sample. Unfortunately, the analysis of only 3 grains of Minoan (Bo-1) material is statistically insufficient to gain an impression of the accuracy of the SIMS analyses when the heterogeneity of the Minoan pumice, as shown by the large inter-shard variation described recently by Pearce et al. (2002), is considered. Despite this, their trace-element analyses for the Bo-1 glass are broadly comparable with other published analyses of Minoan material for many elements (Pearce et al., 2002; Eastwood et al., 1999). As with the major elements, there are again considerable differences between the two sets of data in the Hammer et al. paper, with factors of up to 2.6 for differences in Sr, around 1.5 for Ba, Sm, Nd and Rb and around 1.2

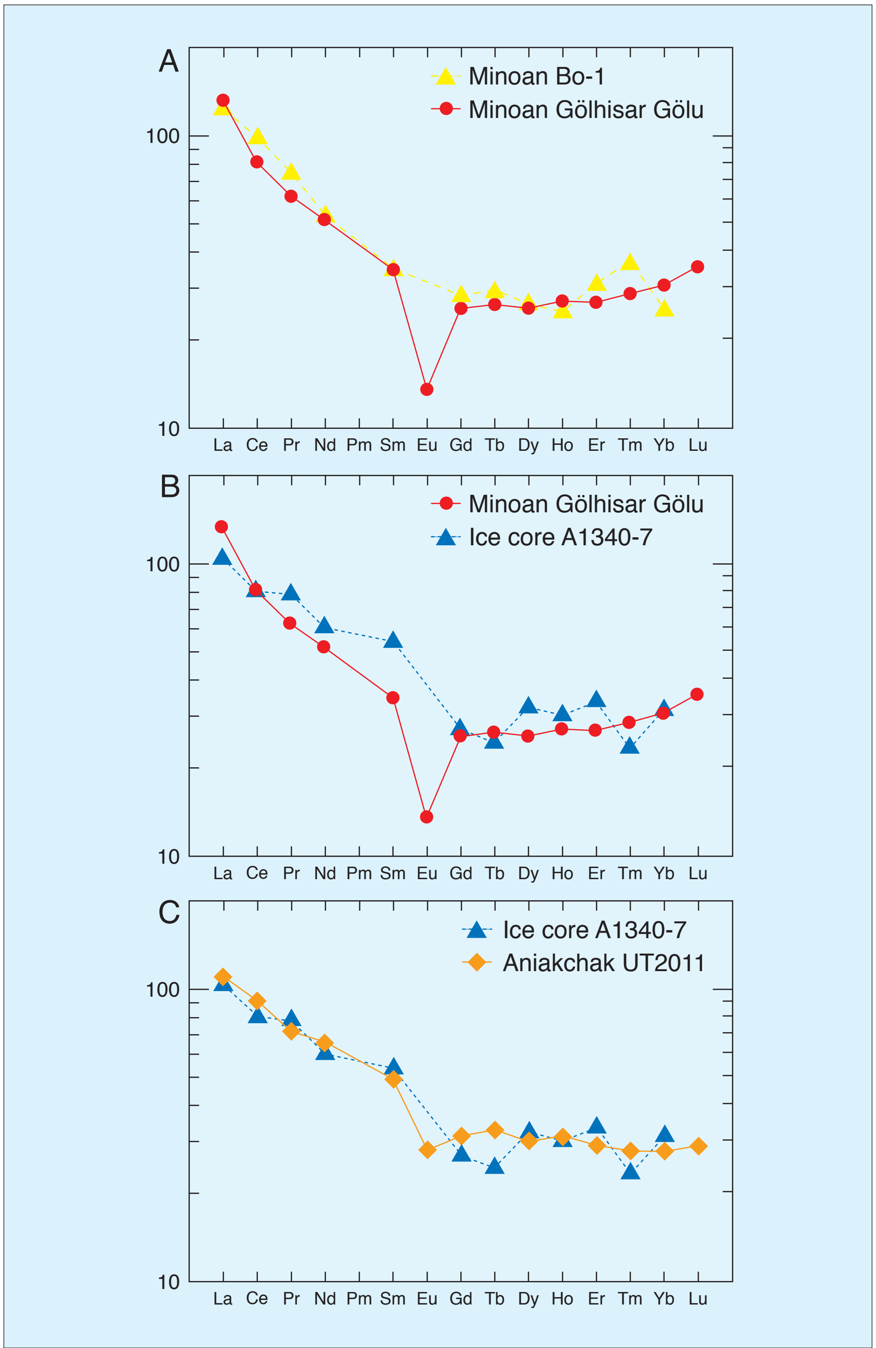

Fig. 2: Chondrite normalized REE spidergrams for glass from the GRIP ice core (A1340-7; Hammer et al., 2003), the Minoan Bo-1 deposit on Santorini (Hammer et al., 2003), the Minoan tephra deposited at Gölhisar Gölü, Turkey (Pearce et al., 2002) and tephra from the caldera-forming eruption of Aniakchak (UT2011; Pearce et al., 2004). (Normalization factors from Sun, S.-s. and McDonough, W.F. (1989)

for the LREE (lighter rare earth elements). Once again, in tephra studies, differences in trace element concentrations of this magnitude rule out a possible correlation. At the reported concentrations (a few 10 to a few 100 ppm), elements such as Ba, Sr, Rb and the LREE should be determined with accuracy and precision (perhaps around ±10%). The differences between the Bo-1 and A1340-7 analyses are well beyond any realistic analytical errors and far too great for these deposits to be considered the same. The differences between A1340-7 and the Minoan ash is further highlighted when they are compared with the 56 single glass shard analyses of the Minoan ash performed by laser ablation ICP-MS (Pearce et al., 2002). The most apparent differences are in the concentrations of Ba, Sr, Rb (Fig. 1) and the LREE (Fig. 2), where it is clear that the REE concentrations determined by Hammer et al. (Bo-1) and Pearce et al. (Gölhisar Gölü) for the Minoan deposit are similar (Fig. 2a), but that there is a marked difference in slope between the Minoan sample and the ice core glass, which has a much lower La/Sm ratio (Fig. 2b).

Trace element data for the Aniakchak tephra (UT2011) has almost identical Sr, Rb, Zr, REE values to A1340-7, as well as very similar Ba, Nb, Y and Cs values (Fig. 1), particularly if some allowance is made for the possible differences in the SIMS analyses of Bo-1 when compared to other analyses of Minoan tephra (Pearce et al., 2002; Eastwood et al., 1999). In Figure 2c, the Aniakchak REE analyses are compared with the ice core A1340-7 analyses, where it is evident that the two data sets have an indistinguishable REE profile. The incompatible element spidergram (Fig. 1) compares the Minoan and Aniakchak tephras with the ice core glass. The Aniakchak tephra and A1340-7 glass are essentially identical, and these both have markedly different Rb, Sr, Ba, Ti, and Sm values from the Minoan tephra.

The trace element analyses concur with the major-element analyses and also rule out the suggested correlation between the ice core glass and Santorini. Instead, they show that the A1340-7 glass was derived from Aniakchak. The chronology of the ice core as defined by Hammer et al. (2003) thus places a firm date of 1645±4 BC on the caldera-forming eruption of Aniakchak. This is also consistent with the suggestion that the acid volcanic signal recorded in the GRIP, North Grip and Dye 3 ice cores is the result of a major volcanic eruption south of Greenland but north of 30°N (Hammer et al., 2003). The presence of glass shards trapped within the ice core in this case directly link the Aniakchak eruption with the acid peak at 1645 BC. While this does not rule out a coincidental eruption of Santorini, it casts severe doubt on the proposed 1645 BC age for the Minoan eruption. Whilst this identification provides an accurate and precise age for the Aniakchak eruption, and a source for one of

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the acid spikes in the Greenland ice cores, our results have two important implications: (i) they leave the controversy about the age of the Minoan eruption unresolved, and (ii) they suggest that the acid spike cannot be attributed to the Santorini Minoan eruption, and therefore the environmental perturbation(s) caused by this eruption were most probably not as widespread or as significant as previously envisaged (Eastwood et al., 2002).

Acknowledgements
We would like to thank Jim Beget for providing the sample of Aniakchak tephra. This work was supported by research grants from the Natural Sciences and Engineering Research Council, Canada to JAW.

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Last Glacial Sea-Levels Reconstructed by Buried Fluvial Terraces and Tephrochronology in a Pacific Coast Plain, Japan

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Introduction

Japanese paleoenvironmental sciences that include tephrochronological studies make a significant contribution to studies of sea-level change during the Last Glacial period. The study here highlights the contribution that Late Pleistocene tephrochronological studies make to a synthesis of findings about past sea-level fluctuations in the Lower Sagami Plain.

Millennial-to-centennial scale climatic fluctuations in the Last Glacial period can be detected in ice-cores (Stuiver and Grootes, 2000) and there is evidence that these are paralleled by changes in sea-level. As a result, much is still to be discovered about eustatic global sea-level changes and corresponding changes in ice volume during parts of the last Glacial period (van Andel, 2002). In coastal areas, however, it is often hard to obtain evidence of sea-levels during the Pleistocene period, as suitable material for study may be submerged or buried under younger deposits.

The small, steep coastal Lower Sagami river plain lacks a distinct continental shelf, therefore changes in sea-level can cause a flight of terraces to form. Tephra layers in deposits from the Lower Sagami Plain provide the means to correlate the formation of the terraces. The area is well-suited to studies that incorporate tephrochronology of Fuji and Hakone Volcanoes for the Last Glacial Cycle.

Fig. 1: Sagami River and its terraces. Minahara (MIS 2) and Tanahara (MIS 3) terraces (back) are steeper than the present river bed (front). Terraces are covered with volcanic ash soil.

Study Site and Methodology

The Lower Sagami Plain has well-developed marine and fluvial terraces and the mouth of the Sagami River (drainage area = 1,680 km^2) faces the ocean trough at a point where there is no distinct continental shelf. The Sagami River has been repeatedly sensitive to past sea-level changes. More than fifteen subaerial terraces from the Last Glacial Cycle can be identified in the lower Sagami Plain, including the Koza (K), Sagamihara (S), Nakatsuhara (N), Tanahara (T) and Minahara (M) terraces. Collectively, these form the Sagamino Upland, from the mouth of the river to about 30 km upstream. The average gradient of the present Sagami River is 2.4x10^{-3} in this section, although most of the upper terraces are steeper (Fig. 1).

The Fuji and Hakone Volcanoes are the major sources of tephra in the terraces. The dates of the major marker tephras have been obtained by fission-track, thermoluminescence, electron spin resonance, K-Ar and 14C. Additionally, the widespread AT (circa 25 ka) and Aso-4 (circa 90 ka) tephras also provide age controls. In the plain, deposition is roughly continuous and the average accumulation rate of volcanic ash soil during the last 100 ka is 0.22 m/kyr (22 m/100 ka). A multi-proxy approach that included tephrostratigraphy, pollen stratigraphy, and correlation with regional stratigraphy was used to determine the chronology of the terraces and their deposits, demonstrating that they correspond to MIS 5e (K terrace), 5c-5a (S terraces), 3 (N and T terraces) and 2 (M terraces), respectively.

The buried terraces in the plain were located by using bore-hole logs. They are recognizable as gravel layers with overlying volcanic ash soil several meters thick beneath Holocene deposits. These buried terraces have steeper profiles than those of the present river plain. Some bore-hole logs describe marker tephras in the volcanic ash soil layer, and in a further core sample, the presence of AT tephra was confirmed by microscopic examination. The occurrence of this tephra layer provided a time horizon for further aspects of the study.

After confirmation of the morphological continuity and tephra sequences, buried terraces and deposits were examined. Buried terraces in the plain correspond to MIS 5a (S), 3 (N) and 2 (M), respectively. The more broadly-extended buried N terrace has thick valley-fill deposits. The base of the buried valley corresponds to MIS 4 (Fig. 2).

Sea-Level Reconstruction

The edge of the continental shelf occurs about 2 km offshore from the present Sagami river mouth, therefore projected terrace height (depth) at its edge represents the sea-level at that time, after tectonic deformation is subtracted. The tectonic component (average uplift rate) is estimated, from deformation of the marine K (MIS 5e) terrace, to be 0.07 m/ky near the present river mouth. Assuming this deformation rate to be constant throughout the period of terrace formation, sea-levels were estimated for the culmination of several stages during the Last Glacial Cycle: -31 to -40 m in MIS 5a; -95 to -109 m in MIS 4; -78 to -89 m in MIS 3; and -102 to -112 m in MIS 2 (Fig. 3).

Sea-level changes show in the changes in the shape of the plain. During MIS 4 and 2, a deep and narrow valley incised the plain. During MIS 3, this deep valley was filled, and a relatively wide plain of compound fans developed, suggesting that a relatively low sea-level remained throughout MIS 3.

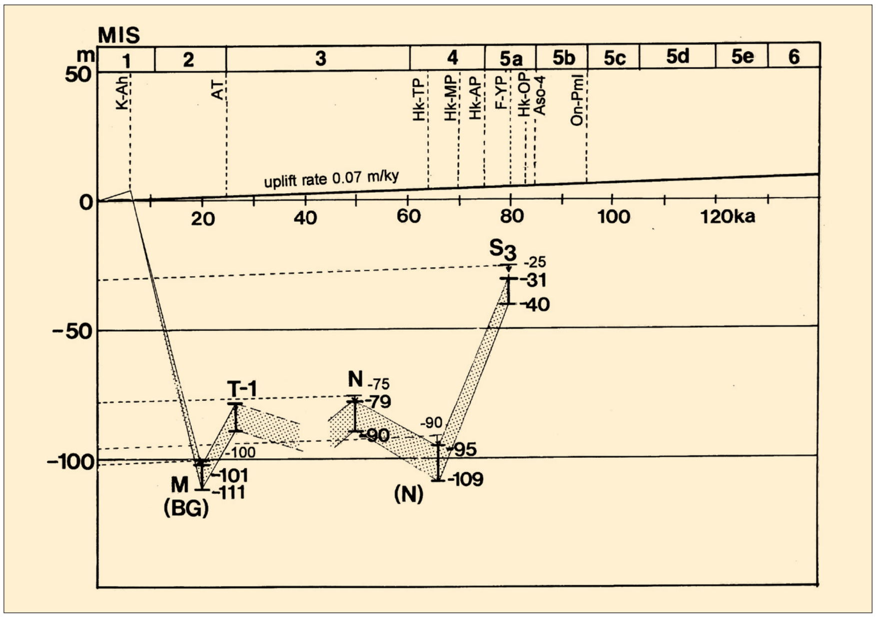

Fig. 3: Sea-level changes during the Last Glacial Cycle reconstructed from buried terraces. Vertical dashed lines show marker tephras. Shadowed area shows estimated sea-levels.

Significance of the Findings

Tephrochronology refined the precision of the chronological framework for the study. With secure time frames at hand, comparing studies of river plain systems during low sea-level stands with studies that employ coral terraces (Chappell, 2002) as well as investigations of fluctuations in ice mass balance will enhance understanding of sea-level fluctuation at times of change in marine systems during the Last Glacial period. In addition, the investigation makes a contribution to studies that investigate early human occupation in Japan.

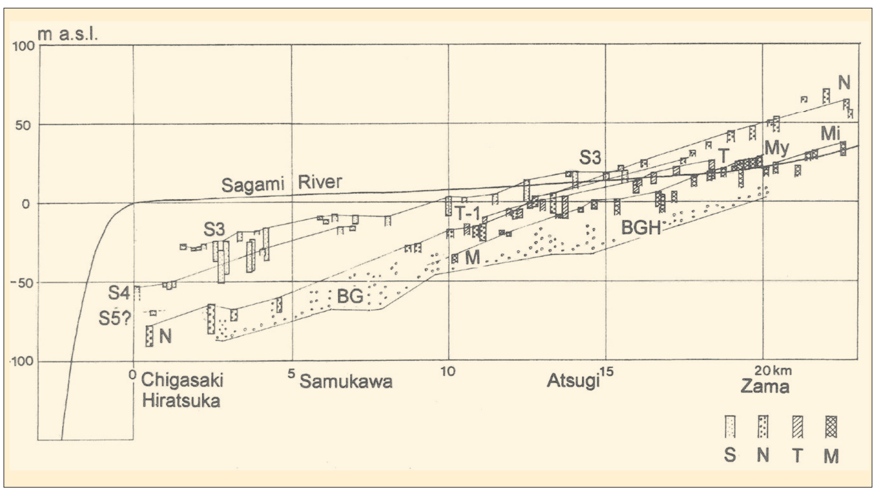

Fig.2: Longitudinal profiles of buried terraces along the Sagami River. S, N, T, M represent the gravel layer of each terrace. BG and BGH are basal gravel of younger deposits.

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Developing Regional Tephrochronological Frameworks for Testing Hypotheses of Synchronous Climate Change

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A key issue in paleoclimatic research is establishing the precise rate and mode of climate response in different parts of the world to abrupt changes in global climate. Crucial to the success of this research is the development of robust regional tephrochronological frameworks. Tephrochronology provides time-parallel marker horizons that allow precise correlation between environmental and climatic records of the recent geological past (Turney and Lowe, 2001). Few (if any) geochronological techniques can provide the precision offered by tephrochronology. The virtually instantaneous atmospheric deposition of tephra following an eruption can often lead to clear tephra layers in a wide range of depositional environments. SCOTAV is dedicated to identifying the global distribution of tephra for a wide range of multi-proxy studies. Nowhere is this more relevant than in the application to studies of past rapid climate change.

As an example of the potential to climate studies, it has long been recognized that in the North Atlantic region, a sequence of abrupt climate changes can be identified through the Last Termination (18-9 ka ^{14}C BP), including rapid warming at 14.7 ka GRIP ice-core years BP ("Bølling" Interstadial, or GI-1 in the Greenland ice-core isotope stratigraphy) and the sustained cooling of the Younger Dryas Stadial (GS-1; 12.8 to 11.5 ka GRIP ice-core yrs BP) (Lowe et al., 2001; Fig. 1). Since 1997, INTIMATE (INTegration of Ice, MArine and TErrestrial records) is a core program of INQUA. Paleoclimate Commission project members have, through a series of international workshops, sought ways to improve procedures for establishing the precise ages of, and effecting high-resolution correlations between, events during this period. With the development

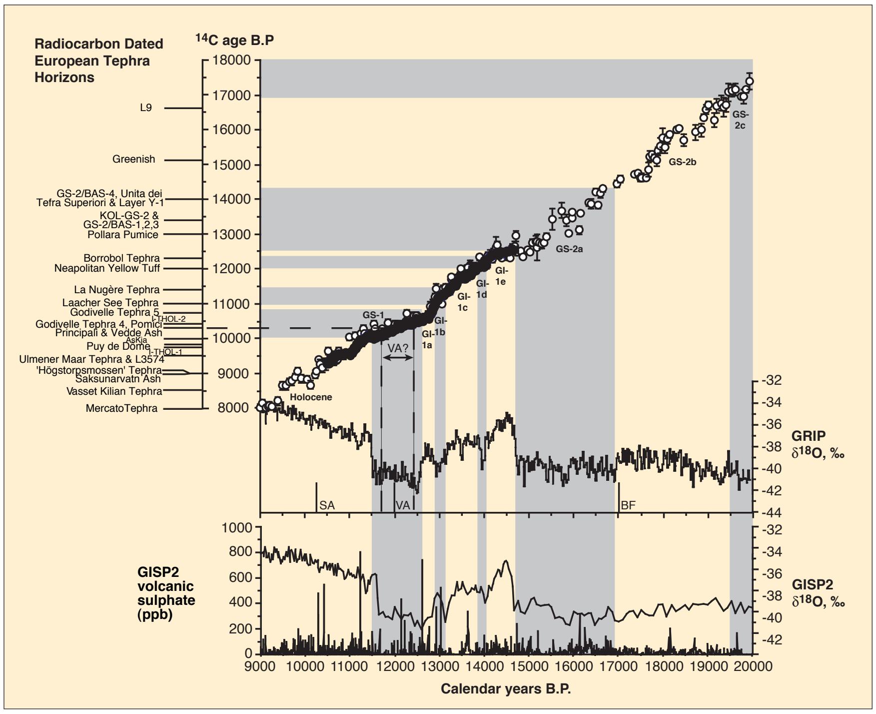

Fig. 1: Radiocarbon calibration curve for Termination 1 and the early Holocene, compared with GRIP and GISP2 $\delta^{18}O$ stratigraphies (Stuiver and Grootes, 2000; Walker et al., 1999). The approximate positions of known European tephra horizons from this period are also indicated. The 'VA?' interval marks the interpolated calendar age range for the Vedde Ash according to the ^{14}C age calibration curve. Abbreviations for GRIP horizons: SA - Saksunarvatn Ash, VA - Vedde Ash, and BF - Black Feather tephra. Open circles: radiocarbon calibration data from Lake Suigetsu (Kitagawa and van der Plicht, 2000). Closed circles: radiocarbon calibration data from Cariaco Basin, assuming a marine reservoir age of 420 ^{14}C years (Hughen et al., 2000). Volcanic sulphate peaks are those reported by Zielinski et al. (1996).

of new methods (e.g., flotation and magnetic separation) for detecting tephra horizons invisible to the naked eye ('cryptotephra') undertaken by members of SCOTAV, the number and geographical extent of horizons has significantly expanded in a North Atlantic context. This raises the potential for a comprehensive tephrochronological framework that will allow high-precision correlation between geographically dispersed paleoclimatic and –environmental records and thereby test hypotheses of synchronous climate change, independent of known fluctuations in atmospheric radiocarbon content.

Not all tephrochronological analyses, however, have been undertaken in the same way, or with the same analytical precision. For instance, electron microprobe analysis of tephra uses energy dispersive spectrometry (EDS) or wavelength dispersive spectrometry (WDS) to measure variations in the concentration of the oxides of the major elements within individual glass shards or mineral grains to characterize tephra horizons. WDS is the preferred method because it enables the relative importance of each major oxide to be monitored individually during analysis. This is particularly important with respect to the oxides of alkali metals, which are vulnerable to mobilization during analysis, though this can often be minimized or corrected for. For all results obtained using electron microprobes, the values are reported as percentages of sample weight. It is rare, however, for the total analysis to reach 100%. In New

Zealand and North America, for instance, it is routine to normalize the data to 100% (Shane, 2000), while in northern Europe it has been argued that no adjustment of the original measures should be undertaken (Hunt and Hill, 1993).

In order to optimize the potential of tephrochronological research, there is a need for improved analytical precision and for less ambiguous classification and terminology across the international scientific community. As a result of the above, SCOTAV has started a program to develop a protocol for improving analytical and reporting procedures, as well as for the establishment of a centralized database of tephra analyses (Turney et al., 2004). Full details can be found on the SCOTAV website at www.gns.cri.nz/inquatephra. Although originally aimed at Europe during the Last Termination, the protocol proposed here is of equal relevance to other regions and periods of interest. Such a protocol (Table 1) should include details about:

1. *Stratigraphical Information*
   Contextual details should be provided about the site, including the stratigraphical context, the coring or other sampling methods employed, the sampling resolution/interval at which tephra were extracted, and whether tephra horizons are visible or traceable only as cryptotephra.
2. *Information on Geochemical Procedures Adopted*
   Information should be supplied concerning the method(s) employed to extract tephra shards, on whether glass shards and other volcanic particles were heated above 350°C, and the type of equipment and analytical procedures used to analyze the shards geochemically. SCOTAV also recommend that the results of geochemical analysis be presented in raw form, irrespective of which methodology is employed or which transformation (e.g., normalization) procedures are adopted, thus enabling re-calibration of the results in the event that revised protocols emerge in the future.

Table 1: Summary of stratigraphical, geochemical and dating criteria recommended by SCOTAV and for inclusion in a centralized tephra database.

1. Site location details
- 1.1 Name of site
- 1.2 Location – eight-figure latitude and longitude position
- 1.3 Location – national grid reference
- 1.4 Site context (open section, infilled lake basin, marine sediment sequence, etc.)
- 1.5 Sampling procedures adopted (coring device used, monolith tin, etc.)

2. Stratigraphical and sedimentological context
- 2.1 Sampling resolution adopted
- 2.2 Associated stratigraphical details (LOI data, paleobotanical details, particle size analysis, etc.)
- 2.3 Visible horizon or cryptotephra
- 2.4 Dissemination of tephra through sequence (quantified concentration data)

3. Tephra characteristics
- 3.1 Morphology of shards
- 3.2 Color and other surface characteristics (e.g., evidence of alteration)
- 3.3 Mineralogical assemblages (if applicable)
- 3.4 Particle size data (where available)
- 3.5 Bedding features (if applicable)

4. Geochemical data
- 4.1. Extraction methods employed
- 4.2. Mineralogical analysis results
- 4.3. Geochemical procedures adopted (EDS, WDS, ICP-AES, etc.)
- 4.4. Major oxide; REE; etc. (raw data)
- 4.5. Normalized and transformed data
- 4.6. Method of transformation
- 4.7. Glass standard(s) used and data

5. Age of tephra
- 4.1 Imported or direct-age estimate
- 4.2 Dating method(s) employed
- 4.3 Data and procedure used for calibration (if relevant)
- 4.4 Statistical uncertainty of age estimates
- 4.5 Materials used for dating

3. *Dating of Tephra Layers*
   Where tephra layers have been dated using independent geochronological methods, the precise procedures and statistical uncertainties of the age estimates should be reported. Tephras can be dated directly (e.g., by fission track dating of the shards) or indirectly (e.g., by radiocarbon dating organic sediments adjacent to the tephra layers, or within which they occur). It is essential that the quality of the age estimates also be assessed and reported.

SCOTAV recommends that in future, the results of tephrochronological investigations be delivered to a regional archive. We propose that regional committees should be initiated throughout the world that develop their own comprehensive databases on behalf of the scientific community. In order to optimize the scientific value of the database, however, it is vital that the reporting of results should follow a systematic and comprehensive internationally agreed upon protocol. An initial draft of the analytical and contextual criteria that should be considered during investigations, and which should be addressed, is provided in Table 1. Few international journals will allow publication of such extensive reports within the main body of the text of a scientific paper and so recourse may need to be made to the use of condensed tables or appendices, and to electronic storage that will be accessible to the scientific community through the internet. Eventually, regional databases could be linked together, allowing the scientific community to access a global dataset. SCOTAV invites expressions of interest for the development of regional tephrochronological committees. The proposed new databases will be managed by a regional steering committee selected from these expressions of interest and the results will be freely available to all scientists with an interest in tephrochronology. We hope to establish the steering committees in early 2005 and their first task will be to consider feedback received on the matters discussed in this paper, and on the content and design of the proposed protocol for the reporting of results (Table 1). Recommendations concerning the draft protocol should be submitted to C.S.M. Turney (turney@uow.edu.au) by the closing date of 31 December 2004.

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Southern Hemisphere Climate Modes: ENSO and Indian Ocean Dipole

8th ICP Conference, Biarritz, France, 6-10 September 2004

During the 8th International Conference for Paleoceanography, a special workshop (Conveyor: Anne Müller, University of Queensland, Australia) was held over two afternoons on Southern Hemisphere Climate Modes. The workshop, with approximately 50 participants over two days, had a strong focus on the ENSO and Indian Ocean Dipole modes. Speakers included Luc Beaufort (Cerege Marseille, France), Tom Koutavas (MIT, USA), Rosalind Rickaby (University of Oxford, UK), Anne Müller (University of Queensland, Australia), Masanobu Yamamotu (Hokaido, Japan), Helen McGregor (Bremen University, Germany), Timothee Ourbak (Bordeaux University, France), and Miriam Pfeiffer (GEOMAR Kiel, Germany). The outcome of this workshop was a summary of current knowledge and gaps in the understanding of Southern Hemisphere climate modes. As an example figure 1 provides an overview of Holocene records of climate change. It was agreed that a focus of future research should be frequencies of ENSO-like climate mean states over glacial cycles, the occurrence of the Younger Dryas in the Southern Hemisphere, the possibility of La Niña-like sea surface patterns, for example, during the Early Holocene, the theory of a suppressed ENSO system during the mid-Holocene, the timing of the onset of the modern ENSO, and the interaction and teleconnection of ENSO and Indian Ocean Dipole modes over geological time, and in particular recent time periods covered by paleoproxies such as corals. The participants also agreed that special attention should be given in the future to the use of, and differentiation between, terminology such as ENSO-like mean states and ENSO-variability

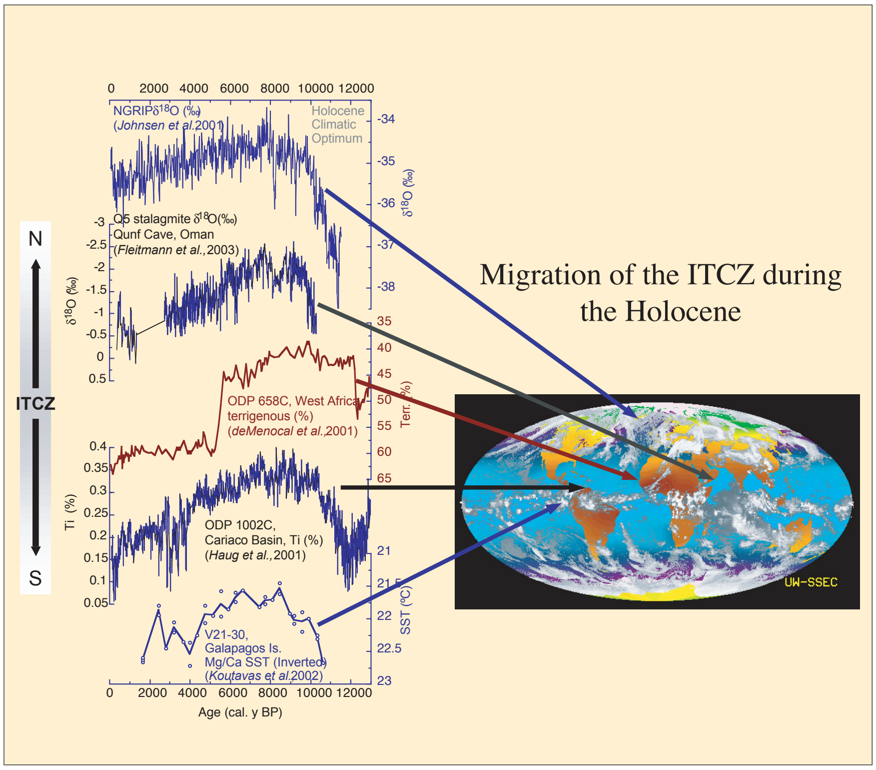

Fig.1: Holocene records of climate change from (top to bottom) Greenland (Johnsen et al., 2001), the Arabian Peninsula (Fleitmann et al., 2003), West Africa (deMenocal et al. 2000), the Cariaco Basin (Haug et al., 2001) and the Galapagos Islands (Koutavas et al., 2002). The cooling trend over Greenland is accompanied by trends to more arid conditions in the northern tropics since the early-middle Holocene. Specifically, oxygen isotopic enrichment of stalagmites from Oman, rising aeolian inputs in marine sediments off West Africa, and decreasing titanium in Cariaco basin sediments, all indicate an effective decrease in rainfall over the course of the Holocene. These trends are consistent with a progressive southward migration of the Intertropical Convergence Zone (ITCZ) over the Atlantic and Indian Oceans. Cooler sea surface temperatures near the Galapagos Islands between 4,000 and 9,000 years ago indicate increased upwelling and support a more northerly ITCZ in the Pacific as well. The base map shows cloud observations during April 1998, with a prominent circum-global ITCZ near the equator.

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Holocene Climate Variability and Climate Forcing

HOLIVAR Workshop, Kastanienbaum, Switzerland, 23-25 September 2004

On 23 September 2004, some 40 scientists met for 2.5 days in Kastanienbaum, Switzerland, to discuss Holocene climate variability and climate forcing within the framework of the HOLIVAR (Holocene Climate Variability) project.

The main objectives of this workshop were to identify and quantify the major forcing factors during the Holocene, to collect evidence for forcing from paleoclimate data, to discuss the role of models in linking climate forcing with climate response, and to develop strategies on how to improve our knowledge of past forcing. The climate system is driven by solar radiation. At the top of the atmosphere, about 30% of the total incoming solar power is reflected back into space, the rest is dissipated within the Earth system and eventually reemitted as infrared radiation. Since the largest input of solar radiation occurs in the equatorial region, the climate system continuously transports

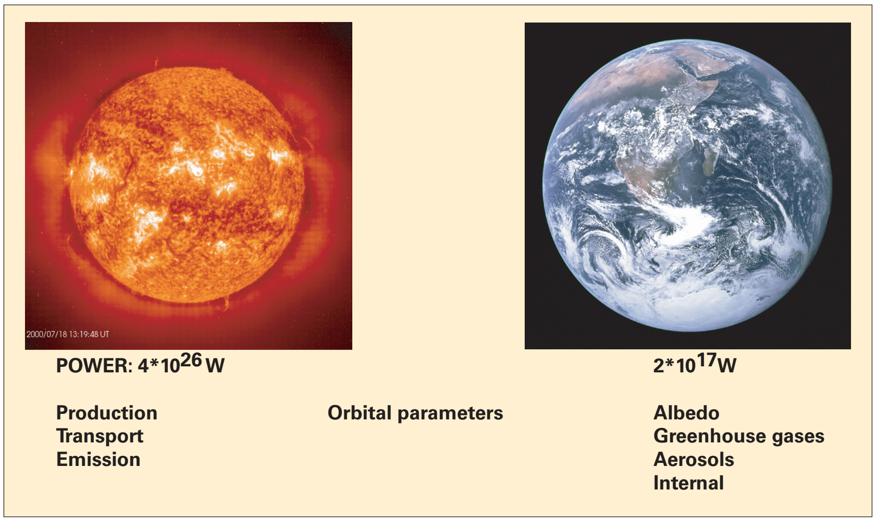

Fig. 1: The Sytem Sun-Earth and related main potential causes for climate changes..

energy through the atmosphere and the oceans towards the poles trying to reach a thermodynamic equilibrium. Any change within this complex system of processes causes either a change in the total power reaching the Earth or in its relative distribution within the Earth system, and therefore leads to climate changes. The main potential causes are listed in figure 1.

All causes of climate change are characterized by relatively large uncertainties, except for two. According to the very robust standard solar model, the energy production in the core of the Sun increases extremely slowly and can therefore be considered as stable for the Holocene period. The distance Sun–Earth, the tilt of the Earth's axis and its precession are affected by the gravitational forces of the other planets and can be calculated with high precision for the past and the future. The variability of all the other potential forcing factors is not yet well understood.

Direct measurements of solar irradiance carried out by satellite-based radiation monitors show that solar irradiance changes in phase with the 11-year Schwabe sunspot cycle. However, the effect is small. During a Schwabe cycle, the average total annual irradiance varies by about 1.5 ‰. On the other hand, the UV part of the spectrum exhibits much larger changes, which affect the ozone layer and stratospheric chemistry. An important question is whether larger changes occurred at times when the average solar activity was considerably different, as for example during the Maunder Minimum (1645-1715), when sunspots were almost completely absent. In fact, there is growing evidence that on longer time scales, the variability in solar irradiance is larger than during the short instrumental period. The strongest evidence comes from the cosmogenic radionuclides (^{10}Be, ^{14}C). Their production rate in the atmosphere is modulated by solar activity. Records from ice cores (^{10}Be) and tree rings (^{14}C) offer the unique possibility of tracing changes in solar activity all the way back through the Holocene. However, there is no physical model available yet to quantitatively link solar activity with solar irradiance.

Forcing by greenhouse gases became an important issue with the burning of large amounts of fossil fuel. Presently, the main open question is how the various sources and sinks will affect the atmospheric concentration during the next few decades. But also the ice-core derived history of greenhouse gas variations during the last 10,000 years still gives rise to some puzzling data. On the one hand, reconstructions of CO_2 concentrations derived from paleo stomata frequency records show unexpectedly large amplitudes on comparably short time scales. On the other hand, even the standard model of CO_2 during the Holocene is not really understood yet. The 20 ppm drop down to 260 ppm between 10 and 8 kyr was followed by a slow rise to modern pre-industrial levels. Several hypotheses have been formulated to explain this evolution of the most important greenhouse gas. The hope to constrain the role of these different processes by additional δ^{13}C measurements made on the CO_2 from ice turns out to be extremely difficult. The possibility of an early influence of man on CH_4 and CO_2 by agriculture and deforestation as suggested by Ruddiman (PAGES News 2004/1) is interesting, however the majority of evidence seems to argue against such a possibility, in particular for CO_2.

The effects of aerosols, which are also strongly related to anthropogenic activities during the past century, are difficult to quantify for two main reasons. Firstly, their radiative properties depend on many different parameters and vary with time. Secondly, by analyzing ice cores, it is extremely difficult to estimate the relevant aerosol properties of past volcanic eruptions and dust picked up by wind in arid areas.

Climate models play a crucial role in estimating the amplitude of the response of the different forcings and their spatial patterns. However, models are far from perfect and may lack important mechanisms. Since 10,000 years is too long for complex model runs, a promising strategy could be to study in detail time slices that are relatively well documented regarding one single forcing factor and spatial climate response.

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Feb. 13 - 18, 2005, Buellton, California, USA
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Further Information:
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