U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Marine Oxygen Isotope Stage 11 and associated Terrestrial Records:

Workshop Report

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Introduction and background

Because of the concern for potential global climate change, there is growing interest in better understanding and documentation of the history of natural climate and environmental changes. Information on recent periods of the Quaternary when conditions were demonstrably warmer than the present provides a way to gain insights into the likely impacts of possible future warming and represents one means for identifying any human-induced diversions from natural variability. Key features include the amplitude and periodicity of decadal to millennial scale climate variability, the identification of systems and areas that are most impacted by warming, and the links between the carbon cycle and global temperature. The potential impact of increasing global temperature on ice caps and sea level is especially critical. Many glaciers and small ice caps around the world are receding rapidly. If larger ice sheets begin to recede, sea level could change dramatically. The most vulnerable ice sheet is the marine-based West Antarctic Ice Sheet, which contains enough water locked up as ice to raise sea level ~ 5-6 meters.

An increasing number of studies point to marine oxygen isotope stage 11 (MIS 11) (423-362 ka) as the longest and warmest interglacial of the past 500 kyr (see Howard, 1997 for summary). Modern barrier reef systems may have originated during or shortly before MIS 11, and sea level may have been substantially higher than present during MIS 11, implying collapse of one or more major ice sheets, like the West Antarctic or Greenland Ice Sheets, or both. Milankovitch forcing due to changes in earth's orbital parameters during MIS 11 was similar to modern conditions, as were millennial-scale climate variations. Thus, MIS 11 is a prime candidate for an interglacial that can provide a credible scenario for a future global warming.

In order to better define research objectives and sampling needs for future work on MIS 11, a one day international workshop with over 25 participants was held in San Francisco on December 5, 1998. The workshop was co-sponsored by the U. S. Geological Survey and the Joint Oceanographic Institutions/U.S. Science Support Program. Five summary presentations, followed by a poster session and informal presentations, generated lively discussions focused on the following issues. How was MIS 11 generated and how long did it last? Was the earth warmer and sea level higher than present during MIS 11?

The agenda and list of workshop participants are in appendices 1 and 2.

Summary and Recommendations

Summary

The morning presentations were designed to summarize current information and identify key issues for the afternoon discussion. The talks were informal, and time was allowed for substantial discussion following each presentation. The topics covered included:

1.	Stage 11 and solar forcing by Richard Muller	UC Berkeley
2.	The Vostok ice-core record by Dominique Raynaud	LGG&E
3.	The sea level record by Julie Brigham-Grette	U Mass
4.	The continental record of Stage 11 by Denis-Didier Rousseau	U Montpellier
5.	The marine record of Stage 11 by Will Howard	U Tasmania

In addition to the scheduled morning presentations and poster sessions, a number of presentations of recent research results and activities were given at the start of the afternoon discussion. Abstracted summaries of workshop presentations are provided in the following section. In general, the workshop presentations and discussions centered on the following primary issues: the mechanism and length of MIS 11, the warmth of stage 11, and sea level during stage 11.

Origin and length of MIS 11

Although MIS 11 is one of the best developed late Pleistocene interglacial stages observed in the marine and terrestrial record, MIS 11 cannot be explained or modeled by changes in solar insolation predicted by the standard Milankovitch mechanisms as can most other late Pleistocene interglacial intervals (Imbrie and others, 1993; Berger and Jansen, 1994; Berger and others, in press). The overall depressed summer insolation within the 60 to 70° N latitude range during MIS 11 is too low to force the unusually strong interglacial conditions associated with MIS 11 and leads to what Imbrie and others (1993) have referred to as the "stage 11 problem". Muller presented an alternative theory "orbital-inclination/dust" model to explain the cyclicity of Quaternary glaciations. He pointed out that variation in orbital inclination is a good match with the Specmap data (see fig. 1 of Muller this volume) and demonstrated that with his model the "stage 11 (and stage 1) problem" disappears.

Discussion on the length of MIS 11 is linked directly to the problem of time scales and dating techniques. MIS 11 falls in between calibration points provided by ^{14}C dating and the radiometrically dated Brunhes/Matuyama boundary. Thus the age estimates for MIS 11 in marine sequences are highly dependent on sediment accumulation rate assumptions and the use and details of "spectral tuning". Several versions of time scales for the Brunhes are available that can cause up to several 10's of thousands of years difference in the age of Termination V – the mid point of the MIS 12/11 deglacial – and the length of the peak warm interval during early MIS 11(e.g., Imbrie and others, 1984, Shackleton and others, 1990; Sarnthein and Tiedemann, 1990). Following much spirited discussion on the Milankovitch versus orbital-inclination mechanisms and "spectral tuning", the group concluded that the Specmap time scale appears to represent the best model for dating MIS 11. Using the Specmap chronology, a number of isotopic records, including high-accumulation rate sites in the Southern Ocean and North Atlantic, suggest that the peak warm interval at the beginning of MIS 11 is on the order of 20,000 to 30,000 years duration. This contrasts with the duration of about 10,000 years for the warmest part of MIS 5e. The length of the climate optimum for MIS 11 could readily explain why many older studies based on coarse sampling intervals found MIS 11 to be the warmest interglacial of the Bruhnes. The wide sampling intervals used in earlier studies were more likely to include the warmest interval of MIS 11 than the warmest interval of other (shorter) interglacial intervals.

Warmth of MIS 11

Lines of evidence for the degree of warming during MIS 11 from the marine, terrestrial, and ice-core records remain complex. The most recent isotopic and planktic faunal data sets from high-accumulation rate marine sequences in the north and south Atlantic, presented by several workshop participants, indicate that MIS 11 was not warmer but even slightly cooler than the Holocene (Howard, this volume; Oppo and others, 1998; Hodell and others, in press). In contrast, terrestrial data reviewed during the workshop by Rousseau indicate that stage 11 was in many instances warmer than the Holocene and MIS 5e. For example, the amount and composition of pollen assemblages in several European sections referred to the Holsteinian, which is considered to be the equivalent of MIS 11, indicate conditions warmer than Holocene. Similarly, pollen assemblages from the New Zealand contain frost-intolerant species in Holocene, MIS 5e and MIS 11, suggesting temperatures during Stage 11 were at least as high as they were in Holocene and MIS 5e(Howard and others, in prep). The most recent data sets from numerous and diverse geochemical and isotopic analyses of the 3500 m-long ice core recovered at Vostock were presented by Raynaud. The ice record includes four full glacial-interglacial cycles characterized by strong 100 kyr (eccentricity) and 40 kyr (obliquity) frequencies that contrast with weak precessional frequencies. Among the four interglacial stages, MIS 9 and MIS 5e clearly were the warmest interglacial stages and have the highest CO_2 and CH_4 concentrations relative to MIS 7 and the Holocene. Raynaud was reluctant to compare these last four interglacial stages with the recorded interglacial MIS 11 at the base of the Vostok ice core. The MIS 11 climatic optimum might be not represented in the ice record, and if represented, the fluctuations of MIS 11 T°C, CO_2 and CH_4 records were likely disturbed by ice flows and should be regarded with suspicion.

MIS 11 sea level

As summarized by Brigham-Grette, there is widespread evidence of a sea level high stand of about + 20 meters from extensive shoreline deposits on the north slope of Alaska that are correlated with MIS 11. Amino acid data and stratigraphic correlations indicate the age of the high stand is pre- MIS 5, but the available data do not preclude the high stand from being related to other Bruhnes interglacials such as MIS 9, MIS 13 or 15. Wave cut platforms near Sussex, UK, which suggest a +20 meters sea level, are also dated as Stage 11 by aminostratigraphy. The platforms fit within a regional framework that is very consistent with the MIS 11 assignment (Bowen, this volume). Further, studies in Bermuda and the Bahamas (Hearty and others, in press) support a +20 meter MIS 11 sea level. Raising sea level +20 meters above current levels requires elimination or large reductions in the West Antarctic and Greenland Ice Sheets. Scherer and others, (1998) have recently proposed, based on the occurrence of diatom assemblages and high concentrations of beryllium-10 in sediments below the West Antarctic Ice Sheet, that the ice sheet collapsed one or more times during the late Pleistocene, most likely during MIS 11. The diatom assemblages are consistent with a MIS 11 correlation but slightly older or younger interglacials cannot be ruled out. Similarly, cosmogenic isotope concentrations in sediments recovered beneath the Greenland Ice Sheet are consistent with the elimination of the ice sheet within the past 500 kyr, and the absence of ice-rafted detritus during the warm peak of MIS 11 in North Atlantic ODP 980 also indicates ice was absent from Greenland during MIS 11 (Stanton-Frazee and others, this volume). Thus, different data sets from a variety of areas point towards significantly higher sea levels during the mid-Brunhes, between MIS 9 and 15.

Note that if a +20m sea level is accepted for MIS 11, the slightly more positive $\delta^{18}O$ values summarized for Stage 11 at the workshop would represent cooler sea-surface temperatures in order to balance the more negative $\delta^{18}O$ of ocean water due to reduced continental ice. Thus, the combined sea level and $\delta^{18}O$ observations would indicate a reduction in continental ice volume took place during an interglacial that was cooler than the Holocene. One possible way to reconcile the sea level and $\delta^{18}O$ data would be to conclude that the Greenland and West Antarctic Ice Sheets became unstable and melted during Stage 11, because the Stage 11 temperature maxima was longer, not warmer than other Pleistocene interglacials.

Recommendations

Based upon the presentations and discussions at the workshop, it is evident that considerable gaps and uncertainties remain in our understanding of the features and details of the temporal and spatial variation of Earth's environment during MIS 11 and the other late Pleistocene interglacials. Specific research issues that require additional work are listed below. We find that the sea level issue is especially important. We also conclude that better information is needed for other late Pleistocene interglacials.

Important research goals for MIS 11 include efforts to determine the :

1. Temporal and spatial distribution, as well as magnitude of warming
2. Amplitude and frequency of millennial and submillennial-scale variability, especially in the first half of MIS 11
3. Global climate mosaic during one or more time intervals of stage 11
4. History of sea level change and, by extension, the fate of ice sheets in Greenland and Antarctica during MIS 11
5. Recovery of a complete MIS 11 ice core record
6. Impact of the establishment of modern barrier reefs on marine and atmospheric carbon reservoirs during MIS 11.

In the past, suggestions that DSDP and ODP consider Quaternary objectives for drilling have been discouraged, largely because such objectives (particularly late Quaternary) could be addressed with conventional piston coring. However, developments in climate and paleoceanographic research over the last decade and the results of this workshop demonstrate that information on millenial- and submillenial-scales are needed to address key questions. Recent studies (e.g., McManus and others, 1999; Oppo and others, 1998) demonstrate that reliable climatic and oceanographic signals can be obtained from close sampling (2-4cm) in deep-sea sediments. Thus, high accumulation rate sequences and laminated deposits, such as those occurring in the Santa Barbara Basin and Cariaco Basin, can provide resolution comparible with ice core records. Even with close sampling intervals, developing millenial- and sub-millenial-scale resolution requires sections that have accumulation rates in excess of ~10 cm/1,000 years. Aside from areas where overlying sediments have been removed or greatly compacted, sequences with >10cm /1,000 years accumulation rates beyond MIS 5 are out of the reach of normal piston coring. Thus, obtaining records of most late Pleistocene interglacial intervals with high accumulation rates requires sampling with the advanced piston coring or extended core barrel techniques of ODP.

Devoting entire cruises to late Pleistocene objectives may be impractical due to lack of sufficient high-priority targets within reasonable transit times. Developing cruises that combine late Pleistocene climate history objectives with other science objectives may be more appropriate. Outlining specific targets for coring is beyond the scope of this workshop report, however; following are several examples of areas that provide clear opportunities for multi-objective science plans.

Gulf of Mexico

Many areas of the Gulf of Mexico (GOM) preserve thick sequences of upper Pleistocene deposits that can provide valuable information on past climate and oceanographic conditions. Results from existing ODP Sites and piston cores demonstrate that sediments in enclosed and semi-enclosed basins on the northern and northwestern slopes of the GOM were deposited very rapidly and that they contain information on the timing and magnitude of deglacial events, fluctuations in bottom waters, changes in surface water faunas, and a record of volcanic activity in the caribbean region (e.g., Kennett and Huddlestun, 1972; Kennett and others, 1985; Joyce and others, 1993). Piston cores also indicate that accumulation rates >10cm/1,000 yrs persist over most of the western GOM. Conventional piston cores do not penetrate beyond MIS 5, and existing ODP HPC cores were taken early in the program and have recovery and disturbance problems. Additional HPC coring in the GOM will likely provide sediments suitable for obtaining a detailed record of most if not all of the late Pleistocene interglacials. These records may also provide important information on variations in the North American continent through sediment and fresh-water signals from the Mississippi and other rivers that drain into the GOM.

There is considerable interest in a GOM drilling program designed to investigate gas hydrate formation and processes. Proposals for one or more gas hydrate cruises are currently being developed. Designing a program that included gas hydrate and late Pleistocene climate history objectives for coring in the GOM could be an effective combination of science priorities that would maximize ship time and science results.

Eastern equatorial Pacific

Although accumulation rates are not as high as in the Gulf of Mexico, the easternmost equatorial Pacific is an important region to test hypothesis about the timing and extent of MIS 11 warming. It not only serves as one end of the east-west equatorial system and the El Nino/la Nina dance, but it also records fluctuations in the cold-water eastern boundary currents. Not only can stable isotopes be used to monitor time and ice volume, but important, widespread and easily recognizable volcanic ash layers occur in cores recovered from along the Central and South American coast. These may be used for high resolution, long distance correlation. Previous work on the Holocene in this region suggest that El Nino was less frequent between about 12,000 and 5,000 years BP; in some cases as many as 95 years elapsed between events during the Holocene while periodicity during the late Holocene was less than 10 years. This has implications for hurricane generation in the Atlantic because the jet stream during El Nino years tends to knock the tops off of Atlantic hurricanes before they can form.

Interestingly, MIS 5e seems also to have witnessed changes in the intensity and periodicity of El Nino events in the eastern equatorial Pacific. Our unpublished data suggests that the MIS 6/5 boundary witnessed an increase in El Nino intensity which lasted for a good portion of MIS 5. This raises questions about El Nino/La Nina activity during MIS 11 and prompts us to call for ODP sites over the location of V19-29 and V19-30, (i.e., some 140 kilometers from the coast of Ecuador).

In summary, the results of this workshop point out the need for developing a long-term program to obtain high accumulation rate sequences appropriate to document and understand the environmental conditions and variability during OIS 11 and other late Pleistocene interglacials. Establishing such a program would allow ODP to contribute significantly to high-priority national and international global change research efforts.

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ABSTRACTS

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+23 m STAGE 11 SEA-LEVEL IN SOUTHERN BRITAIN

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Based on an assumed average uplift rate calculated from a 5e sea level at 2 m, an eustatic sea level for dated stage 11 marine deposits is estimated to have been at least 23 m above present.

Two major wave-cut platforms border the English Channel from east to west in Sussex, UK. The higher is up to 2 km wide and ranges between ~ 20 m and an old cliff at ~35 m that is mapped for about 40 km. The lower is up to 15 km wide and lies between about 2.5 m and a cliff at about 15 m that is mapped for about 50 km (Shephard-Thorn and others, 1982). Both platforms are overlain by fossiliferous marine sands and gravels. A north-south 10 km traverse between Boxgrove in the north and Bognor Regis in the south intersects the few fossiliferous localities that are known at Boxgrove, Norton, Oving, and Nyetimber (Lovell and Nancarrow, 1983).

Those localities provided samples for an aminostratigraphy that is correlated with an independently calibrated marine aminostratigraphic model applicable to this area (Bowen & Sykes, 1988), as well as one for terrestrial mollusks (Bowen and others, 1989; Bowen and others, in press).

Site	Species	D-alle-L-Ile slow & moderate racemisers	$\delta^{18}O$	$\delta^{18}O$ mid-point	Highest dated elevation	Uplift corrected sea-level	Eustatic sea-level estimate
Oving	*M. balthica*	0.21 +/- 0.01 (7)	5e	-	8.8	6	2
Nyetimber	*L. saxatilis*	**0.17 +/- 0.005 (3)**	7	214	6	10.7	4.7
Norton	*M. balthica*	0.31 +/- 0.2 (3)	9	306.5	9.8	15.3	5.5
Boxgrove	*L. littorea*	**0.28 +/- 0.2 (36)**	11	395.5	43	19.8	23.2

Table 1: Data for estimating sea-levels on a north-south 10 km transect from Boxgrove to Bognor Regis based on an assumption of an average uplift rate of 0.05 m/ka. D-aIle/L-Ile data gives mean value with one standard deviation and number of samples (x). D-aIle/L-Ile slow racemisers (bold) are standardised to *Littorina* s.l. *torea*; thus data for Boxgrove are from *L. littorea, L. saxatilis* and *Nucella lapillus.*

In addition, further ratios from Boxgrove were measured on *Neptunia contraria* (0.32 +/- 0.02 [3]), and a single measurement on the `moderate` epimeriser *Macoma balthica* on nearby Waterbeach, at 34.5 m, gave a ratio of 0.38. Farther east at ~ 6 m on the lower platform at Portslade *Littorina littoralis* shells provided a ratio of 0.12 +/- 0.004 (5) that is consistent with the 5e ratio for `slow` epimerising species.

Aminostratigraphy shows that the upper platform bears marine sediments of one sea level, whereas the lower one was reoccupied on three occasions. It is not known if all three sea levels represented on the lower platform reached the cliff line at ~15 m, but it is presumed that the oldest deposits of stage 9 were contemporaneous with it. This agrees with the interpretation of the British Geological Survey who suggested that the upper platform carried sediments of one marine transgression and regression, while the lower one had been re-occupied on more than one occasion (Shepard-Thorn and others, 1982). It does not agree with Bates and others (1997) who suggested that the deposits of three sea-levels occurred on the higher and two on the lower platforms.

Szabo and others (1994) estimated that global sea-level during sub-stage 5e was between 1 and 3 m above present. A figure of 2 m is adopted from his work to test the age and field relationships along the traverse from Boxgrove to Bognor Regis. Szabo and others (1994) further suggested that sea level was high by 130 ka as indicated by numerous uranium-thorium ages throughout the world.

To calculate an uplift correction graph, the sea level for sub-stage 5e is assumed to be 2 m. This is subtracted from the highest known elevation for the aminostratigraphically dated 5e deposits at Oving at 8.8 m to relate them to their contemporary sea level. Thus, the Oving deposits were uplifted by 6.8 m in 130 ka at an average uplift rate of 0.05 ka. If it is assumed that this uplift rate is capable of extrapolation backwards, then comparison of predicted elevations against actual ones may provide an estimate of contemporary eustatic sea levels (Chappell, 1974). On such assumption, elevations of sea-level are calculated for the midpoints of oxygen isotope stages 7,9 and 11 (Bassinot and others, 1994). The difference in elevation between the marine deposit and the uplift corrected sea-level is a measure of the height below above present sea-level at which it was deposited.

The uplift-corrected stage 11 sea level is 19.8 m,. Given that the highest Boxgrove sands are at 43 m, the contemporary eustatic sea level was at least 23.2 m higher than present. Thus, it is possible that substantial deglaciation of parts of West Antarctica and Greenland may have occurred.

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Marine Isotopic Stage 11 High Sea Level Record from Northwest Alaska

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The northwest coast of Alaska, stretching from Nome northward to the Alaskan Arctic Coastal Plain and the Canadian border, contains a record of at least 6 high stands of sea level (see reviews in Brigham-Grette and Carter, 1992; or Kaufman and Brigham-Grette, 1993). Preserved as a series of shorelines, terrace deposits, and superposed shelf sequences, these features contain depositional and fossil evidence of brief periods since the middle Pliocene when relative sea level was much higher, and climatic conditions were as warm or much warmer than today. Only the Gubik Formation on the Alaskan Arctic Coastal Plain contains all 6 high stands in superposition.

The most prominent shoreline on the northwest Alaskan coast formed during the Pelukian Transgression, correlated with marine isotopic stage 5e (MIS 5e). At an altitude of about 10-12 m, the fossil beaches, barrier islands, and spit complexes found remaining today represent storm beaches developed at a time when seasonal sea ice was less than now (Brigham-Grette and Hopkins, 1995). The next most prominent shoreline landward of the 5e level lies at about 22-23 m above sea level. On the Alaskan Arctic Coastal Plain, the shelf, beach, and lagoonal complexes deposited during this high sea stand are lithologically known as the Karmuk member of the Gubik Formation deposited during the Wainwrightian transgression (Brigham-Grette and Carter, 1992). Correlative deposits include the Cape Blossom Formation in the Kotzebue region (Huston and others, 1990; Roof, 1995) and the Anvilian transgression on the Nome Coastal Plain (Kaufman, 1992). Like 5e, some of these deposits are also storm beach deposits, elevated some 4 m or so above what may have been mean sea level.

Following several lines of evidence, local workers all consider the 22-23 m shoreline correlative with the MIS stage 11 interglacial high sea stand. The Karmuk member of the Gubik Fm is dated by U-trend dating at 540 ka +/- 60 ka (Brigham, 1985). An amino acid age estimate calibrated to the MIS 5e shoreline yields an age estimate of about 475 ka, and Pushkar (QSR, in press; Pushkar and others, in press) places the deposits into the middle part of the *Rhizosolenia barboi* diatom zone (0.43-0.36 Ma). At Kotzebue, the deposits are older than the Old Crow Tephra dated to 140ka (Roof, 1995), and on Seward Peninsula the Anvilian transgression is overlain by diamicts of the Nome River Glaciation bracketed by basalt flows with Ar/Ar numerical ages between 300 and 500 ka (Kaufman and others, 1991). Following the reasoning outlined by Shackleton (1987), the most likely shoreline, besides the 5e interglacial, to be preserved on a relatively stable coast is probably MIS 11; however, we cannot entirely rule out the possibility that this shoreline is correlative with MIS 9, or even less likely MIS13.

Other coastal areas around the world record high stands of relative sea level during Stage 11. For example in southern Britain, the Hoxian interglacial lies at an altitude of about +23 m (Bowen, this volume). Hearty (1998) reported evidence for stage 11 oolitic limestone sequences at +20 m, in the Bahamas, while Rohling and others (1998) speculated that the Stage 12 sea level lowering to -140m may have been followed by a rise to +20 m across the sill at the southern end of the Red Sea during Stage 11. The Hawaiian Islands may also contain evidence of a stage 11 high sea stand, but the dating is poorly constrained (Chip Fletcher, personal communication., 1998).

No one has speculated about a direct connection between such a high sea level and the extent of ice sheets during Stage 11 because it has always been easier to dismiss the elevation of these features to uncertainties in regional tectonism and denudation. In addition, our traditional interpretation of marine isotopic evidence for Stage 11 is inconsistent with the demise of either the Greenland or West Antarctic Ice Sheet (WAIS) (Shackleton, 1987). However, the discovery by Scherer and others (1998) of middle Pleistocene age marine diatoms under Ice Stream B of the WAIS should compel us to reconsider our traditional views and the possibility of a collapse of the WAIS and maybe even Greenland during Stage 11. The Anvilian shoreline at Nome and the Wainwrightian shorelines on the Alaskan North Slope are at roughly the same elevation, yet they are in different tectonic regimes. For 15 years, we in northwest Alaska have been asking ourselves, is this just a coincidence? Or could Stage 11 have been a time of major ice sheet collapse unlike anything we have imagined for interglacials of the middle and late Quaternary. If it happened, then the climate system has more surprises for us to consider. Chappell (1998) pointed to the urgency of determining whether sea level was really as high as +20m; without question, we need to confirm 'what melted?', and if it 'could happen now'?

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Oxygen Isotope 11 in Southern Ocean Sediments

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A number of criteria were used to identify oxygen isotopes stage 11 in Southern Ocean deep-sea sediments: 1.) Last occurrence of the radiolarian, *Stylotractus universus*, occurs globally at the Stage 11/12 boundary. 2.) First Abundant Appearance Datum (FAAD) of the diatom, *Hemidiscus karstenii*, occurs at the Stage 11/12 boundary. However, there are limits to this datum; it does not occur in a continuous record well south to the Polar Front (PF). 3.) In the Subantarctic region, Stage 11 exhibits the highest calcium carbonate content of the last half million years. When combined with other criteria, this can be used as an aid to identifying Stage 11 cores. 4.) Oxygen isotopes. 5.) Well to the south of the PF, Stage 11 can be recognized by counting glacial/ interglacial cycles. Using these criteria, more than 20 stage 11 cores have been identified in the Southern Ocean. To determine the average position of the SubAntarctic Front (SAF), PF and Spring sea ice limit during Stage 11, percent biogenic calcium carbonate and opal were determined in surface (Holocene) sediments of the Southern Ocean. These measures in surface sediments could be used to identify the average position of the SAF, the PF and spring sea ice limits. This model was tested for the Last Glacial Maximum (LGM). Results closely agree with the CLIMAP reconstruction for the PF and the SAF and with Burckle and others (1982) for Spring sea ice limit. Similar data reconstruction for both of the PF and Spring sea ice were south of their modern locations during this time.

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Oxygen Isotope 11; An Analog for Future Climate Change?

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While the last interglacial (oxygen isotope substage 5e) has been considered the most likely analog for the future climate change, recent workers have suggested that oxygen isotope stage 11 may have been a better candidate. Current studies suggest that stage 11 was the longest and warmest interglacial of the past half million years compromising the stability of both the West Antarctic (WAIS) and Greenland (GIS) Ice Sheets. Detailed land-based studies of substage 5e and stage 11 have at least one thing in common: the highest sea level appears to come at the end of the interglacial. Several things are apparent when this observation is put within the context of the present interglacial: 1.) while the present interglacial has lasted for some 10,000 years, the drawdown of ice sheets has lasted since the end of the Last Glacial Maximum (LGM), and is continuing today; 2.) the level to which sea level will rise is largely dictated by the length of an interglacial. This appears to have been the case for oxygen isotope substage 5e and oxygen isotope stage 11. If a long interglacial is in our immediate future then we face a world in which 2 of the 3 extant major ice sheets in the world may draw down and the sea may rise to more than 10 meters above present levels. In order to predict future behavior of vulnerable ice sheets, such as the WAIS and GIS, it is important to determine which, if any, past interglacial is the nearest analog for the present and future.

Marine Isotope Stage 11 in the South Atlantic Sector of the Southern Ocean

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Marine Isotope Stage (MIS) 11 is recognized in Southern Ocean sediment cores by nature of its white, high-carbonate sediments at high latitude (Gersonde, Hodell and others, in press). Previous studies in the Southern Ocean have suggested that MIS11 may have been warmer than today (Howard and Prell, 1992; Hodell, 1993), prompting speculation that the West Antarctic Ice Sheet may have collapsed at this time (Scherer, 1991; Scherer and others, 1998). A comparison of planktic oxygen isotopic records from the Atlantic sector of the Southern Ocean for peak interglacial conditions during the past 450 kyrs revealed that MIS 11 was not substantially warmer than other interglacials at high southern latitudes (Hodell and others, in press). However, the duration of warm interglacial conditions may have been longer for MIS11 than other interglacial stages of the late Pleistocene. The duration of sustained interglacial warmth was controlled by the eccentricity modulation of the precession cycle. MIS 11 was long in duration because eccentricity was low and the amplitude of the precessional cycle was damped, thereby resulting in fewer cold substages during the interglacial. Because the Holocene orbital geometry of the Earth was similar to Stage 11 (i.e., low eccentricity and reduced precessional amplitude), we might expect the pattern of climate change during the Holocene to be similar to MIS 11.

Deglaciation and sea level rise of up to 20 m above modern have been proposed for MIS11 (Hearty and Kindler, 1997; Bringham-Grette, this volume). During MIS11, global benthic $\delta^{18}O$ values were only about 0.1‰ less than the Holocene and similar to Stage 5e. Using the standard calibration of 0.11‰ change in $\delta^{18}O$ per 10 m of sea level rise (Fairbanks, 1989), a maximum of only ~10 m above present would be permitted for MIS11. If the West Antarctic Ice Sheet (WAIS) collapsed during MIS11, then sea level would have risen by 5-6 m with a negligible effect on the $\delta^{18}O$ of seawater because of the relatively heavy oxygen isotopic composition (-20‰) of the WAIS. A 20-m rise in sea level during MIS11 cannot be ruled out by the benthic oxygen isotopic record if most of the melted ice was relatively heavy isotopically, but 20 m of sea level rise is close to the limit that is permissible without a significant change in the mean $\delta^{18}O$ value of seawater.

The most distinctive feature of MIS 11 was the carbonate and carbon isotope chemistry of surface and deep waters in the Southern Ocean. Increased carbonate production occurred at high southern latitudes and decreased the ΣCO_2 and alkalinity of Antarctic surface waters. Both increased carbonate production at high southern latitudes and massive reef buildup during stage 11 (Droxler and others, 1997) are expected to have resulted in higher atmospheric pCO_2 levels during MIS 11 via the polar alkalinity

(Broecker and Peng, 1989) and coral-reef (Berger, 1982) hypotheses, respectively. Evidence for higher pCO_2 is lacking, however, in the long Vostok ice core record, although this result may not be definitive because ice at the level of Stage 11 may be disturbed (Raynaud and others, 1998; Raynaud, this volume). Nevertheless, planktic oxygen isotopic results from MIS 11 fail to indicate warming of surface waters in the high-latitude South Atlantic above the level of other interglacial periods as would be expected if pCO_2 levels were elevated.

Benthic $\delta^{13}C$ values in cores bathed by Circum Polar Deep Water (CPDW) were greatest during MIS11, supporting a strong input of North Atlantic Deep Water (NADW) to the Southern Ocean. Increased transport of NADW during MIS11 may have changed the chemical characteristics (decreased alkalinity and ΣCO_2) of CPDW, and upwelling of this water may have transmitted the signal to Antarctic surface waters. MIS 11 is marked by the highest values of planktic $\delta^{13}C$ in late Pleistocene sediment cores at high latitude in the South Atlantic. This may have been a consequence of increased flux of NADW and/or the "carbonate ion effect" (Spero and others, 1997) whereby carbonate precipitation south of the Polar Front lowered alkalinity and carbonate ion concentrations in Antarctic surface waters and resulted in higher planktic $\delta^{13}C$ values.

In summary, Stage 11 in the high-latitude South Atlantic is not remarkable in terms of degree of warmth compared to other interglacial stages, but rather is noted for its long duration and unique carbonate and carbon isotope chemistry of Antarctic surface and deep waters.

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The Marine Record of the MIS 11 Oscillation

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The Marine Isotope Stage (MIS) 11 interval (approx. 420-360 ka) has drawn the recent attention of the paleoclimate community because of its apparent high-amplitude during an interval of relatively weak orbital forcing due to low eccentricity. This anomalous behaviour presents a particular challenge to paleoclimate models seeking to explain the late Pleistocene record as a response to insolation forcing [e.g. Imbrie and others, 1993 and references therein]. The manifestations of this event in the marine record include a high-amplitude deglacial warming, a high-amplitude enrichment in benthic carbon isotopes, and sharp changes in calcium carbonate deposition. In addition, the chronology of the MIS 12-through-10 interval has been problematic because of the difficulty of extracting a distinct and unambiguous precession component for tuning.

The duration of MIS 11

One feature of the oxygen isotope record as compiled by the SPECMAP project and placed on that timescale, is that it appears to "skip" a precession cycle. That is, ice-volume appears to stay low longer into the interglacial than in subsequent interglacials. In MIS 5, for example, ice growth appears to be relatively rapid after a short interval of low ice volume. This unusual feature of MIS 11 raises the question: is the SPECMAP chronology wrong in its definition of the placement and dating of the end of MIS 11? Alternatively, is there a low-amplitude precession cycle unresolved by the records that make up the SPECMAP stack? Although a tropical Indian Ocean record [Bassinot and others, 1994] suggests that the latter scenario may be correct, the MIS 11-10 interval needs to be better defined with more records of appropriate resolution [e.g. Raymo, 1997; Oppo and others, 1998]. The difficulty of directly dating sediments in that time interval, of orbitally tuning paleoclimate records, and the distance from the nearest magnetic reversal, make constructing chronologies of the MIS 12-10 interval difficult, and make it an interval over which orbital time scales may be most open to revision. Magnetic intensity variations may provide better tuning targets, if they are phase-locked to orbits [Channel and others, 1998].

MIS 11 as Analog for future warming?

Another point of interest is the possible “orbital analog” the MIS 11 interval may represent for the Holocene and near future. This similarity is due to the fact the earth is in a low-eccentricity geometry similar (though not identical, due to the relative phases of precession and obliquity) to that ~400 ka, thus the possibility that we could look to the MIS 12-11-10 progression as a guide for what climate would do in the absence of any human impact. Milankovitch theory would suggest we are already on our way into the next glacial (leaving aside the phase of higher-frequency cycles such as Dansgaard-Oeschger oscillations). But a long MIS 11, if truly an analog for the Holocene, would suggest longer persistence of interglacial conditions. Is MIS 11 really warmer than the Holocene? If so, where?

A number of studies have suggested sea-surface temperatures during MIS 11 warmer than the Holocene [e.g Howard and Prell, 1992; Burckle, 1993], especially in the Southern Ocean. However recent faunal and isotopic evidence indicates that MIS 11 may be no warmer, even slightly cooler, than the Holocene [e.g. Hodell and others, submitted; King and Howard, in prep.].

Indeed, the fact that neither planktonic nor benthic oxygen isotope records show distinct depletions *requires* cooler ocean temperatures, if estimates of higher-than-Holocene sea levels during MIS 11 are correct. The conditions capable of maintaining a combination of high sea level and cooler temperatures would be an interesting challenge to climate models.

Stage 12 cold or Stage 11 warmth?

One clear pattern in marine isotopic and faunal records is that MIS 12 is a cooler glacial than some subsequent glacial intervals; perhaps this cold glacial is what makes the Termination V transition so high-amplitude, and drives the perception of MIS 11 warmth. In this regard studies of the MIS 11 interval should cover the entire MIS 12-through-10 oscillation (a model for such a reconstruction may be the CLIMAP [1984] compilation of MIS 5 records.)

Geochemical anomalies

MIS 11 appears as a prolonged maximum in calcite burial in the subpolar Atlantic and Indian Oceans [e.g. Howard and Prell, 1994], with maxima in carbonate dissolution in the Pacific [Peterson and Prell1985; Farrell and Prell, 1989]. The burial maxima in the Atlantic and Southern Oceans appear to be driven partly by deep-water preservation, possibly a result of enhanced northern source water input [Oppo and others, 1990]. (However MIS 11 does not show up as a benthic carbon isotope maximum in all records; see for example Curry [1996]).

To the extent that the MIS 11 calcite maximum represents production, it may correspond to warming of polar/subpolar oceans, with increased areas within the SST range of nannofossil calcite production. The calcite reservoirs laid down at this time may be part of explanation for the Equatorial Pacific and Indian Ocean dissolution, and would represent ecological forcing of geochemical change in addition to sea-level forcing [Opdyke and Walker, 1992].

Priorities for future MIS 11 studies should include:

- Relative timing of paleoclimate change through this interval (interhemispheric, SST vs. ice volume) in higher-resolution records
- More complete accounting for the oceanic carbonate budget, especially deep-basin burial rates
- A global reconstruction of SST
- Refinement of chronology

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$^{40}Ar/^{39}Ar$ dating of Glacial Termination V and duration of the Stage 11 highstand

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Assigning ages to geologic events is of fundamental importance to the earth sciences. While there are many radioisotopic and non-radioisotopic methods being employed to date climate change events, the accuracy and temporal resolution of most non-radioisotopic methods is insufficient to answer questions such as the timing and duration of glacial or interglacial cycles. One exception to this is the method of tuning climate proxies in sediment to Earth's orbital parameters. While details of the tuning procedure are in some respects still controversial (e.g. Muller and MacDonald, 1997, and references therein), a growing number of direct comparisons between radioisotopic vs. orbitally tuned chronologies suggests that tuning can be fairly accurate through the last million years. However, the predicted timing of discrete events may vary by 10 kyr or more when different orbital tuning targets are used (e.g. Berger and others, 1993 vs. 1995).

Radioisotopic dating systems based on ^{238}U and ^{40}K decay provide the most accurate and precise age constraints for events that have occurred from 0.1-1.0 Ma. U-series methods have been used extensively to date coral reefs, which grow near sea level, and have provided good age constraint for the Stage 5 and (to a lesser extent) Stage 7 sea-level highstands. However, U-series methods have not provided reliable ages for older highstand deposits, such as Stage 11, the focus of this work. The $^{40}Ar/^{39}Ar$ method, on the other hand, can be used to date reliably all of the Pleistocene highstand deposits, including those from Stage 11 (e.g. Karner and Renne, 1998).

We have used the $^{40}Ar/^{39}Ar$ method to date volcanic ash layers intercalated with coastal sediments in the Tiber River Valley and Delta (Karner and Renne, 1998; Karner and Marra, 1998). Using the Pleistocene-Holocene transition as an analogue for past glacial terminations, we interpret the onset of significant (10s of meters) alluviation in the Tiber River Valley and Delta to occur at, or shortly following, glacial terminations, analogous to the buildup of coral reef material on carbonate-dominated ocean margins. A detailed discussion of the Tiber River and Delta alluvial deposits and their relationship to sea-level variations is given by Karner and Marra (1998).

Figure 1.

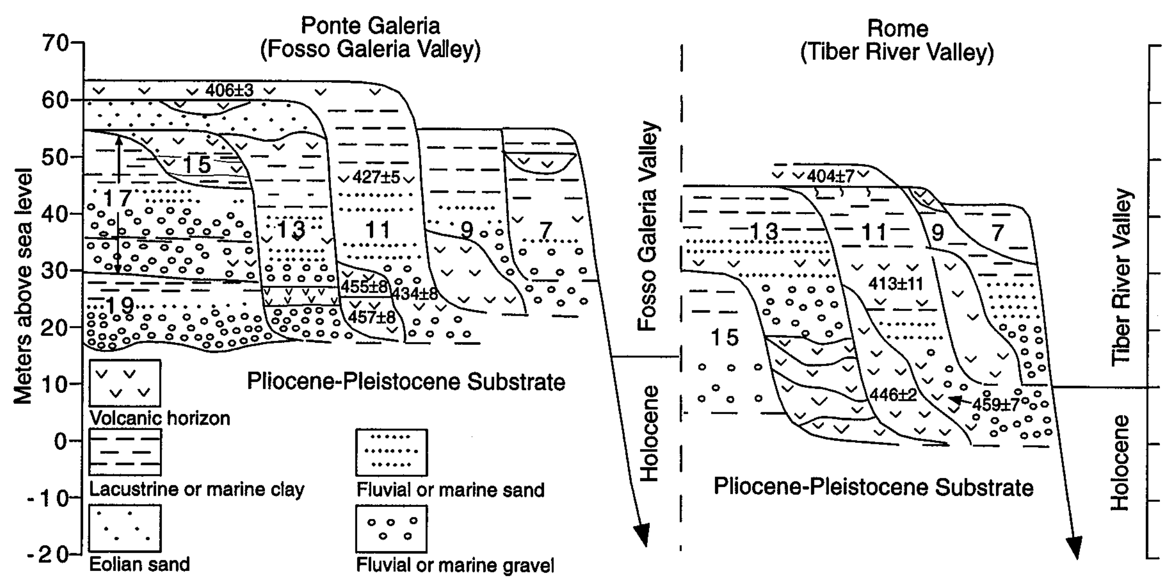
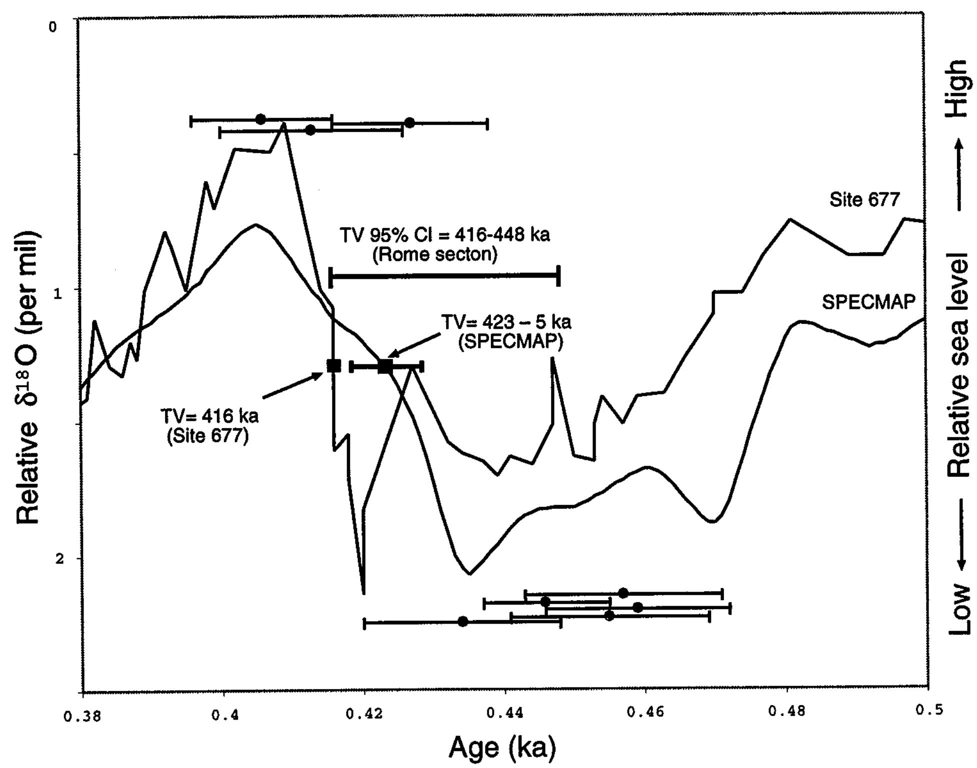


Figure 1 is a composite stratigraphic column of alluvial sections around Rome, corresponding to the Holocene plus eight previous interglacials. Tephra ages relevant to Stage 11 are from Karner and Renne (1998), plus one added $^{40}Ar/^{39}Ar$ age of 406 ± 3 ka (2_ analytical precision, Karner and others, in press.) on sanidine from a pumice horizon. This pumice is the uppermost airfall horizon identified so far in the Stage 11 section, and therefore can be used to approximate the end of the Stage 11 sea-level highstand.

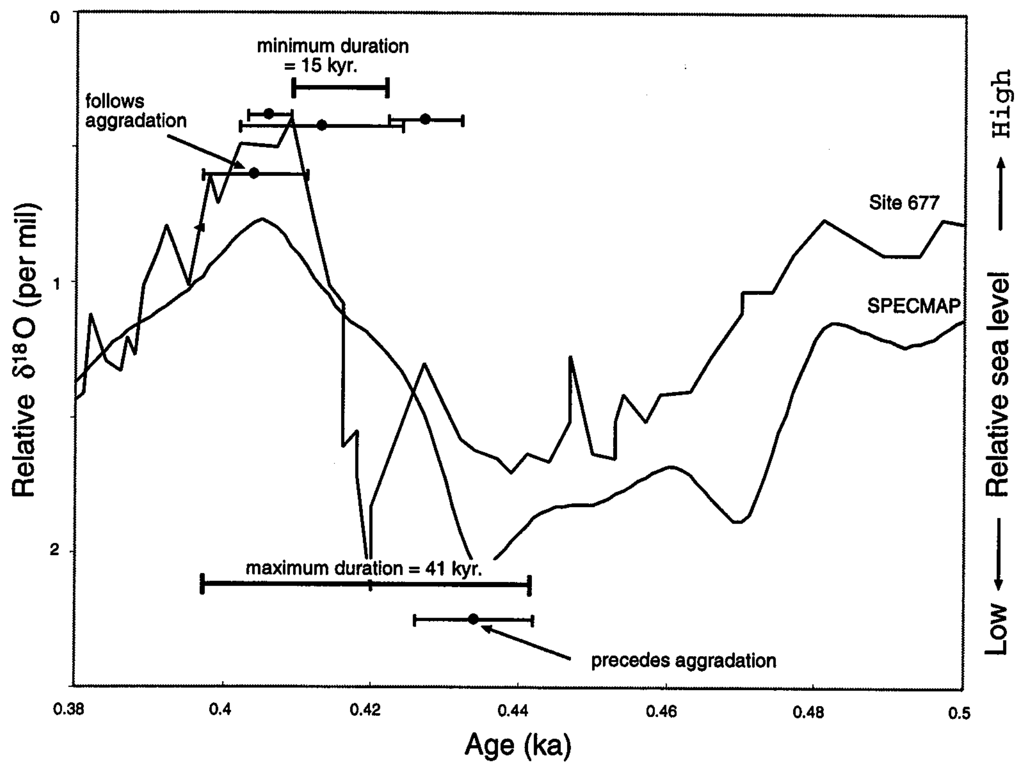
Ages of ash layers that stratigraphically bracket the start of aggradation can be used to estimate the timing of the glacial termination. This termination age can then be compared with termination ages from other dating methods, so long as all systematic errors inherent to each method are propagated into their age errors. From the Rome section, Glacial Termination V, which led to the start of Stage 11, was determined to occur within the interval 416-448 ka (95% confidence interval, including $^{40}Ar/^{39}Ar$ systematic errors, Karner and Renne, 1998). This can be compared to orbitally tuned deep-sea sediment records for agreement (Figure 2). Imbrie and others (1984) determined the age of Termination V in the SPECMAP record to be 423 ± 5 ka, whereas Shackleton and others (1990) determined the age to be 416 ka at ODP Site 677 (no error reported). While the SPECMAP record falls well within the 95% confidence interval of the $^{40}Ar/^{39}Ar$ ages, the Site 677 record is at the extreme limit of the 95% confidence interval, and may therefore be suspect.

Figure 2.



There are additional timing considerations with the Rome and Site 677 records. No time lag is assumed between the termination and the resumption of coastal sedimentation, and therefore the true age of the termination should be somewhat older than predicted from the Rome sections. Additionally, the age uncertainty of the Site 677 record is not given by Shackleton and others (1990), but is probably at least that of the sample spacing, about 2-5 kyr for Stage 11. These additional errors do not bring the two records into better agreement, however, because, at best, they would pull each time scale in the same direction. At worst, the Rome section could be pulled in the older direction and Site 677 in the younger direction, at which point the two records would disagree at the >95% confidence level. Based on our comparison with the SPECMAP and Site 677 time scales, we suggest that the SPECMAP chronology is more accurate than that of Site 677 for the timing of Termination V.

Figure 3.



The duration of the Stage 11 highstand (Figure 3) can be assessed from the Rome section $^{40}Ar/^{39}Ar$ ages without inclusion of systematic errors, since the $^{40}Ar/^{39}Ar$ ages are all calibrated against the same standard and therefore would all be shifted in the same direction by a systematic error. The minimum duration of aggradation in the Rome section can be calculated using the broadest range of ages from airfall horizons within the aggradational section. The oldest airfall tephra age determined in the Stage 11 section is 427 ± 5 ka, and the youngest is 406 ± 3 ka (2_). Therefore, a minimum duration of 15 kyr (427-406 = 21 kyr - 6 kyr for errors added in quadrature) can be assigned to the Stage 11 alluvial section. The maximum duration of the Stage 11 alluvial section can be assessed using the youngest age from volcanic material reworked in the base of the alluvial section (434 ± 8 ka), and the oldest age from volcanic material unconformably above the alluvial section (404 ± 7 ka). These ages provide a maximum duration of 41 kyr (434-404 = 30 kyr + 11 kyr for errors added in quadrature) for Stage 11 alluviation. Since a large portion (17 kyr) of this 15-41 kyr (95% confidence) duration interval is due to analytical errors associated with the $^{40}Ar/^{39}Ar$ ages, additional analyses could reduce the analytical error contribution.

A recent discussion of the last four interglacials by Winograd and others (1997) suggests that contrary to the long-held view that interglacials last about 10 kyr, continental sections dated by means other than orbital tuning suggest that their durations were closer to 20 kyr. The present work supports this observation for Stage 11, with a minimum duration of 15 kyr and maximum duration of 41 kyr at 95% confidence. With additional $^{40}Ar/^{39}Ar$ analyses on the key ash layers, the Rome sections may be able to answer the question of whether the Stage 11 highstand lasted for 20 kyr (as suggested by Winograd and others, 1997) or whether it was anomalously long (e.g. 29 kyr) as suggested by Sarnthein and Tiedemann (1990).

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A Paleoceanographic Interpretation for a Middle Pleistocene Interglacial Based on Micropaleontology and Ostracode Mg/Ca Shell Chemistry, Arctic Coastal Plain, Alaska

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Introduction

Marine and terrestrial records spanning the past 500 ka indicate that oxygen isotope stage 11 (423-362 ka) was one of the warmest interglacials on record, resulting in high global sea levels and temperatures possibly even warmer than present (i.e. Zhongli and others, 1991; Rousseau and others, 1992; Burckle, 1993; Hodell, 1993; Ortlieb and others, 1996). The Karmuk Member of the Gubik Formation, Arctic Coastal Plain, Alaska, is composed of middle Pleistocene transgressive marine sediments deposited up to 22 m above present sea level, suggesting deposition during an unusually high sea level event. Currently, the best estimates suggest a depositional age for the Karmuk Member corresponding to stage 11 (Kaufman and others, 1991; Kaufman and Brigham-Grette, 1993). This study will establish a temperature estimate for the stage 11 interglacial based on comparisons between marine ostracode assemblages and ostracode Mg/Ca shell chemistry, thus documenting a high latitude northern hemispheric record for one of the warmest periods in Earth's history.

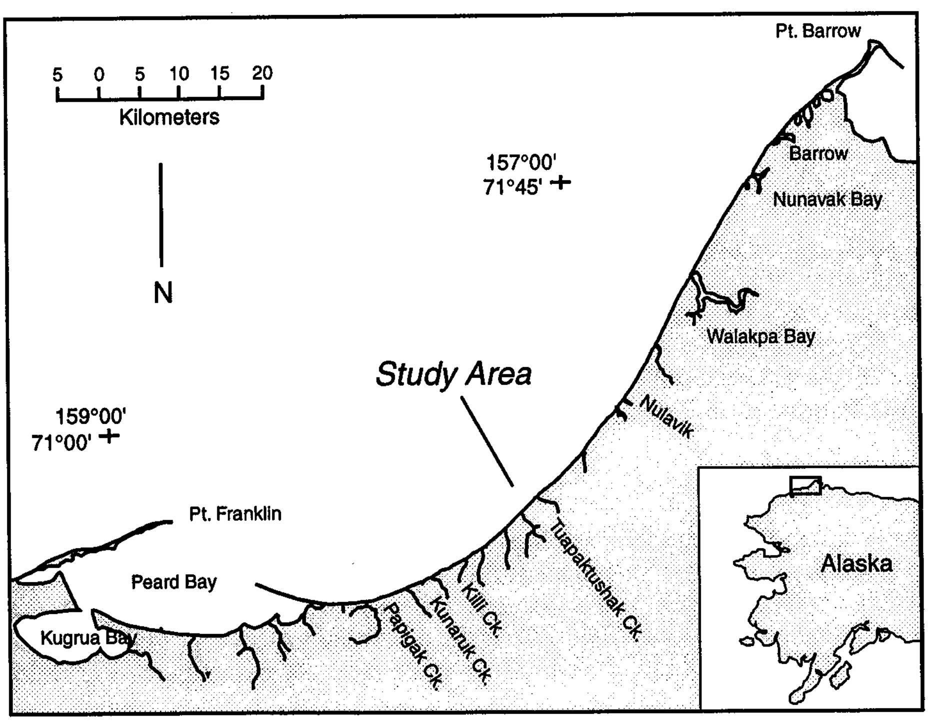

Figure 1. Study area at Skull Cliff, northern Alaska. Skull Cliff extends 80 km between Barrow and Peard Bay

The Gubik Formation consists of a series of Pliocene to Pleistocene-aged marine transgressive sequences which record late Cenozoic high sea-level events (Brigham, 1985). These transgressive sequences comprise most of the exposed sediments along Skull Cliff, which extend 80 km between Barrow and Peard Bay (Figure 1). The Karmuk Member of the Gubik Formation represents one of the Pleistocene transgressive units. This sequence was deposited during the Wainwrightian transgression, when relative sea-level was 23 m above present level and marine conditions are thought to be similar to modern conditions (Kaufman and Brigham-Grette, 1993).

Materials and Methods

Materials used in this study were collected from exposed gullies along Skull Cliff. Sediment was collected from three sampling localities at 10 cm intervals. The most complete section yielded 700 cm of sediment and may represent an entire transgressive sequence consisting of offshore (a lower marine mud unit), nearshore (an interbedded fine sands and mud unit), and beach (a medium to coarse pebbly sand unit) deposits.

Paleontology

A total of 26 ostracode taxa were identified from 50 intervals. Four species dominate Karmuk sediments with a combined average relative abundance of 91%. The four dominant species are *Paracyprideis pseudopunctiallata*, *Normanicythere leioderma*, *Rabilimis septentrionalis*, and *Sarsicytheridea bradii*. Both dominant and diagnostic taxa have been selected for qualitative and quantitative taxonomic analysis.

Paleontological associations yield paleoenvironmental inferences. Euryhaline and eurythermal taxa present include *R. septentrionalis*, *P. pseudopunctillata*, *Loxoconcha venepidermoidea* and indicate very shallow, nearshore conditions. Other species which prefer more stable salinity and temperature conditions are found in deeper, offshore environments and include *N. leioderma* and *Robertsonites tuberculata*.

Mg/Ca Shell Chemistry

The Mg/Ca ratio in ostracode shell calcite is used in deep sea studies as a paleotemperature proxy based on the temperature-dependent uptake of Mg into the shell calcite. For this study, trace elements were analyzed on specimens of *P. pseudopunctillata*. Preliminary results indicate that the marine paleoenvironment during Karmuk deposition was relatively stable. There is a general trend toward decreasing Mg/Ca values during sediment deposition punctuated by fluctuations within the Mg/Ca record. Comparisons to modern shell chemistry analyses will be used in order to address the significance of the fluctuations seen in the fossil chemistry record, as well as in assessing a paleotemperature history (i.e. Dwyer and others, 1995; Cronin and others, 1996; Ingram, 1998).

Conclusions and Future Work

Paleoenvironmental inferences obtained from both qualitative and quantitative analyses of microfaunal assemblages suggest that deposition of the Karmuk Member occurred in middle to inner neritic water depths. Fossil ostracode assemblages indicate that stage 11 conditions were similar to present marine conditions. The ostracode assemblages are dominated by normal marine, frigid to cold temperate species indicating fairly stable temperature and salinity conditions.

Decreasing Mg/Ca ratios from the paleotemperature-inferred ostracode shell chemistry record suggest a gradual decline in water temperature over time, possibly indicating a climatic deterioration from optimum interglacial conditions. Fluctuations in the Mg/Ca record likely record fluctuations in the paleoenvironment and remain to be assessed for their significance.

These preliminary results document an extremely warm interglacial in northern Alaska characterized by a sea level up to 22 m above present. The current findings will be supplemented by further investigation of species associations. Additionally, the shell chemistry results will be compared to modern chemistry data with the goal of quantifying significant temperature changes. By establishing a marine paleotemperature estimate in northern Alaska for stage 11, we hope to add to the understanding of the global sea level record for one of the warmest periods in Earth's recent history.

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Solar Forcing and Glaciation

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In the early-to-mid 1980's, there appeared to be strong indications that the Croll-Milankovitch insolation theory of glacial cycles had been confirmed. Spectral analysis of ice volume proxy data showed cycles with periods near 100 kyr, 41 kyr, and 23 kyr, good matches to the frequencies that appear the insolation model. Although there were remaining difficulties, many researchers considered it virtually inconceivable that the theory could be fundamentally wrong. Since then, for a decade and a half, many scientists have not only accepted the theory, but they have built it into the analysis of their data. Insolation forcing is used to tune the time scale of deep sea sediment data, in an attempt to try to remove the effects of varying sedimentation rates.

However, the problems that remained have not found entirely satisfactory solutions. Several of the most problematic features of the data are (a) the dominance of the 100 kyr cycle, (b) the weakness of the 23 precession kyr cycle, (c) the presence of strong modulation in the glacial cycles at stages 1 and 11, when the insolation modulation is very weak, (d) the absence of the expected strong 400 kyr insolation cycle in ice volume proxy data, and (e) a causality problem: Data at a site known as Devil's Hole indicate that glacial terminations sometimes precede the rise in insolation that is supposed to have caused it (Winograd and others, 1992).. Most of these problems have been discussed in detail by Imbrie and others(1992, 1993).

Many modifications of the insolation model have been proposed to address the problems. The nonlinear ice model of Imbrie and Imbrie (1980) is one of the most successful. It provides a mechanism for an enhanced 100 kyr cycle by attributing it to the envelope of the precession cycle. Virtually any nonlinear mechanism operating on precession will provide this effect since the precession parameter literally is a product of the eccentricity (which has a quasi-100 kyr cycle) and the true precession. But, by itself, the nonlinear ice model leaves a 100 kyr cycle that is weaker than the 23 kyr cycle, whereas in fact the 100 kyr cycle is dominant and the observed 23 kyr cycle so weak that in the ice-proxy data it verges on non-presence. To try to address these problems, it is common to assume an ad-hoc amplifier that enhances the 100-kyr signal, and to invoke "chatter" in the sedimentation rate to suppress a 23 kyr signal. And an additional suppressor must be hypothesized to account for the absence of the 400 kyr cycle. The causality problem has been addressed by disputing the interpretation of the Devil's hole data. However recent measurements of sea levels recorded in corals have confirmed the Devil's Hole results (Esat and others, 1999).

Rather than see if we can add enough parameters to the old model to make it fit the data, it is a worthwhile exercise to ask what conclusion paleoclimatologists might reach today, if they weren't already deeply committed to the Milankovitch mechanism. A second orbital cycle, inclination, has been discovered (Muller 1994, Muller and MacDonald, 1995) that matches the 100 kyr cycle of the ice ages, so we even have an alternative to eccentricity to consider for this dominant cycle. Figure 1 shows the best fits of these two models to the data. Orbital inclination provides a much better fit than does eccentricity.

Excellent new data are now available. We know, for example, that at Sites 607 and 677, an extremely strong 41 kyr cycle is present during the period from 1 to 2.5 Ma, and that this signal is evident in spectral analysis even when no tuning is applied to the sedimentation rate (Muller and MacDonald, 1997). The strength of this signal implies that the sedimentation rate has been constant on the 41 kyr time scale; the 41 kyr period is close enough to that of precession that it makes chatter in sedimentation an unlikely explanation for the absence of the 23 kyr precession cycle.

In addition, there is compelling evidence for relatively constant sedimentation at Site 806 in the Western Pacific for the last 800 kyr (Muller and MacDonald 1997). This fact allows one to look for fine structure expected from the insolation model. In particular, it is well known (Berger, 1978; Quinn and others, 1991) that the "100 kyr" peak in eccentricity is actually a split peak, consisting of two components, with periods 95 kyr and 125 kyr. Yet spectral analysis shows that the expected splitting is absent, in contradiction to every published insolation-based theory known to the present author. This is evident in the data shown in Fig. 2. The spectrum does provide a good match to that of the new orbital inclination parameter. To salvage the Milankovitch theory, one must now invoke a mechanism that somehow suppresses the 125 kyr peak, while enhancing the 95 kyr one. Such fine tuning ability is absent in virtually all geologic processes that have previously been considered. For example, the spectrum of the nonlinear ice model has a strong split peak, shown in Fig. 2(d), in disagreement with the data Fig. 2 (a) and (b).

The link of orbital inclination to the 100-kyr glacial cycle was first suggested by Muller and MacDonald (Muller, 1994; Muller and MacDonald, 1997). In these papers, we proposed that the coupling mechanism could be accretion of interplanetary dust, although we were unwilling (and unable) to predict whether the dust would cause the ice to grow or decline. This model has been criticized for the lack of a detailed mechanism, although we respond by pointing out the ad-hoc nature of the models that are used in the Milankovitch theory. If we are allowed to be equally ad-hoc, then we too can find mechanisms. For example, we hypothesize that accreting dust affects the ozone concentration in the mid-stratosphere. It can do this through several mechanisms: the delivery of significant bromine (known to be enhanced in such dust; see Flynn (Flynn and others, 1993; Flynn, 1994), and by providing solid surfaces for heterogeneous chemistry (similar to the surfaces that are known to be important in the Antarctic Ozone hole creation). The ozone variations cause changes in the height of the tropopause (the presence of ozone is what creates the tropopause), which in turn affects the global circulation patterns and the latitudinal transport of water vapor to the northern glaciers. All these phenomena can be summarized by one adjustable parameter, which we use to fit the amplitude of Fig. 1.

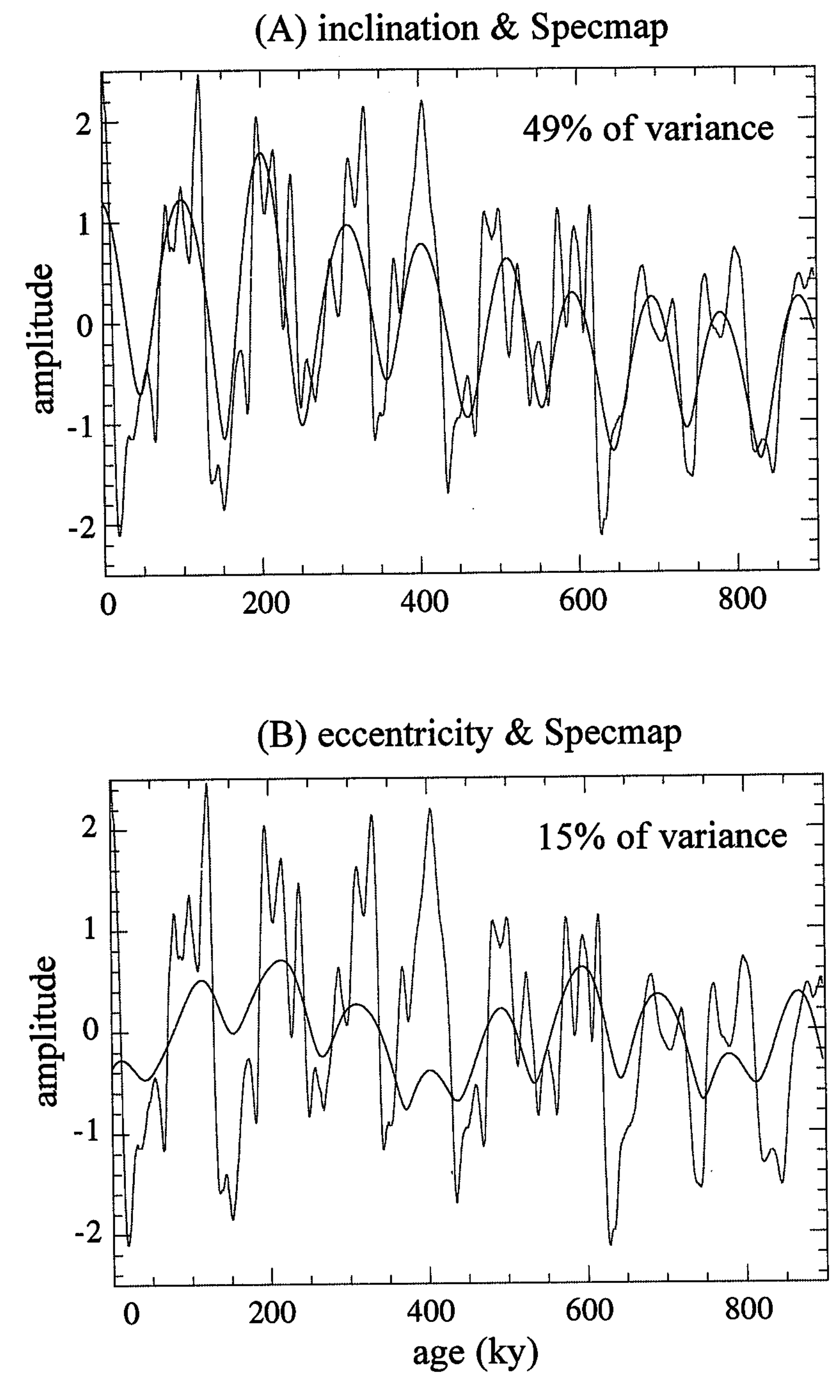

Figure 1. Best fits of global ice proxy data (Specmap) to two orbital parameters: (A) orbital inclination (smooth curve) plotted over the Specmap data; (B) eccentricity (smooth curve) plotted over the Specmap data. Each fit has two parameters: amplitude and time lag. Orbital inclination accounts for 49% of the variance of the data; eccentricity accounts for 15%. If the fits are done simultaneously, inclination accounts for 49% and eccentricity for less than 2%. The Stage-1 and Stage-11 problems are evident in the poor agreement near 0 and 400 ky for the eccentricity fit; there is no similar problem in the inclination fit.

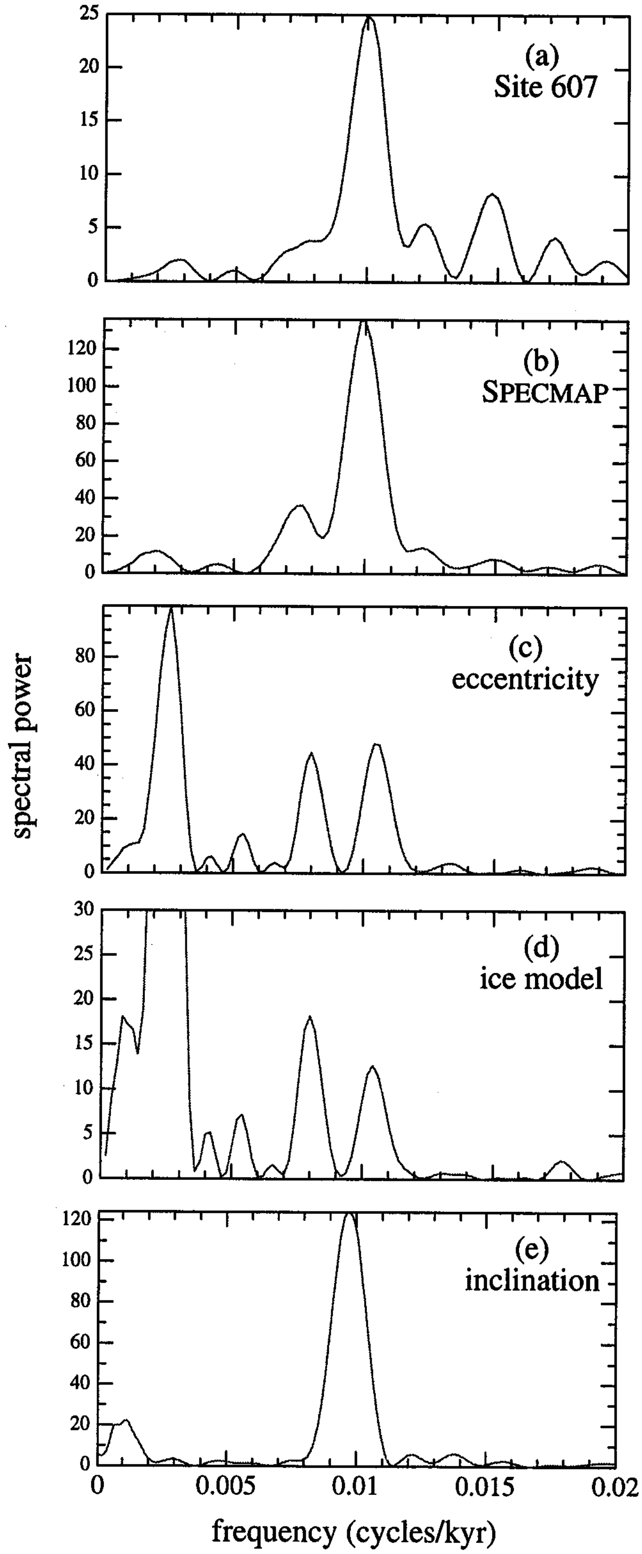

Figure 2. Spectral fingerprints of two $\delta^{18}O$ data sets and three models. Both the data and the models cover the ages 0 to 600 ka. The frequency scale has been expanded to facilitate comparison of peak shapes near 0.01 cycles/kyr (period 100 kyr). All the data show a similar pattern: a single narrow peak near frequency f = 0.01 cycles/kyr (period 100 kyr), in good agreement with the orbital inclination theory, and in disagreement with the complex spectra predicted by the eccentricity and nonlinear ice theories.

Thus, with one parameter, this model can account for the observed relationship between orbital inclination and global ice. We don't claim this is an adequate model; we only claim that it is no more ad hoc than the models used in the Milankovitch approach, and therefore equally deserving of serious consideration.

We speculate that if the data we have today were available in 1985, and if it had been known that the orbital inclination of the earth was a better match to that data, that the adoption of the Milankovitch theory as the standard model would not have proceeded at that time. With the orbital inclination model, there is no stage-11 problem, no stage-1 problem, no causality problem, no 400 kyr problem, and no mystery about the small amplitude of the 23 kyr cycle. The inclination model even has a natural explanation for the sudden appearance of the 100 kyr cycle at about 1 Ma, since solar system dust is known to have gone a sudden increase at that time (Farley, 1995). Indeed, if this were all known in 1985, it is possible that the orbital-inclination/dust theory might itself have been prematurely adopted as the standard model.

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Tropical Atlantic Paleoceanography Over the Past 580 Kyrs: High-Resolution Records from the Cariaco Basin

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Introduction

Ocean Drilling Program (ODP) Site 1002 is located in the Cariaco Basin, a structural depression on the northern continental shelf of Venezuela, which, after the Black Sea, is the largest anoxic marine basin in the world. The Cariaco Basin is well positioned to record a detailed history of Trade Wind-induced upwelling along the southern margin of the Caribbean, as well as surface ocean changes that result from variations in the large-scale circulation of the Atlantic. Previous studies have shown that Cariaco Basin sediments record environmental variability recorded to large-scale climatic and oceanographic processes (Overpeck and others, 1989; Peterson and others, 1991; Hughen and others, 1996, 1998; Lin and others, 1997; Haug and others, 1998). Sediments collected at ODP Site 1002 (10°42.4'N, 65°10.2'W; water depth: 893 m) extend the Cariaco Basin paleoceanographic record back to ~ 580 kyrs BP and provide an unparalleled opportunity for high-resolution studies of tropical Atlantic climate in the late Quaternary, including Marine Isotope Stage (MIS) 11.

Along its northern margin, the Cariaco Basin is separated from the open Caribbean by the shallow Tortuga Bank that extends from Margarita Island to Cabo Codera on the Venezuelan mainland. The deepest connections are at 147 m water depth near Farallon Centinela at the western end of the basin and near 120 m between Tortuga and Margarita Island (Richards, 1975; Peterson and others, 1991). These shallow sills restrict horizontal exchange with the open Caribbean and cause anoxic conditions today below about 300 m in the basin, as high oxygen demand created by surface water production exceeds the limited rate of deep water ventilation. The surface water production in the Cariaco is supported by upwelled, nutrient-rich, sub-thermocline waters that enter from the open Caribbean (e.g., Richards, 1975; Peterson and others, 1991). Upwelling along the Venezuelan coast that feeds biological production in Cariaco surface waters is driven by the Trade Winds and shows a large seasonal signal forced by the annual migration of the Intertropical

Convergence Zone (ITCZ) in the Atlantic Ocean. The strongest Trade Winds and Ekman-induced upwelling occur during the winter dry season when the ITCZ is at its southernmost position. In the summer, when the ITCZ moves north, the Trade Winds diminish, upwelling decreases or shuts off, and the regional rainy season is triggered north of about 5°N. This alternation of a dry upwelling season and a rainy non-upwelling season produces laminated sediment sequences consisting of seasonally alternating light-colored plankton-rich layers and darker-colored terrigenous grain-rich layers (Peterson and others, 1991; Hughen and others, 1996).

Site 1002 Stratigraphy and Potential for High-Resolution Studies

The major drilling objectives at Site 1002 were to recover a continuous and undisturbed late Quaternary stratigraphic section that could be used to 1) document how climate change in the southern Caribbean and northern South America relates to climatic forcing mechanisms and to global-scale change, especially to high latitude changes recorded in ice cores and in other high-deposition rate marine sediment sequences; 2) study the rates and magnitudes of tropical climate change at interannual to millennial time scales over the last several glacial-interglacial cycles; 3) examine the stability of tropical climate in response to past changes in large-scale global boundary conditions; and 4) to study the relationships between climate variability and processes that influence the burial of organic carbon in anoxic settings. The recovery objectives were successfully achieved with the drilling of five holes at Site 1002, two of which were single mudline cores taken for geochemical studies, and three that were taken for high-resolution paleoclimatic reconstructions and that together penetrated to a maximum depth of 170.1 meters below surface.

The late Quaternary sediments at Site 1002 are generally dominated by terrigenous sediment components with variable biogenic contributions of nannofossils, diatoms, foraminifers (both planktic and benthic), and pteropods. Throughout much of the sequence, the presence of aragonitic pteropods is characteristic of the generally excellent preservation of calcareous microfossils. Much of the sediment at Site 1002 is laminated, indicating deposition under largely anoxic conditions. Nevertheless, significant subsurface intervals showing clear evidence of bioturbation testify to a history of oscillation between oxic and anoxic environments in the deep basin. The present $\delta^{18}O$-based age model indicates a basal age of ~580 kyrs BP for the recovered Cariaco Basin sequence, yielding an average sedimentation rate of about 35 cm/kyrs (350 m/m.y.). This rate is in line with sedimentation estimates previously derived for the uppermost sediment column and ensures the Cariaco Basin's role as an important archive of high-resolution paleoenvironmental information.

Nutrient Cycling and Production Changes in the Cariaco Basin

Throughout the Holocene sea level highstand, Trade Wind-induced changes in upwelling have affected surface production in the Cariaco Basin. Over longer time-scales, however, it is clear that sea level must also play a role in modulating surface productivity in the basin as the shoaling of sill depths during glacial lowstands appears to restrict the input of nutrient-rich subsurface waters from the open Caribbean. Although numerous lines of evidence are being pursued to reconstruct and unravel paleoproductivity in the Cariaco Basin and its relationship to climatic, oceanographic, and sea level variability, results of recent nitrogen isotope studies (Haug and others, 1998) are highlighted here. The results from ODP Site 1002 indicate that there have been large glacial/interglacial variations in N_2 fixation in the Cariaco Basin, with higher rates during interglacial periods. This sense of change is not easily explained by a trace metal dependence of N-fixers (Falkowski, 1997), since trace metal supply was unlikely to have been lower during glacial times. Based on our work and on previous studies, we suggest that nitrogen fixation responds to glacial/interglacial changes in the $[NO_3]/[PO_4]$ ratio of the nutrient supply to Cariaco surface waters, driven by changes in the rate of denitrification. The N_2 fixation response may stem from changes in denitrification within the Cariaco Basin itself, or it may be driven by previously recognized glacial/interglacial variations in open ocean denitrification (Altabet and others). If such an N_2 fixation response occurs more broadly in the global ocean, then it would tend to compensate for large denitrification-driven changes in the ocean nitrate reservoir on glacial/interglacial timescales, and work against the occurrence of large changes in the $[NO_3]/[PO_4]$ ratio during the Quaternary.

Although the evidence reported here suggests a response of N_2 fixation to changes in denitrification, it remains to be seen exactly how tightly these two processes are coupled. If the coupling is tight, nitrate reservoir changes could only be driven by changes in the oceanic phosphate reservoir. Given the long residence time of dissolved phosphate (~16-38 kyr) (Ruttenberg, 1993), large changes in the oceanic P reservoir at rather abrupt glacial/interglacial transitions are unlikely. Consequently, depending on the tightness of the coupling between denitrification and N_2 fixation, our findings may argue against the nutrient reservoir explanation for glacial/interglacial atmospheric CO_2 changes.

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Millenial-Scale Climate Variability in the Western North Atlantic During Marine Isotope Stages 11 and 12: Results from ODP Leg 172

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The time period represented by oxygen isotope stages 11 and 12 (approximately 480 to 362 ka) contains the most extreme climatic variations of the late Pleistocene. The MIS 12-11 transition is the largest of the last 650 kyrs, is preceded by one of the most severe glacial stages of the late Pleistocene, and is followed by a long and warm interglacial. These changes in the climate system are not associated with significant changes in the Earth's orbital configuration: insolation changes are relatively small at this transition, and MIS 11 is a time of low orbital eccentricity and low precessional amplitude. Recent work suggests that sea level during glacial stage 12 was ~140 m below present (Rohling and others, 1998). During interglacial stage 11, temperatures were warmer and sea level was ~20 m higher than during the Holocene.

Ocean Drilling Program Leg 172 was designed to recover a sequence of high deposition rate sediment cores from sediment drifts that can be used to document changes in the properties and circulation patterns of intermediate and deep-waters in the North Atlantic during the late Pliocene and Pleistocene. In order to address this problem, a bathymetric transect of eleven sites has been cored between 1,300 to 4,600 m water depth on the Carolina Slope (CS), Blake-Bahama Outer Ridge (BBOR) and Bermuda Rise (BR). Sites were chosen so that at least one lies within each modern watermass, and one lies at each boundary between watermasses.

The recognition of stages 11-12 was based on the extinction of the calcareous nannofossil *Pseudoemiliania lacunosa*: a biostratigraphic event that occurs within stage 12. We sampled two sites (1058 and 1063, located on the Blake Bahama Outer Ridge and the Bermuda Rise, respectively) at an average time interval of ~500 yrs, and all the other sites at an average time interval of ~3000 yrs. Sedimentation rates at these sites tend to be high (usually greater than 10cm/kyr) allowing us to examine high frequency climate and oceanographic changes during the stage 11-12 time period using color reflectance, calcium carbonate content and benthic foraminiferal carbon and oxygen isotopes. Using both %$CaCO_3$ and lightness data, we calculated average sedimentation rates between MIS 9 and 13. The results indicate increasing values from the shallower to the deeper sites, except for sites 1062 and 1063.

Preliminary results show an excellent correspondence between color reflectance data (lightness L) collected onboard and carbonate content, thus confirming that lightness is a good proxy for carbonate content in this region. The typical western North Atlantic glacial-interglacial changes in %$CaCO_3$ (with higher values during interglacials) are evident for this time interval. The stage 11-12 transition is characterized by abrupt changes in the carbonate content at the deepest sites (bathed today by Antarctic Bottom Water, AABW) and by somewhat smoother changes at the shallower sites (North Atlantic Deep Water, NADW). Our high resolution data indicate that MIS 11 is marked by three distinct carbonate peaks (x, y and z). At sites 1063 and 1062, the records clearly show 4 to 5 carbonate peaks during early MIS 12, followed by an interval of uniformly low carbonate values, suggesting some instability preceding the glacial maximum. The carbonate peaks are similar to features previously reported for this region for the last glacial (Keigwin and Jones, 1994) and correlated to the interstadial events contained in ice cores. Thus, our data suggest the occurrence of similar interstadial events during stage 12.

The $\delta^{18}O$ record for Site 1063 contains a 2.2‰ change at the MIS 12-11 transition. Since the estimated ice-volume contribution to this signal is ~1.5‰ (Chappell, 1998), the residual change is indicative of a bottom water temperature change of 3-4°C. This is significantly larger than most previous estimates of glacial-interglacial changes in bottom water temperatures.

The $\delta^{13}C$ data show a close covariance with percent $CaCO_3$, particularly at site 1063, suggesting that the two proxies are responding to the same forcing. Previously published data from the BBOR and BR areas for the last 140 kyrs show similar sub-orbital scale changes in carbonate patterns, and have been attributed to changes in terrigenous dilution and bottom water chemistry (Keigwin and Jones, 1994). Our data indicate that the bottom water mass bathing the Bermuda Rise during MIS 12 was more enriched in the AABW component than during MIS11, when $\delta^{13}C$ values are close to present day NADW values. Additionally, the periods of low carbonate content during interglacial MIS 11 are interpretted to be times of reduced NADW formation.

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The Vostok Ice Core in the Context of Stage 11

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Ice core records compliment the marine and continental records. They are unique in providing the most direct atmospheric signature of the past climatic and environmental changes. The information is obtained by measuring the composition of the ice itself and of the gas entrapped. The ice record gives access to paleoclimate series including polar temperature and precipitation rate, atmospheric trace gases, wind strength, aerosol fluxes of marine, volcanic, terrestrial, cosmogenic and anthropogenic origins.

The recently extended Vostok ice core record provides a unique, complete, and undisturbed picture of the atmospheric changes over the last 4 climatic cycles (Petit and others, 1997 ; Petit and others, in press). Most of the variability occurs with periodicities corresponding to that of the precession, tilt and eccentricity of Earth's orbit with the dominance of the 100 ka cycle. The record confirms that greenhouse gases and ice volume changes have played the role of strong amplifiers of the external insolation forcing to stimulate the observed glacial-interglacial climatic changes.

In the context of the interglacial periods of the late Quaternary, including stage 11, the Vostok record shows interglacials which differ in shape. Antarctic temperature was warmer and atmospheric CO2 and CH4 higher during interglacial 5.5 and 9.3 than during the Holocene and interglacial 7.5. The record, which can be interpreted with confidence down to 3310 m, also documents at least the last part of stage 11 (11.3). It does not show stage 11- ice especially warm or with CO2 and CH4 concentrations particularly high (the properties of this stage 11 - ice are similar to those during the Holocene or stage 7.5). Below 3310 m there are indications that the record is disturbed, probably because of ice flow anomalies affecting the deepest layers of the ice sheet (Petit and others, in press). So, we cannot be sure that the undisturbed Vostok ice sequence provides a record of the extreme condition (the warmest and the highest in terms of greenhouse gas concentrations) of stage 11.

This "frustrating" situation is not without solution. There are, indeed, potential sites in Antarctica (but not in Greenland) which may deliver an undisturbed record going back to stage 12 (i.e. with a complete stage 11). Candidates are, for instance, sites in the vicinity of Vostok but with thicker ice, or sites on a dome (like Dome A in East Antarctica) with a cold base (in contrast with the Vostok ice under which exists a deep subglacial lake).

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The continental record of Stage 11

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Terrestrial Quaternary stratigraphy in Europe has been strongly influenced by the Alpine glaciation chronology on the one hand and the recognition of temperate interglacial intervals on the other hand. Because both kinds of records did not occur in the same location, different interpretations and correlations occur in the stratigraphical community (Sarnthein, and others, 1986). Thus, there is uncertainty about which terrestrial interglacial correlate with marine isotope stage 11. Here, I adopt the view of Kukla (in Smiley and others, 1991) who determined, by comparing marine and continental records, that marine stage 11 corresponds to the terrestrial interglacial named Holsteinian in northern Europe (Fig. 1).

Identifying the continental stage 11 requires study of long sequences which yield superimposed climatic cycles and have reliable chronostratigraphies (Fig. 2). However, time resolution is not always good enough to describe in detail the observed climatic and environmental changes. The following review will be three fold: pollen and lake sequences, loess series, and an example of a particular European faunal record.

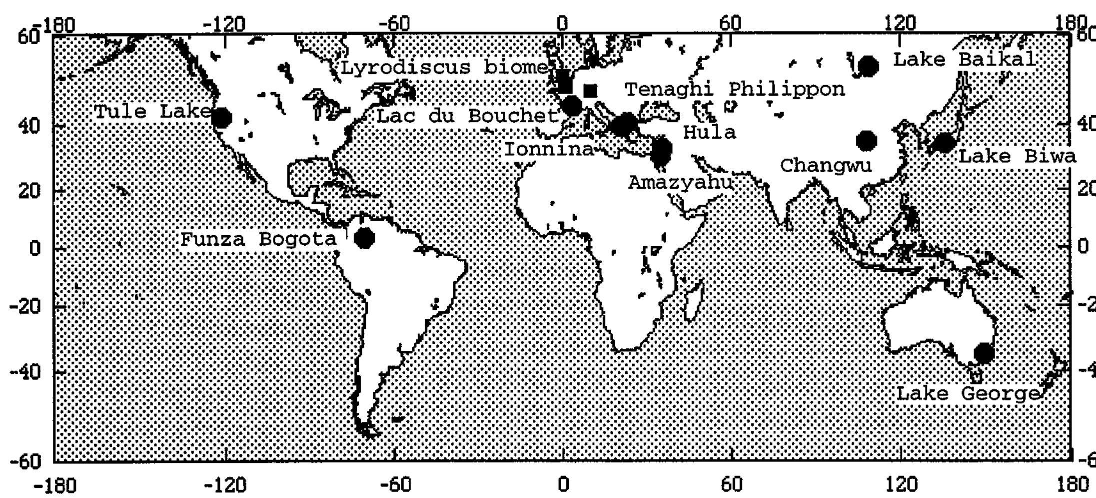


Fig. 1. Location of the different records discussed in the text. Plain circles corresponds to individual long sequences; plain squares correspond to the occurrence of the European mollusk localities of marine stage 11.

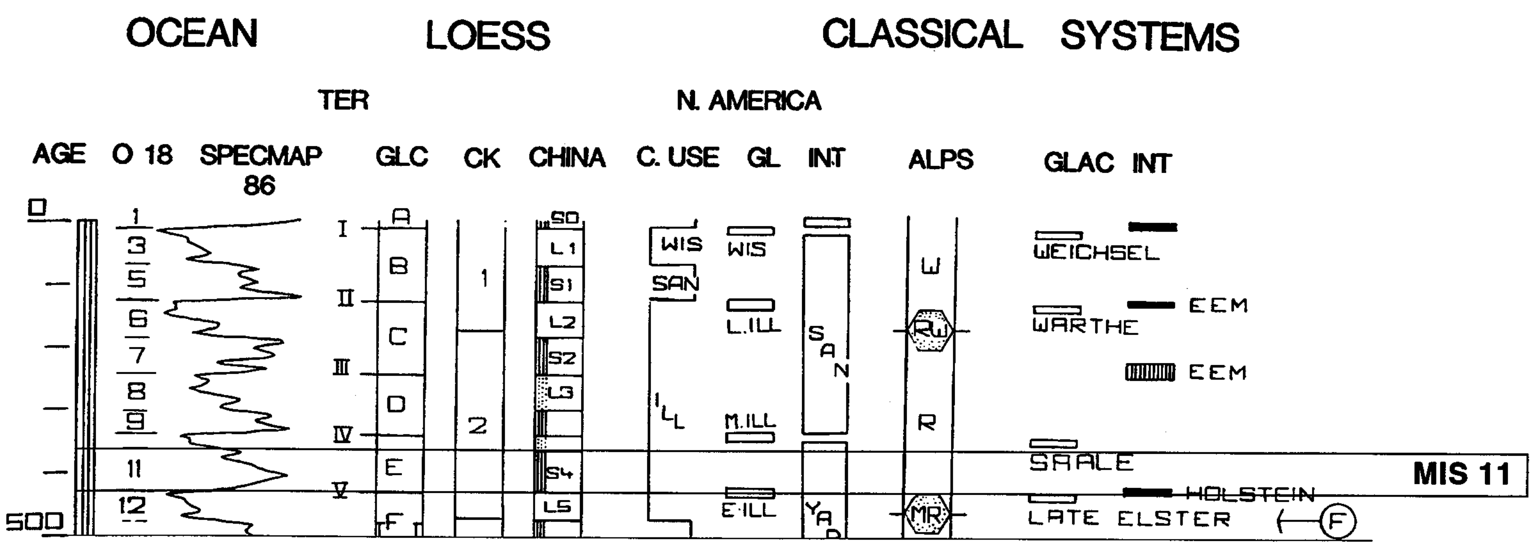


Fig. 2. Continental records of MIS 11. Marine isotope stage 11 according to SPECMAP and comparison with the loess (European, general and Chinese), North American, European Alpine and North European Plain Quaternary Stratigraphies. (from Kukla,1991. modified)

Pollen and lake records

Pollen and lake sequences yield numerous records of stage 11 which permit the characterization of environmental changes with varying magnitude because of the geographical location and the time resolution reconstructed. Cores taken at Tule Lake in North America record MIS 11 (Adam and others, 1989). However, the time resolution is so poor that no interesting information can be deduced for this time interval.

Europe, although located on the eastern bank of the Atlantic Ocean, and thus directly under the influence of the variations of the thermo-haline circulation, shows at least 4 well developed long lacustrine pollen series, among which 3 recorded marine isotope stage 11 : Lac du Bouchet-Praclaux in the French Massif Central, Ionnina, and Tenaghi Philippon in Greece (Fig. 2). The variations in the aboreal pollen curve allow the recognition of several climatic cycles, where interglacials are characterized by a logical succession of vegetation leading to high percentages of arboreal pollen grains.

In Lac du Bouchet-Praclaux, the Holsteinian is well recorded and characterized by few *Carpinus,* while *Abies* and *Fagus* are dominant (Reille and de Beaulieu, 1995). A small interval is marked by the occurrence of *Taxus,* and some thermophilous taxa like *Buxus* and *Vitis* are present. The interpretation of this vegetation is that the interval was not warmer than the other following interglacials but moister (Fig. 3).

At Ionnina (Tzedakis, 1994) (Fig. 4), Stage 11 is well developed. The pollen concentration is the highest during the early part of Stage 11 and interpreted as the occurrence of a dense forest environment. It is characterized by high pollen concentration of warm taxa such as *Buxus, Ulmus, Zelkova, Alnus* or even *Fagus,* the latter indicating low precipitation and high temperate conditions. This record is in complete agreement with that in Tenaghi Philippon in Macedonia (Wijmstra and Young, 1992) which recorded the past 700 ka and showed a strong terrestrial biomass development during MIS 11 .

Two long sequences in Israel show a different pattern (Fuji and Horowitz, 1989; Horowitz, 1989). There, interglacials are interpluvial with a strong influence of the Sahara and reduced precipitation. The comparison between northern and southern Israel indicates different conditions, implying that a steep gradient occurred between N and S (Fig. 5). The vegetation in northern Israel indicates a desert environment during MIS 11 while southern Israel experienced moist, steppe conditions. The two areas are, at present time, under contrary conditions (Fig. 5).

In Japan, the Biwa sequence (Fuji and Horowitz, 1989) covers the last 1.5 Myrs. The sequence shows that the vegetation succession during the different interglacials was similar to present conditions, especially under the influence of marine currents (Fig. 6). However, MIS 11 indicated warmer environment than during present time.

Finally, the Funza Bogota pollen record in Colombia shows a complete sequence of the past 3.5 Myrs (Hooghiemstra and Melice, 1994; Hooghiemstra and others, 1993).

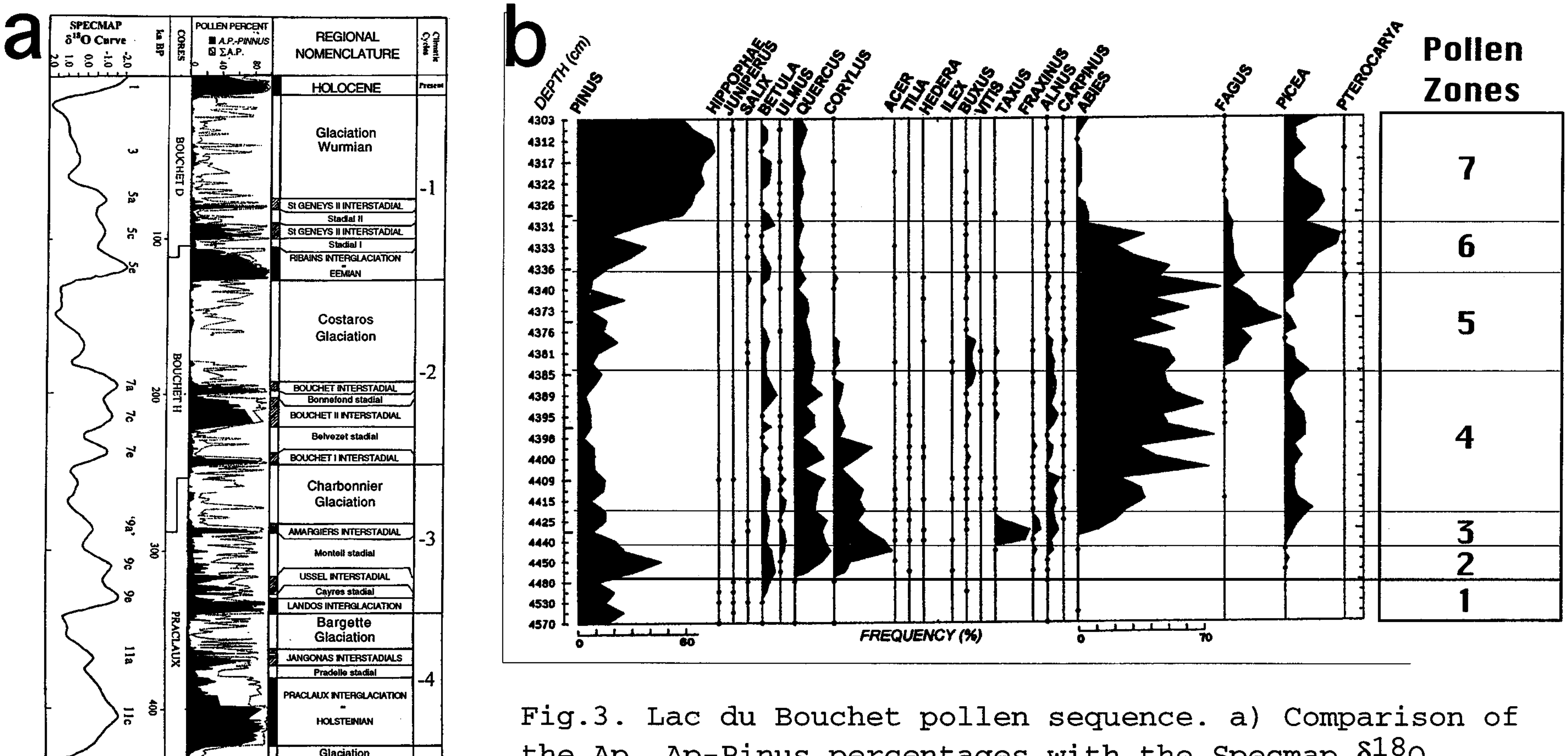


Fig.3. Lac du Bouchet pollen sequence. a) Comparison of the Ap, Ap-Pinus percentages with the Specmap $\delta^{18}O$ curve. Indication of the stratigraphy. b) Pollen diagram (selected trees) of the Holsteinian from Reille & De Beaulieu 1995 modified

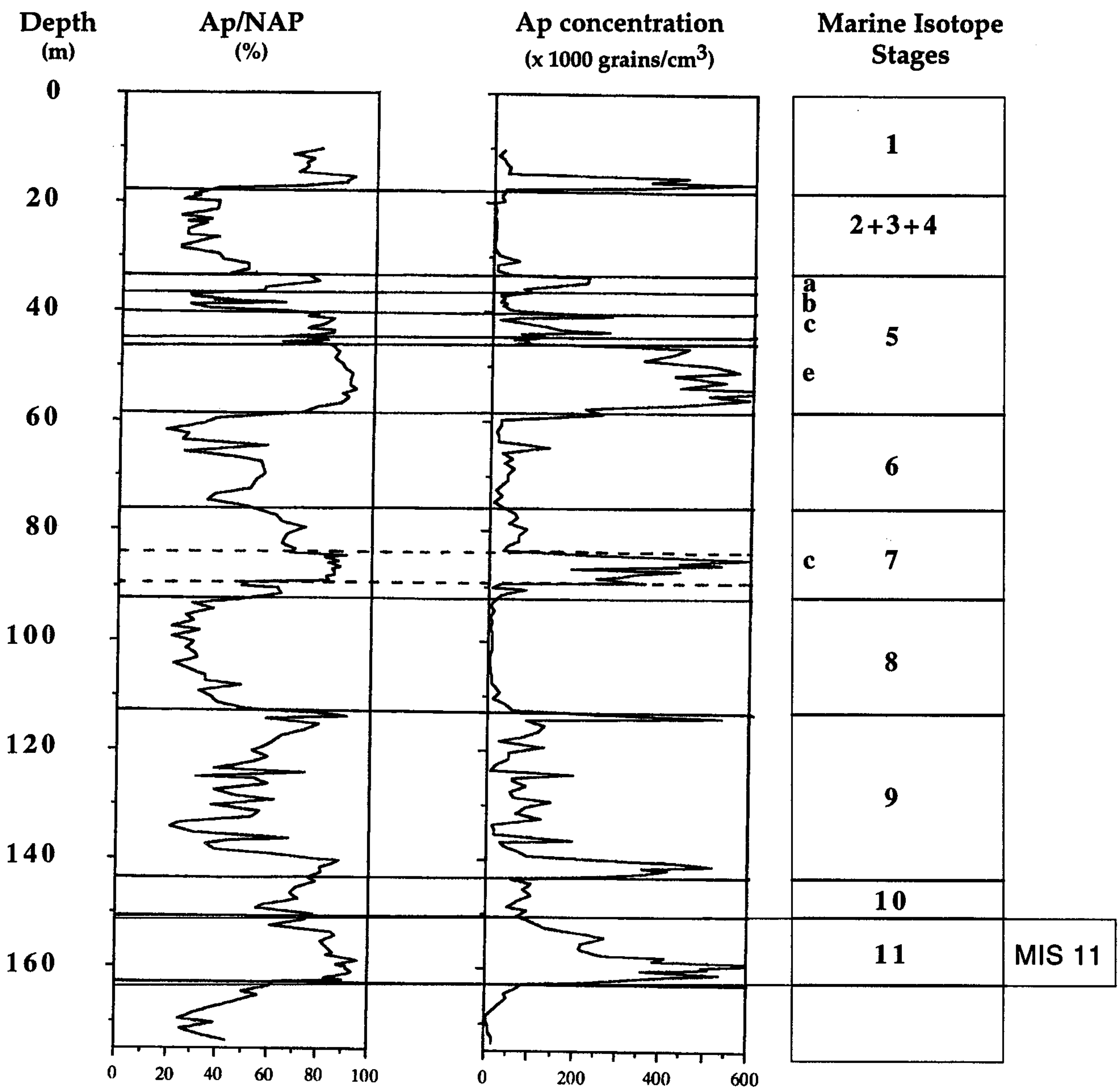


Fig. 4. Pollen sequence at Ionnina (Greece). Variation in AP-NAP% on the left, in AP concentration, correlation with the marine isotope chronology. from Tzedakis 1994 modified.

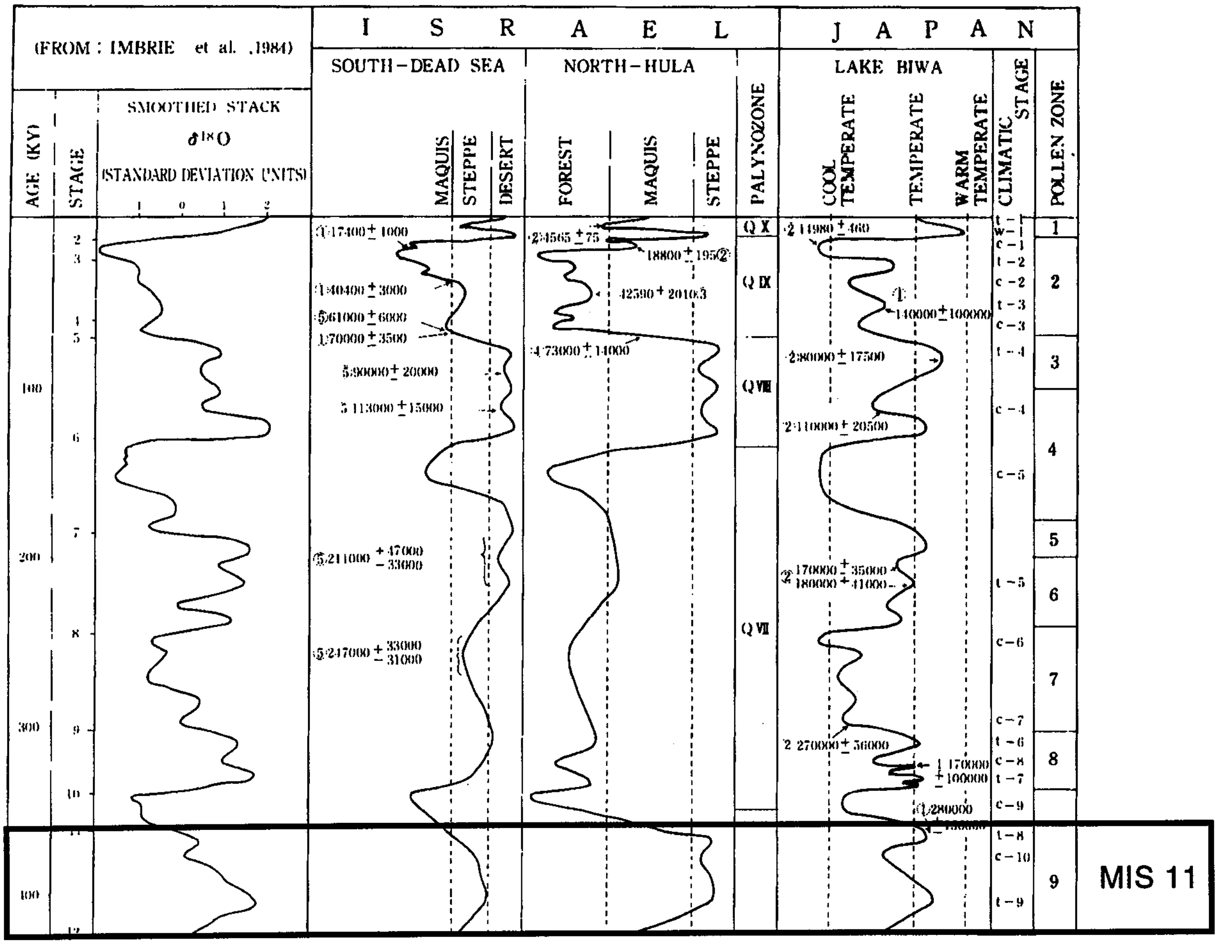


Fig. 5. Comparison between the long terrestrial pollen records in Israel and Japan, and correlation with SPECMAP chronology. (from Fuji and Horowitz 1989 modified).

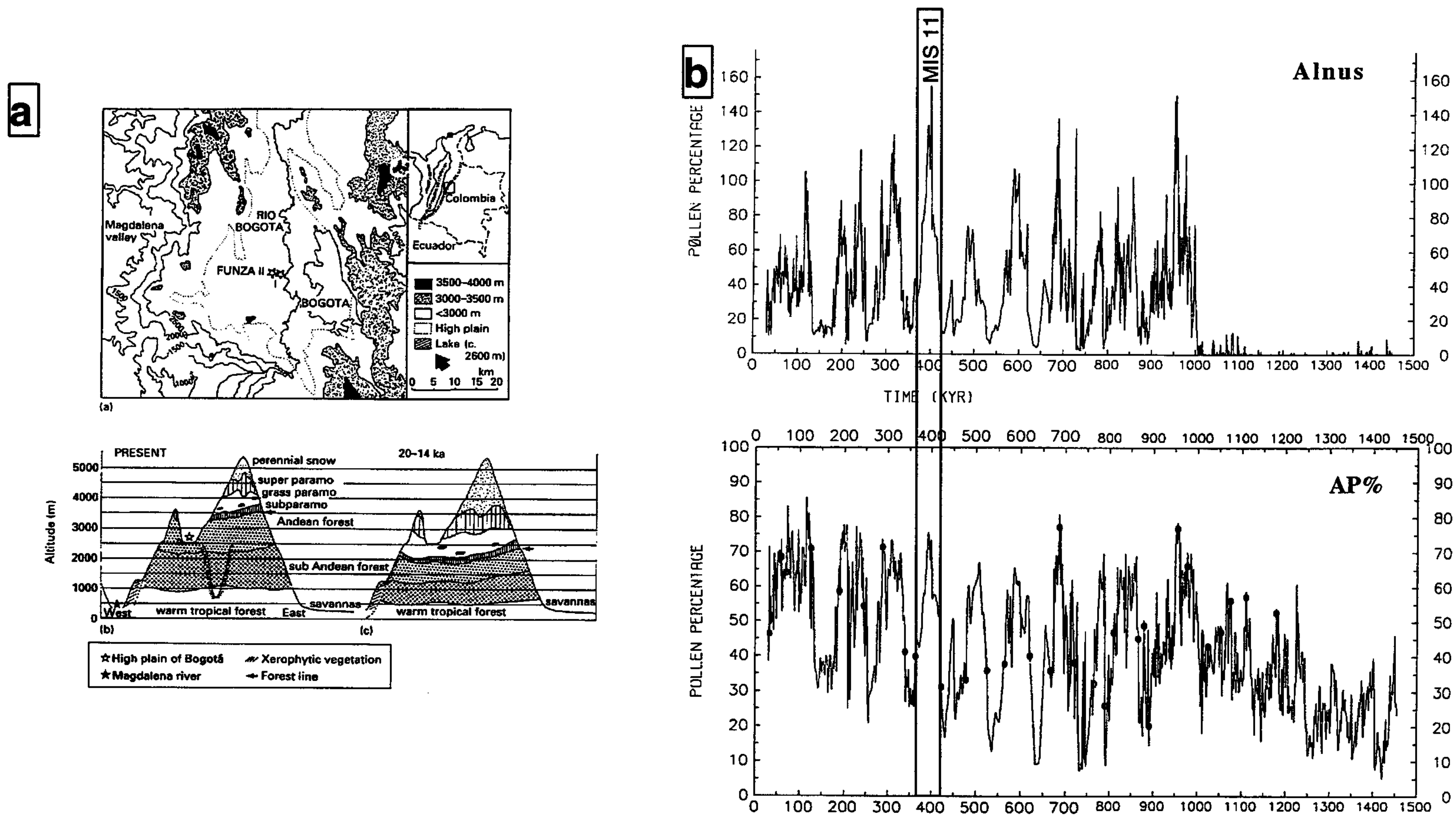


Fig. 6 . Pollen sequence of Funza Bogota (Colombia) a) location and variation of the vegetation according to the present interglacial and last glacial maximum scenarios. b) variations of Ap and *Alnus* percentages versus time. Indication of stage 11 interval.from Hooghiemstra and others. 1993 modified

The AP curve indicates that during isotope stage 11, the upper limit of the Andean forest was higher than 3000 m with a temperature higher than 14.8°, which is the present value. However, a high percentage of *Alnus* is recorded. In the Bogota area, *Alnus* lives mostly in swampy zones and its high concentration could be interpreted as an indication of high humidity (Fig. 5).

A long pollen sequence in Australia also recorded marine isotope stage 11 (Williams and others, 1993). However, no interpretations in terms of temperature or moisture are possible because no pollen is preserved during that interval (Singh and Geissler, 1985). There are, nevertheless, charcoals which indicate that this interval was a period with less fires than the following interglacials (Fig. 6).

Lake Baikal, in another context, provides a record of continental climate for the past 5 Ma (Williams and others, 1997). The study of the biogenic silica flux shows that of the past 800 ka, the production during MIS 11 was among the highest - indicating high blooming of diatoms in Spring.

Loess record

Although both are continental records, loess sequences and pollen records correspond to different environments. Loess sediment occurrs mostly in the northern hemisphere at the southern margin of former ice-sheets or on the pathway of winds connecting high pressure to low pressure cells. Loess sequences can provide reliable records of past climatic changes especially for long sequence spanning several cycles. In China, the sequences within the Central Chinese loess plateau yield a record of the past 2.4 Myrs, an includes a complete Quaternary record (Kukla, 1987). The succession of loess and soil units and magnetic scale permit correlations with marine records. The analysis of the magnetic susceptibility has been correlated with the eolian dust record from Pacific cores (Hovan, and others, 1991) and thus is a good climatic index, even if the interpretation for paleosols also include bacterial activity. In the Chinese series, marine isotope stage 11 is represented by a soil complex named S4 within the Upper Lishi formation. The magnetic susceptibility shows high values that are not the highest in the record. However, the study of the Iron Oxide ratio (an index of weathering) does show the highest values during the deposition of soil S4 (Guo and others, 1998). The interpretation is that, compared to the present time, the climatic conditions were the wetter during marine stage 11. This conclusion is supported by the interpretation of the pollen content in Luochuan. A rich pollen assemblage with *Anacardiaceae* and *Thalicrum* lead Wang and others (in Kukla, 1987) to conclude that the soil surface during S4 was wetter compared to the soils of the Lower Lishi formation. A reinforcement of the summer monsoon regime during marine isotope stage 11 over central China must then be considered (Fig. 8).

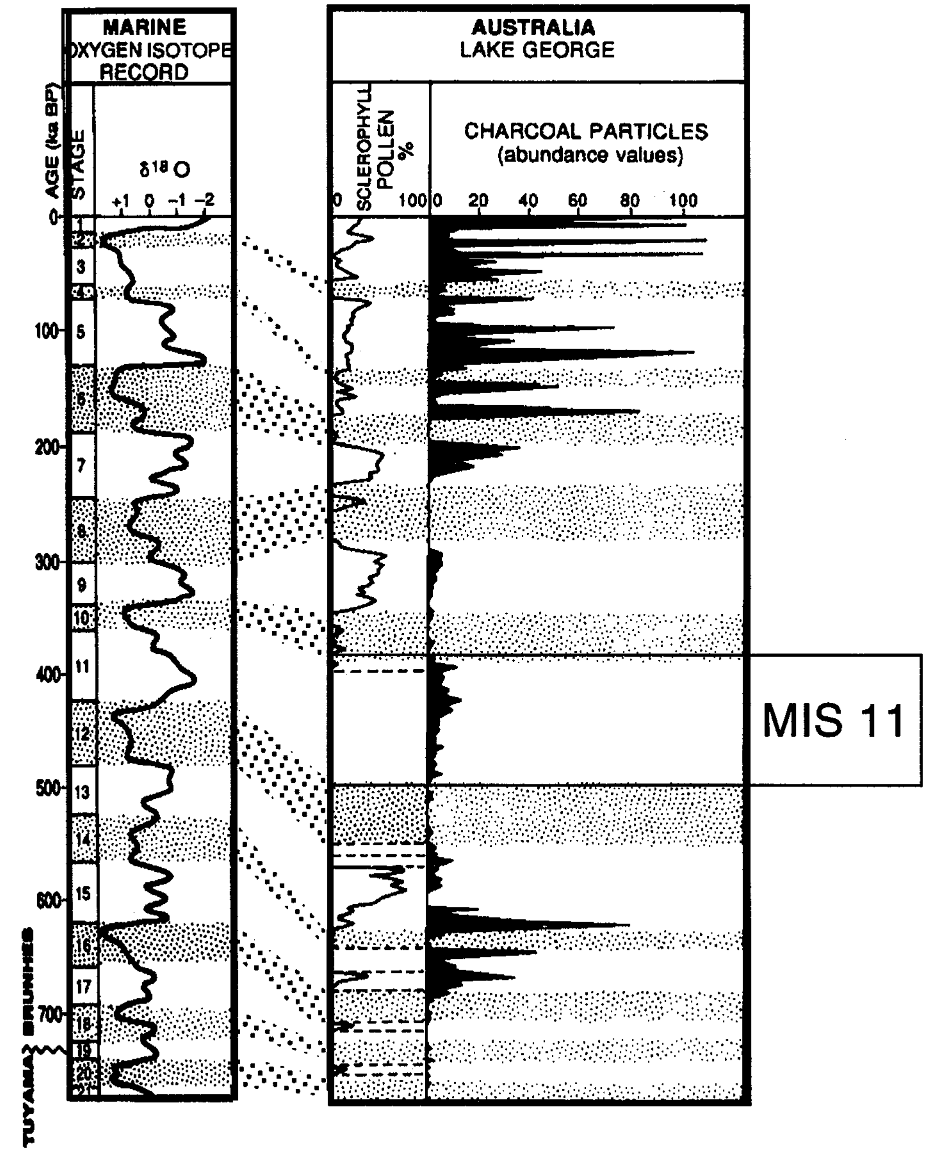
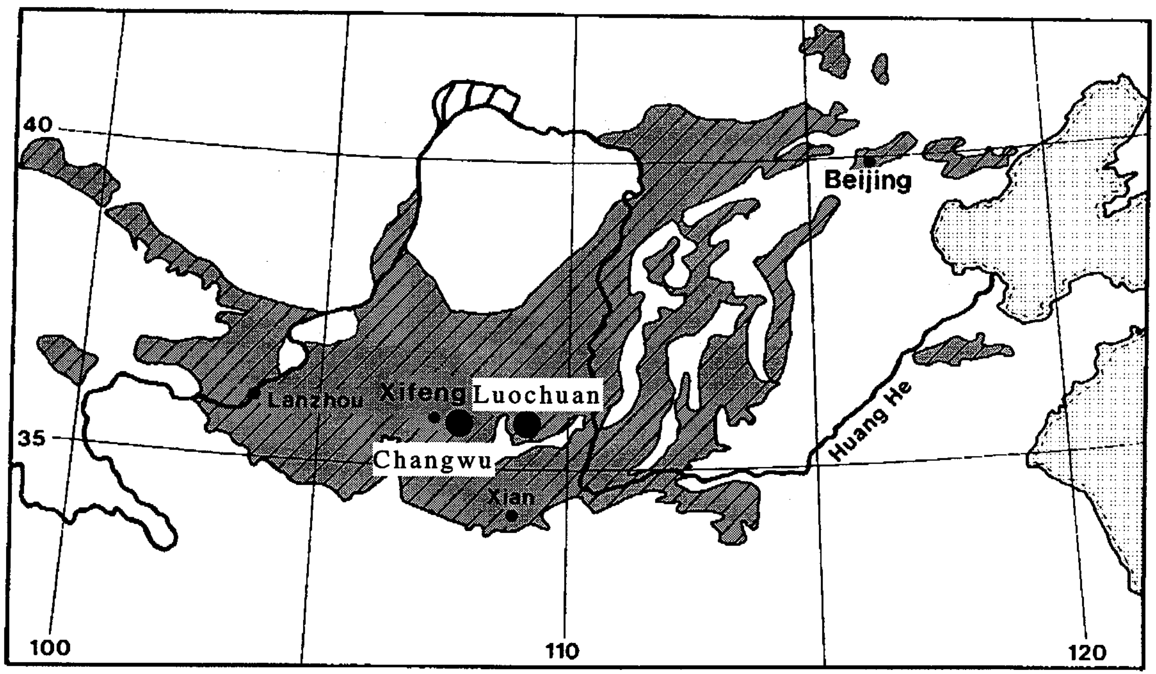


Fig.7.Comparison between marine isotope record and the charcoal and pollen sequences from Lake George (Australia). (from Williams and others 1993 modified).



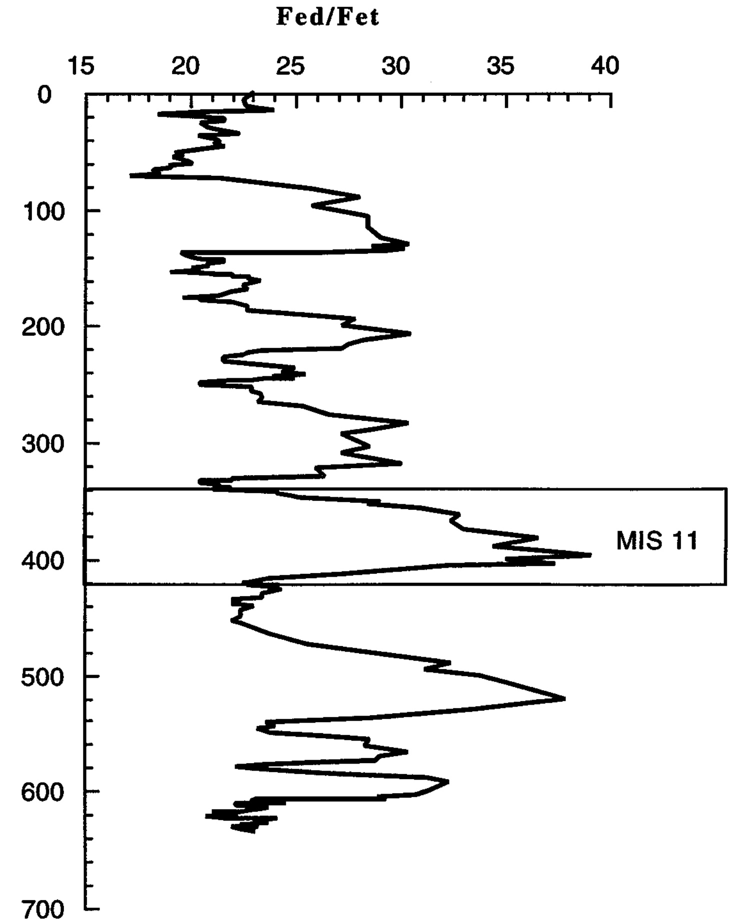


Fig. 8 Variation of the weathering intensity in the Chinese loess plateau.
a) location of the Changwu sequence. b) variation in the Fed/Fet ratio representing the weathering intensity.(from Guo and others 1998 modified).

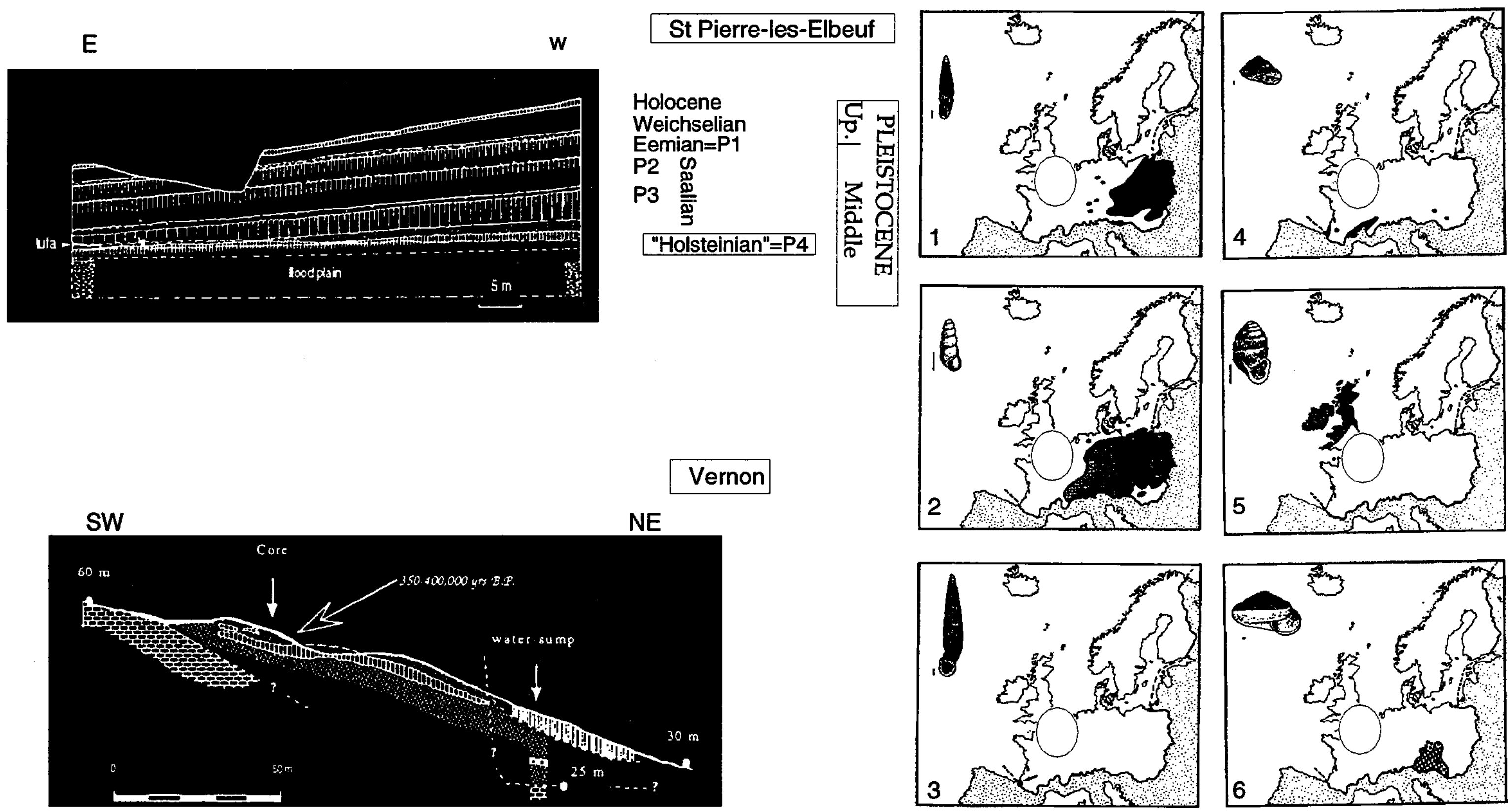


Fig.9. European mollusk record of stage 11. Left, St Pierre-les-Elbeuf loess sequence (top) and Vernon section (bottom) in France showing the stratigraphic position of the deposits. Right, present distribution of mollusk species belonging to the Lyrodiscus biome 1) *Ruthenica filograna,* 2) *Acicula polita,* 3) *Laminifera pauli,* 4) *Hygromia cinctella,* 5) *Leiostyla anglica* and 6) *Aegopis verticillus.* The hatched zone indicates the distribution of this particular biological assemblage.

A particular European faunal event

In Western Europe, loess sequences also recorded the equivalent of stage isotope 11. In the series of St. Pierre-lès-Elbeuf in the Seine Valley, north-west France, the loess sequence is mainly composed by the alternation of loess and soil units (Lautridou and Verron, 1970). Elbeuf IV, the soil complex equivalent to MIS 11 shows the peculiarity of including a tufa (Fig. 9). This sediment yielded a terrestrial malacofauna which shows an unusual composition by comparison to the present fauna (Rousseau, 1992; Rousseau and others, 1992). A few kilometers to the east, still in the Seine Valley, another tufa deposit which base has been dated by U/Th to about 400 ka yielded a similar fossil terrestrial malacofauna. Other sites in northern France, southeastern England (Hoxnian age) and south-western Germany yielded that malacofauna and have been correlated together. The composition of the snail assemblage is very special. The forest species are dominant indicating a temperate conditions, but moisture was high too. Moreover, whereas the identified species one still living today in the surroundings of the localities, other show at the present time a rather different pattern. Some are living in Central Europe, some are southern (one is endemic of Bayonne area), one is endemic of northern area of British Islands (Fig. 9). Two species are fossil among which one is related to a subgenus which present distribution is endemic of the Canary Islands (Rousseau and Puisségur, 1990). Also plant macrofossils include Mediterranean and tropical trees, and among them the Laurel of the Canary Islands. Using the Biome concept, this particular assemblage was named the *Lyrodiscus* biome. According to this study, MIS 11 climate in western Europe, or at least the second half, with regards to the stratigraphic position of the tufa above the paleosol Elbeuf IV in St Pierre-lès-Elbeuf, was warmer but also moister than today.

Conclusions

Terrestrial records of stage 11 show contrasted conditions with a marked N/S gradient in Europe indicating higher temperature than today in some places but generally more humid conditions in mid-latitudes while low precipitation in the Mediterranean basin. On the contrary, the SE Asian monsoon was reinforced, fires reduced in SE Australia and the high plain of Bogota experienced hot and wet conditions.

Acknowledgments

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A Submerged Stage 7 Terrace and Reevaluation of the Late Pleistocene Stratigraphy of Oahu, Hawaii

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Results of sedimentologic and geochronologic investigations of a nearshore terrace require a reevaluation of the late Pleistocene stratigraphy and relative sea-level/tectonic history of Oahu. The shallow submerged slope of Oahu consists of a shallow-dipping shelf extending from the shoreline out to the ~-20 m contour where there is a sharp break (wall) down to ~-30 m forming the start of a deeper terrace. The composition, as well as shoreward zonation of facies, suggests that the nearshore terrace represents an in situ fossil reef complex. Th-U ages of in situ corals indicate that the terrace complex is entirely Pleistocene in age and suggest that the bulk of the feature is composed of a fossil reef complex formed during marine oxygen isotope stage 7.

The emerged carbonate record on Oahu contains two well-identified upper Pleistocene formations. The Kaena Formation, which reaches elevations as high as +30 m, has been correlated with marine oxygen isotope stage 13 or 15. The Waimanalo Formation, which reaches elevations as high as +12.5 m, has been correlated with marine oxygen isotope stage 5e. The age and position of these formations has been used to determine the long-term uplift rate for Oahu. In coastal sections, the Waimanalo Formation either rests unconformably on the Kaena Formation or is separated from it by the Bellows Field Eolianite of undetermined age.

The data presented here suggest relative sea levels on Oahu during stage 7 were much lower than sea levels during stage 5e or stage 13/15. In addition, hiatuses in the emerged record of Oahu may be accounted for in the nearshore submarine terraces.

The Stage 11 Problem as seen at ODP Site 982

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ODP Site 982 (57° 30' N, 15° 32' W, 1133 m water depth) on the Rockall Plateau in the North Atlantic, contains a superb history of ice rafting of the last 2 million years, tied directly to the stable-isotope record. Here, we concentrate on the time span around 400,000 ka, namely the State 11 (Holsteinian) interglacial. This interglacial is characterized in Alaska by a high sea stand, known as the Wainwrightian Transgression (Karmuk Member of the Gubitz Formation) on the North Slope (J. Brigham-Grette, personal communication). Because this high sea stand is about 20 m above present sea level, planetary ice-volume may have been below present volume, resulting in higher sea level (ignoring possible vertical uplift of the North Slope for the purpose of this initial discussion).

The combined record from Site 982 shows the following: the strong Stage 12 glacial was followed by an abrupt transition to Stage 11. This transition, Termination V, coincided with the highest ice-rafted debris (IRD) peak of the record. This large, Terminal Ice Rafting Event (TIRE) was followed by 23 ka without IRD deposition (only 1 sample contains some IRD), in turn followed by an interval of only sporadic IRD delivery. Because the non-volcanogenic IRD at Site 982 reflects mainly glaciations on Greenland, the complete absence of this material during much of Stage 11 may indicate a major deglaciation of Greenland. In turn, because of the teleconnection via rising sea level to the Westantarctic Ice Sheet (WAIS), a reduction in the size of the WAIS is also likely, Therefore, a reduction in planetary ice volume during Stage 11 may partially explain the transgression noted in Alaska.

Appendix 1

Workshop Agenda

Stage 11 Workshop Crowne Plaza Hotel 5 December, 1998

8:20	Introduction and schedule - outline of session	Sutter III
8:30	1 - **Stage 11 and solar forcing** - Richard Muller	
8:50	discussion 1	
9:05	2 - **The ice-core record** - Dominique Raynaud	
9:25	discussion 2	
9:40	3 - **The sea-level record** – magnitude and timing - Julie Brigham-Grette	
10:00	discussion 3	
10:15	break	
10:35	4 - **The continental record of Stage 11** - Denis-Didier Rousseau	
10:55	discussion 4	
11:10	5 - **The marine record of Stage 11** - Will Howard	
11:35	discussion 5	
12:00	lunch	
1:00	posters and informal discussion	Sutter I & II
2:15 – 5:00	formal discussion session - topics to include:	Sutter III

- **The continental record** - what are the problems- where are the gaps – what types and resolution of data are needed

2. **The sea-level and ice record** - same questions as for the continental record
3. **Drilling targets** - what areas and specific sites offer potential to provide new information bearing on data needs and problems.
4. **1999 AGU Symposium**

Appendix 2

Workshop Participants

John Barron	USGS
Julie Brigham-Grette	U Mass
Lloyd Burckle	LDEO
Harry Dowsett	USGS
André Droxler	Rice U
John Farrell	JOI
Chip Fletcher	U
Christina Gallup	U Md
Gerald Haug	USC
Dave Hodell	U Fl
Will Howard	U Tasmania
Daniel Karner	UC Berkeley
David Korejwo	U Mass
Ron Litwin	USGS
Mitch Lyle	Boise State
Korie Mielke	UC Davis
Richard Muller	UC Berkeley
Delia Oppo	WHOI
Lisa Osterman	USGS
Larry Peterson	U Miami
Serena Poli	U SCarolina
Dick Poore	USGS
Christina Ravelo	UC Santa Cruz
Dominique Raynaud	Lab. Glac. d Geophy. Envir.
Yair Rosenthal	Rutgers
Denis Rousseau	U Montpellier
Scott Starratt	USGS
Dietz Warnke	CSU Hayward