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博士論文

**Hydrological evolution of the eastern tropical Pacific
during the last 430,000 years**

(過去 43 万年間の東部熱帯太平洋の水理学的
変化)

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主要論文要旨

The eastern tropical Pacific (ETP) is a key region in paleocenography to understand the response of upwelling, the position of the intertropical convergence zone (ITCZ), and the zonal and meridional atmospheric circulations to orbital forcing. In this study, the author reconstructed the hydrological evolution of the ETP by analyzing glycerol dialkyl glycerol tetraethers (GDGTs), alkenones and the oxygen isotopes of foraminifera and bulk carbonate in sediments from Ocean Drilling Program Sites 1237, 1239, and 1241 during the last 430,000 years.

In the first chapter, the author describes the outline of modern oceanography of the ETP and the history of paleoceanographic studies for the ETP. He also presents the purpose and strategy of this study.

In the third chapter, the author proposes that the difference between $\text{TEX}_{86}^{\text{H}}$ - and U_{37}^{K} -derived temperatures (ΔT) and the abundance ratio of GDGTs to alkenones (GDGT/alkenone ratio) are potential upwelling indices which show consistent results with other upwelling indices, and discusses changes in upwelling intensity in the eastern equatorial Pacific (EEP) at the offshore of Ecuador (Site 1239) over the past 430 ka. The ΔT and GDGT/alkenone ratio were maximal during the last five deglaciations, suggesting intensified upwelling. The intensification of upwelling in the EEP coincided with those at

the Peru margin and in the Southern Ocean. This coincidence suggests that the reorganization of the Southern Hemisphere atmospheric circulation induced the intensification of the subtropical high-pressure cell, causing stronger southeast trade winds along the west coast of South America and the southern westerlies over the Southern Ocean, enhancing upwelling in both regions.

In the fourth chapter, the author discusses the hydrological evolution of the eastern Pacific warm pool region (EPWP) at the offshore of Panama (Site 1241) during the last 150,000 years. GDGTs and alkenone concentrations showed higher values in MIS 2 and MIS 6, which suggest the enhancement of primary production at glacial periods. The $\text{TEX}_{86}^{\text{H}}$ - and U_{37}^{K} '- derived temperature depicted the different surface temperature evolution. U_{37}^{K} '-derived temperature was marked by small variation during the glacial-interglacial cycles, whereas $\text{TEX}_{86}^{\text{H}}$ - showed a pronounced variation that was similar to Mg/Ca-derived temperature records obtained at a nearby core in the EPWP. Given that enhanced primary productivity during glacials suggest nutricline shoaling, unchanged U_{37}^{K} ' over glacial-interglacial cycles can be interpreted to be related to the shift of alkenone production depth. $\text{TEX}_{86}^{\text{H}}$ seems not to be influenced by glacial-interglacial changes in nutricline depths, recording an integrated temperature in surface and thermocline water. The shallow nutricline in the EPWP during glacial maxima most likely reflected the intense formation of Antarctic intermediate water.

In the fifth chapter, the author describes the SST evolution in the Peru margin (Site 1237) and discusses changes in the intensity of the Peru-Chile Current (PCC) by reconstructing the latitudinal gradient of SST along the western margin of Central and South America during the last 90,000 years. GDGTs and alkenones were analyzed for

sediment samples retrieved from ODP Site 1237 (Peru margin) and compared the SST record with the records at Site 1241 (off Panama) and Site 1239 (off Ecuador). A decrease of temperature gradient between the Peru margin (Site 1237) and the EEP (Site 1239) during the last deglaciation suggests that the PCC intensified over the coastal boundary region. The intensification of the PCC coincided with the thermocline shoaling in the EEP and the enhanced upwelling in the EEP and the intensified anoxia at the Peru margin during the last deglaciation. This coincidence suggests that the intensification of the PCC is a part of regional hydrological change in the eastern Pacific during the last deglaciation.

In the last chapter, the author summarizes the results and discussion this study. Both the enhanced upwelling in the EEP and the intensification of the PCC, along with other evidence from published records, suggest the intensification of the South Pacific subtropical gyre circulation during deglaciations. In the EPWP, thermocline shoaled in glacial maxima, likely reflected the intense formation of the AAIW.

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CHAPTER 1: General Introduction

1.1 The eastern tropical Pacific

The modern eastern tropical Pacific (ETP) is characterized by large zonal and meridional asymmetries generated by the productive upwelling system and ocean-atmospheric interactions (Xie et al., 2007). The interaction of the ocean-atmospheric in this region was thoroughly discussed in the several review papers (e.g., Amador et al., 2006; Kessler, 2006; Fiedler and Talley, 2006; Lavin et al., 2006). Two important phenomena which are significantly associated with the modern hydrological system in the ETP are the seasonal displacement intertropical convergence zone (ITCZ, Fig. 1-1) and the interannual El Niño Southern Oscillation (ENSO) event (Fig. 1-2). The northward displacement of the ITCZ is linked to the meridional asymmetry of sea surface temperature (SST), warm water at the north and colder water at the south of the equator (Xie and Philander, 1994). The El Niño events are characterized by anomalous warming of the SSTs and weaken upwelling in the ETP. However, the influence of both phenomena on the hydrology of this region is a hot topic in modern oceanography.

1.2 Paleooceanographic studies in the eastern tropical Pacific

In the recent decades, paleoceanographers have given more efforts to understand the hydrographic and atmospheric evolutions in the ETP (e.g., Romine and Moore, 1981; Loubere 1999; Feldberg and Mix, 2002; Koutavas and Lynch-Stieglitz, 2003; Kienast et al., 2006). The changes that occurred in ocean water column are the best paleo gauge to understand the oceanography evolution in this region because it reflects the ocean-

atmospheric interactions of the past. A number of marine proxies have been applied intensively in this region i.e., alkenone-derived temperature, Mg/Ca-derived temperature and $\delta^{18}\text{O}$ of planktonic foraminifera, coccolithophore assemblages and foraminiferal assemblages. Application of these proxies has opened the way for better understanding about the paleoclimate evolution in this region.

The variability of sea surface temperature (SST) in this region was reconstructed using alkenone (e.g., Lyle et al., 1992; Kienast et al., 2006; Koutavas and Sach, 2008; Rincon-Martinez et al., 2010) and Mg/Ca (e.g., Lea et al., 2000; Koutavas et al., 2002), radiolarian assemblages (e.g., Pisias and Mix, 1997) and foraminiferal faunal species (e.g., Feldberg and Mix, 2002). An early effort to reconstruct the salinity in this region has been carried out by Lea et al. (2000). Lea and co-worker assumed that the $\delta^{18}\text{O}$ record of planktonic foraminifera *Globigerinoides ruber* (*G. Ruber*) was reflected the salinity of the surface water column. Primary production records generated by proxies such as organic carbon and opal contents (e.g., Lyle et al., 1988; Loubere et al., 1999; Kienast et al., 2006; Dubois et al., 2011). These studies have provided evidence for an early response by the ETP to orbital forcing (e.g., Imbrie et al., 1992), and this region is thus thought to play an important role in amplifying climatic changes through positive feedback mechanisms.

Paleoceanographic studies suggested that the changes in the ETP during deglaciations were associated with the climate changes in high latitude (e.g., Liu and Herbert, 2004; Lee and Poulsen, 2005; Toggweiler et al., 2006; Lawrence et al., 2006; Koutavas et al., 2008; Anderson et al., 2009). It has been suggested that the orbital signal may have propagated from high-to-low latitudes via atmospheric teleconnections (Chiang

and Lintner, 2005) or through thermocline circulation via the “oceanic tunnel” (Lee and Poulsen, 2005; Fedorov et al., 2006). Pena et al. (2008) proposed an idea about the latitudinal teleconnection which connected the ETP with the high latitude changes. The linkage between low- and high-latitude climates is not fully understood and under intense debate in paleoclimatology.

A conceptual model analogy of the modern ENSO has often been applied to understand the hydrological evolution of the ETP (e.g., Lea et al., 2000; Koutavas et al., 2002; Koutavas and Lynch-Stieglitz, 2003; Martinez et al., 2003; Pena et al., 2008; Rincon-Martinez et al., 2010), but different proxy records (e.g., alkenone and $\delta^{18}\text{O}$) have led to different conclusions. Some researchers, for instance, have suggested that the glacial ETP was El Niño-like (e.g., Koutavas et al., 2002; Koutavas and Lynch-Stieglitz, 2003), but others have inferred a glacial La Niña-like condition (e.g., Beaufort et al., 2001; Rincon-Martinez et al., 2010). This disagreement has been discussed based on the different behavior of proxies (e.g., Dubois et al., 2009).

1.3 GDGTs and $\text{TEX}_{86}^{\text{H}}$ -paleothermometry

TEX_{86} is a paleotemperature proxy based on the composition of isoprenoid glycerol dibiphytanyl glycerol tetraethers (isoGDGTs). The isoGDGTs with a varying number of cyclopentyl moieties are biosynthesized by marine Thaumarchaeota, and the relative abundance of these moieties changes with growth temperature (Wuchter et al., 2004). Thaumarchaeota are ubiquitous and abundant in seawater (Massana et al., 2000; Karner et al., 2001) and in terrestrial environments (Weijers et al. 2006). TEX_{86} index was proposed by Schouten et al. (2002). The calibration was subsequently improved by Kim

et al. (2008) and Kim et al. (2010). In culture experiments, TEX₈₆ was not affected by salinity and nutrient concentration (Wuchter et al., 2004) and by redox conditions (Schouten et al., 2004). However, the interpretation of this proxy in marine environment needs a caution when the terrestrial soil organic matter contribution is high (Weijers et al., 2006). The other factor that may influence the interpretation of TEX₈₆ is the contribution of thermophilic Euryarchaeota (Kates et al. 1993) that is associated with the anaerobic oxidation of methane (Panchost et al., 2001). High contribution of caldarchaeol from methanogenic Euryarchaeota may bias the interpretation of TEX₈₆ temperature estimates (Blaga et al., 2009; Sinninghe Damste et al., 2009).

1.4 Alkenone and U^K_{37'}-paleothermometry

Long-chain unsaturated methyl (C₃₇, C₃₈, and C₃₉) and ethyl ketones (alkenones) were first discovered in sediments by Boon et al. (1978), and later identified by de Leeuw et al. (1980). They were found in *Emiliana huxleyi* (Volkman et al., 1980). Alkenones are produced by a specific group of Haptophytes such as *Emiliana huxleyi* and *Gephyrocapsa*. Prahl and Wakeham (1987) proposed the first calibration index with growth temperature, as measured in laboratory cultures of the *E. huxleyi* strain 55a. U^K_{37'} is defined based on the degree of di-unsaturated and tri-unsaturated C₃₇ ketone (Appendix 2). A decrease in temperature leads to an increase in the degree of unsaturation and vice versa. A decade later, Muller et al. (1998) established a new U^K_{37'} calibration from core top samples from the South Atlantic.

1.5 Motivation and the purpose of study

There are many proxies have been applied to understand the hydrological and paleoclimate changes in the ETP region. However, those proxies have led to the different interpretation of the hydrological evolution in this region. We applied the combination of the $\text{TEX}_{86}^{\text{H}}$ and U_{37}^{K} for sediment samples retrieved from Ocean Drilling Program (ODP) Sites 1241, 1239 and 1237 (Fig. 1-3). There was no specific research have been carried out using GDGTs to understand the hydrological evolution in this region during the late Pleistocene. In contrast, the U_{37}^{K} was intensively used to study the paleo-hydrological changes in the ETP (Koutavas et al., 2002; Liu and Herbert, 2004; Horikawa et al., 2006; Koutavas et al., 2008; Rindon-Martinez et al., 2010). A comparative study between these organic proxies proposed a new perspective of the oceanography evolution in this region.

The author tried to understand the hydrological evolution in the ETP during glacial-interglacial cycles. In order to facilitate the discussion, the author has divided this study three parts; 1) The establishment of the upwelling index in the EEP and the hydrological evolution over the last four glacial terminations, 2) the variation of thermocline in the eastern Pacific warm pool (EPWP) during the last two glacial maxima and 3) the intensity of coastal current in the Peru margin during the last 90 ka.

1.6 The outline of study

First, we tried to understand changes in the upwelling intensity of the past. We established the upwelling index derived from the temperature difference of $\text{TEX}_{86}^{\text{H}}$ and U_{37}^{K} and the GDGT/alkenone ratio. We used this index to discuss the hydrological

changes. To test its reliability, we compared this index with the other established upwelling proxies in this region (Chapter 3).

Secondly, we investigated changes in the nutricline depth in the EPWP during glacial-interglacial cycles. In order to understand the shift of thermocline depth we compare the variability of GDGT and alkenone concentrations, $\text{TEX}_{86}^{\text{H}}$ -, U_{37}^{K} '- and Mg/Ca-derived temperature during the last 148 kyrs (Chapter 4).

Lastly, we focused on the intensity of the Peru-Chile Current (PCC) by reconstructing SST gradient along the coast of South and Central America. This facilitated better understanding about the intensification of the PCC and the formation of equatorial Pacific cold tongue in this region during the last deglaciation (Chapter 5).

CHAPTER 2: Samples and method

2.1 Study sites and core samples

The sediment samples of Site 1241 (5°50.57'N, 86°26.68'W, 2027 m water depth) were retrieved during Ocean Drilling Program (ODP) Leg 202 that was conducted in 2002. Site 1241 is located in the EPWP on the northern flank of the Cocos Ridge in the Guatemala Basin (Mix et al., 2003a). The sediments between 0.05 and 3.15 meters composite depth (mcd) consisted of olive gray clay-bearing foraminifer-nannofossil ooze and light olive gray nannofossil ooze (Fig. 4-3) (Mix et al., 2003a).

ODP Site 1239 (0°40.32' S, 82°4.86' W; 1414 m water depth) is located near the eastern crest of the Carnegie Ridge and ~120 km off the coast of Ecuador (Fig. 3-1). The sediments are dominated by light to dark olive gray foraminifera-nannofossil ooze with varying amounts of diatoms, clay, and micrite (Fig. 3-3) (Mix et al., 2003b). The age-depth model of this core was established by Rincon-Martinez et al. (2010) based on correlation of the $\delta^{18}\text{O}$ record of the benthic foraminifera *Cibicidoides wuellerstorfi* with the LR04 global stack (Lisiecki and Raymo, 2005). In total, 236 samples were taken from 0.02 to 14.73 meters composite depth (mcd) at 2–10 cm intervals.

Site 1237 (16°0.42'S, 76°22.69'W, 3212m water depth) is located on a flat bench of the easternmost flank of Nazca Ridge and about 140 km off the coast of Peru (Mix et al., 2003c). This site is situated near the eastern edge of the northward flowing of the PCC, a major medium of cool-water transport from high to low latitudes. The sediments of the studied interval (0.04 to 5.25 mcd) from Site 1237 consist of diatom nannofossil

clay and silty clayey diatom nannofossil ooze, and sediment color varies between olive and olive gray (Fig. 5-3) (Mix et al., 2003c).

2.2 Lipid extraction and separation

Extraction and separation of lipids followed a modified method of Yamamoto et al. (2000) and Yamamoto et al. (2008). Freeze-dried and homogenized samples (~2 g) were extracted using an accelerated solvent extractor (ASE 200, DIONEX) with a mixture of dichloromethane and methanol (6/4 v/v) at 100°C and at 1000 PSI. The extract was separated into four fractions, F1 (3 ml hexane), F2 (3 ml 3/1 v/v hexane–toluene), F3 (4 ml toluene), and F4 (3 ml 3/1 v/v toluene–methanol), by column chromatography (SiO₂ with 5% distilled water; i.d., 5.5 mm; length, 45 mm).

2.3 Alkenone analysis and U_{37}^K

The F3 fraction was analyzed with a Hewlett–Packard Model 6890 gas chromatograph with on-column injection and electronic pressure control inlet systems and a flame ionization detector (FID). Helium was used as carrier gas with the flow velocity maintained at 30 cm.s⁻¹. The column was a Chrompack CP-Sil5CB capillary (60 m; i.d., 0.25 mm; thickness, 0.25 µm). The oven temperature was programmed from 70 to 290°C at 20°C min⁻¹, from 290 to 310°C at 0.5°C min⁻¹, and then held for 30 min. Quantification of di- and tri-unsaturated C₃₇ alkenones were achieved by comparing the peak areas with that of an internal standard (*n*-C₃₆H₇₄) on the gas chromatogram.

The alkenone unsaturation index U_{37}^K was computed from the concentrations of di-unsaturated ($C_{37:2}MK$) and tri-unsaturated ($C_{37:3}MK$) alkenones using the following equation by Prahl et al. (1988):

$$U_{37}^K = [C_{37:2}MK] / ([C_{37:3}MK] + [C_{37:2}MK])$$

The temperature was calculated according to an equation derived by Prahl et al. (1988) based on experimental results for cultured strain 55a of *Emiliania huxleyi*:

$$U_{37}^K = 0.034T + 0.039$$

where T = temperature ($^{\circ}C$). Analytical accuracy (standard deviation of replicate sediment analysis) was $0.24^{\circ}C$.

2.4 GDGT analysis and TEX_{86}^H

An aliquot of F4 was dissolved in hexane-2-propanol (99/1, v/v). GDGTs were analyzed by high-performance liquid chromatography–mass spectrometry (HPLC-MS) with an Agilent 1100 HPLC system connected to a Bruker Daltonics micrOTOF-HS time-of-flight mass spectrometer. Separation was conducted using a Prevail Cyano column (2.1 x 150 mm, 3 μ m; Alltech) maintained at 30 $^{\circ}C$ following the method of Hopmans et al. (2000) and Schouten et al. (2007). Detection was achieved by atmospheric pressure positive ion chemical ionization–mass spectrometry with full scan mode (m/z 500–1500). Compounds were identified by comparing mass spectra and retention times with those of

GDGT standards (formed from the main phospholipids of *Thermoplasma acidophilum* via acid hydrolysis).

Quantification was achieved by integrating the summed-peak areas in the (M+H)⁺ and the isotopic (M+H+1)⁺ ion traces and comparing these to the peak area of an internal standard (C₄₆ GDGT) in the (M+H)⁺ ion trace, following to the method of Huguet et al. (2006). The correction value of ionization efficiency between GDGTs and the internal standard was obtained by comparing the peak areas of *T. acidophilum*-derived mixed GDGTs and C₄₆ GDGT of known amounts. The standard deviation of a replicate analysis was 3.0% of the concentration for each compound. Concentration of TEX₈₆^H as calculated from the concentrations of GDGT-1, GDGT-2, GDGT-3, and a regioisomer of crenarchaeol using the following expressions (Schouten et al. 2002; Kim et al. 2010):

$$\text{TEX}_{86} = ([\text{GDGT-2}] + [\text{GDGT-3}] + [\text{Crenarchaeol regioisomer}]) /$$

$$([\text{GDGT-1}] + [\text{GDGT-2}] + [\text{GDGT-3}] + [\text{Crenarchaeol regioisomer}])$$

$$\text{TEX}_{86}^{\text{H}} = \log (\text{TEX}_{86})$$

Temperature was calculated according to the following equation based on a global core-top calibration (Kim et al. 2010):

$$T = 68.4\text{TEX}_{86}^{\text{H}} + 38.6 \text{ (when } T > 15^{\circ}\text{C)}$$

where T = temperature (°C). Analytical accuracy (standard deviation of replicate sediment analysis) was 0.45°C. We prefer TEX₈₆^H to TEX₈₆ for temperature estimation in this study

because the calibration of $\text{TEX}_{86}^{\text{H}}$ is better than that of TEX_{86} in warm water region ($> 15^{\circ}\text{C}$; Kim et al., 2010).

2.5 Foraminifera picking and $\delta^{18}\text{O}$ analysis for Site 1241

Homogenized sediment sample (~ 0.5 g) was soaked in distilled water at 90°C for an hour. The sample was sieved through a $63\ \mu\text{m}$ mesh sieve under a water flow to remove mud. The residue was flushed with distilled water onto filter paper, then dried in an oven at $\sim 50^{\circ}\text{C}$ overnight until the sample is thoroughly dry. The dried sample was sieved again through the different mesh sizes in the order of 350, 250, 125 and $63\ \mu\text{m}$. Only the samples above the $250\ \mu\text{m}$ were used for the identification and picking of foraminifera species because the stable isotopic composition is often dependent on the shell size (Peeters et al., 2002). About 15 to 20 tests of planktonic foraminifera *Globigerinoides ruber* (*G. ruber*) were identified and carefully picked out under microscope. The specimens were cleaned and homogenized by an ultrasonic homogenizer in methanol for 10 seconds, and the methanol solution was then taken out immediately from the sample in order to eliminate the dispersed materials.

The stable isotope analysis was followed the protocol of Watanabe et al. (2001) and Oba and Murayama (2004) with some modifications. The powdered homogenized samples ($\sim 30\ \mu\text{g}$) of *G. ruber* tests were reacted with 100% phosphoric acid (H_3PO_4) at 70°C with a Kiel IV automated individual-carbonate reaction device. The $\delta^{18}\text{O}$ compositions of the extracted CO_2 were determined by a Finnigan MAT 253 isotope-ratio mass spectrometers. Isotopic values were expressed relative to the isotopic ratio of Vienna Pee Dee Belemnite (VPDB) after calibration with National Bureau of Standards

(NBS)-19 carbonate standard. The $\delta^{18}\text{O}$ values of *G. ruber* were expressed in per mil (‰). Analytical precision of $\delta^{18}\text{O}$ values is ± 0.05 ‰, based on multiple analysis of a laboratory standard.

2.6 Bulk sediment $\delta^{18}\text{O}$ analysis for Site 1237

Carbonate content was analyzed using a Bruker MX-Labo X-ray diffractometer (XRD) with $\text{CuK}\alpha$ radiation at 40 kV and 20 mA. The scanning speed and stepped diffraction angle were $4^\circ/\text{min}$ and 0.02° respectively. The sample was finely powdered and mounted on a glass plate. The X-ray ranged between 2° and 50° . The MacDiff 4.2.5 software was used to identify calcite content from its peak characteristic. The calcite content was quantified in count per second (Cps), and was changed to percentage unit to calculate.

The stable oxygen isotope analysis was followed the protocol of Watanabe et al. (2001) and Oba and Murayama (2004) with some modifications. The powdered sample was weighted (sample weight are based on the calcite content from the XRD analysis) and placed into a reaction vessel. CO_2 was liberated from each sample using a Finnigan Kiel automated individual-carbonate reaction device (Kiel device) and analyzed in line with a Finnigan MAT 253 isotope-ratio mass spectrometer. In the Kiel device, the 100% H_3PO_4 was dripped on sample in a reaction vessel at 70°C . Purified- CO_2 produced from the H_3PO_4 -reaction was introduced into a mass spectrometer and measured against a mass spectrometer reference standard of known isotopic composition. Conversion of $\delta^{18}\text{O}$ to the Vienna Pee Dee Belemnite (VPDB) scale was performed using the NBS-19 carbonate

standard. Analytical precision of $\delta^{18}\text{O}$ values was $\pm 0.05\text{ ‰}$, based on a multiple analysis of a laboratory standard.

CHAPTER 3: Enhanced upwelling in the eastern equatorial Pacific at the last five glacial terminations

3.1 Introduction

The eastern equatorial Pacific (EEP) is a region between subtropical gyres of the North and South Pacific and contains the eastern terminus of the equatorial current system of the Pacific (Kessler, 2006). This region is important for its roles in climate variability as a result of the El Niño-Southern Oscillation (ENSO) and its significance for global carbon cycle (Fiedler and Lavin, 2006).

Glacial-interglacial changes in the oceanic condition of the EEP have been reconstructed by various studies, including of sea surface temperature (SST) (e.g., Lyle et al., 1992), salinity (e.g., Lea et al., 2000), export production (e.g., Lyle et al., 1988), and intermediate water properties (e.g., Spero and Lea, 2002; Ganeshram et al., 2000). These studies have provided evidence for an early response by the EEP to orbital forcing (e.g., Imbrie et al., 1992), and the EEP is thus thought to play an important role in amplifying climatic changes through positive feedback mechanisms.

ENSO-like variability has often been used to interpret changes in the oceanic condition of the EEP (e.g., Lea et al., 2000; Koutavas et al., 2002), but different proxy records have led to different conclusions. Some researchers, for instance, have suggested that the glacial EEP was El Niño-like based on foraminiferal Mg/Ca and $\delta^{18}\text{O}$ (e.g., Koutavas et al., 2002; Koutavas and Lynch-Stieglitz, 2003), but others have inferred a glacial La Niña-like condition (e.g., coccolith assemblages by Beaufort et al., 2001; foraminiferal assemblages by Martinez et al., 2003; alkenones by Rincon-Martinez et al.,

2010). This disagreement has been attributed to differences in the behavior of different proxies (e.g., Dubois et al., 2009).

In this paper, we present temperature records derived from $\text{TEX}_{86}^{\text{H}}$ and U_{37}^{K} for Ocean Drilling Program (ODP) Site 1239 and interpret the U_{37}^{K} and $\text{TEX}_{86}^{\text{H}}$ records for the last 430,000 years. On the basis of this interpretation, we propose the difference between $\text{TEX}_{86}^{\text{H}}$ - and U_{37}^{K} -derived temperatures and the abundance ratio of glycerol dialkyl glycerol tetraethers (GDGTs) to alkenones as potential upwelling indices and discuss the response of the EEP upwelling system to orbital forcing.

3.2 Modern physical oceanography

The zonal surface current system in the eastern tropical Pacific (ETP) consists of westward- and eastward-flowing currents (Fig. 3-1). The main westward currents are the North Equatorial Current (NEC; 8°N and 20°N) and the South Equatorial Current (SEC; 3°N to 10°S). The SEC originates as a combination of the waters from the North Equatorial Counter Current (NECC), the Equatorial Undercurrent (EUC), and the Peruvian Undercurrent (Kessler, 2006) through equatorial upwelling, mixing and advection. Two main lobes of the SEC are observed at latitude of about 3°S to just north of the equator. The NECC, an eastward current flows just north of the equator and is centered at about 5°N (Wyrski, 1967; Talley et al., 2011). This current transports warmer water from the western Pacific warm pool to the ETP region. Between the SEC and the NECC there is a narrow equatorial front (EF) that separates warm low-salinity waters in the north from cool high-salinity waters in the south (Fig. 1; Strub et al., 1998). This front is observable from July to September at about 2.5°N with a strong meridional SST

gradient. In contrast, the EF position is unclear from January to April, when the southeast trades winds collapse and SST south of the Equator increases owing to reduced upwelling. The condition of the EF is correlated with the displacement of the intertropical convergence zone (ITCZ) (e.g., Pak and Zaneveld, 1974; Chelton et al., 2001; Raymond et al., 2004). The ITCZ reaches its northernmost extent in the month of August ($\sim 12^{\circ}\text{N}$) when southeast trade winds are stronger; the ITCZ is located closest to the equator in April ($\sim 2^{\circ}\text{N}$) when northeast trade winds are stronger (Waliser and Gautier, 1993).

The most influential subsurface current in this region is the EUC that flows eastward beneath the SEC. The EUC is fed by the saline New Guinea Coastal Undercurrent at its western boundary (Talley et al., 2011) and flows within the equatorial thermocline and shoals as it approaches the Galapagos Islands (Kessler, 2006). When it reaches the Galapagos Islands, it splits into two branches (Steger et al., 1998) with the main branch flowing southward to merge with the Peruvian Undercurrent, which provides a source for the Peru coastal upwelling (Brink et al., 1983), the other branch continues to flow eastward, merging with the NECC (Wyrki, 1967; Fieldler and Tally, 2006; Kessler, 2006).

The EEP is a region that has been impacted by coastal upwelling. Coastal upwelling in the EEP is driven by Ekman transport generated by southeast trade winds that blow along the west coast of South America (Wyrki, 1981). The Ekman transport moves surface water offshore, away from the coastal boundary and replaces it with water from below the thermocline to maintain the mass balance. Seasonally, coastal upwelling is at its highest intensity when the strongest southeast trade winds blow over this region in boreal summer, and is reduced when southeast trade winds are relatively weak in

boreal winter (Wrytki, 1975, 1981; Kessler, 2006). The seasonal variability in the EEP is superimposed by interannual El Niño events (Wang and Fiedler, 2006), which occur every 2–7 years and last for 6–18 months (Penington et al., 2006). Hydrological conditions that characterize El Niño (La Niña) phases in the EEP are a deeper (shallower) thermocline and weaker (stronger) upwelling (Kessler, 2006).

Modern observation shows a clear seasonal and interannual SST variability in the EEP region (Fig. 3-2a). Seasonally, higher SST is recorded during boreal winter (February), and the lowest SST is recorded in boreal summer (August). The vertical temperature gradient is larger in boreal winter than that in boreal summer. Interannually, higher SST is observed in strong El Niño years and lower SST is observed in strong La Niña years (Fig. 3-2a). The thermocline depth at the study site is approximately 30–50 m (Fig. 3-2b).

3.3 Results

3.3.1 GDGTs and TEX₈₆

The isoprenoid GDGTs detected in ODP 1239 sediments consist of caldrachaeol (GDGT-0), GDGT-1, GDGT-2, GDGT-3, crenarchaeol, and its regioisomer (Appendix I). The total concentration of isoprenoid GDGTs in sediment varied between 0.6 and 12.8 $\mu\text{g}\cdot\text{g}^{-1}$ with an average of 5.81 $\mu\text{g}\cdot\text{g}^{-1}$ (Fig. 3-4b). The relative abundances of different isoprenoid GDGTs were nearly uniform with range of 37–54% for crenarchaeol, 26–35% for caldrachaeol and 15–35% for others.

The TEX₈₆^H-derived temperature of the core-top sample (25.1°C) agreed with the mean annual SST at the study site (24.5°C, Locarnini et al., 2010). TEX₈₆^H-derived SST

varied between 20.2 and 27.2°C and was generally higher during interglacials and lower during glacials (Fig. 3-4a).

The branched isoprenoid tetraether (BIT) index, an indicator of soil bacteria contribution (see Hopmans et al., 2004), varied between 0.01 and 0.06 (Fig. 3-4d) suggesting a low contribution of soil organic matter in the study samples. Weijers et al. (2006) noted that samples having high BIT (>0.4) may show anomalously high $\text{TEX}_{86}^{\text{H}}$ -derived temperatures, but this concern was not relevant for the samples used in this study.

3.3.2. Alkenones and U_{37}^{K} '

The total concentration of C_{37} - C_{39} alkenones in sediment varied between 0.5 and 28.7 $\mu\text{g.g}^{-1}$ with an average of 8.9 $\mu\text{g.g}^{-1}$ (Fig. 3-4b). The alkenone concentration tended to be higher in the interval between 400 ka and 240 ka than in the intervals between 430 and 400 ka and between 240 and 0 ka.

The U_{37}^{K} '-derived temperature of the core-top sample (25.6°C) agreed with the mean annual SST. U_{37}^{K} '-derived SST varied between 21.5 and 26.6°C and was generally higher in interglacials and lower in glacials (Fig. 3-4a). The U_{37}^{K} ' record obtained in this study was nearly identical to a record for the study site by Rincon-Martinez et al. (2010).

3.4 Discussion

3.4.1. Difference in proxy-derived temperatures

The variation of $\text{TEX}_{86}^{\text{H}}$ -derived temperature is roughly consistent with those of the U_{37}^{K} '-derived temperature at the study site (Fig. 3-4a), but significant difference was observed in the intervals of late MIS 11, and MIS 10, and MIS-6 when the U_{37}^{K} '-derived

temperature was a maximum of 5.5°C higher than the $\text{TEX}_{86}^{\text{H}}$ -derived temperature (Fig. 3-4a).

Dubois et al. (2009) and Kienast et al. (2012) assumed that U_{37}^{K} reflects mean annual SST because the U_{37}^{K} -derived temperature in EEP core-top sediments corresponded to mean annual SST. A sediment trap study at two sites in the central tropical Pacific showed no significant difference in the sinking flux of alkenone producers (*Emiliania huxleyi* and *Gephyrocapsa oceanica*) between strong and weak El Niño periods (Broerse, 2000), suggesting that the production of alkenone is not sensitive to upwelling intensity. We thus assume that U_{37}^{K} does reflect the mean annual SST at the study site.

The behavior of Thaumarchaeota and the production of GDGTs are not fully clear in the EEP. Thaumarchaeota (GDGTs producer) are ubiquitous and abundant throughout the seawater column (e.g., Massana et al., 2000; Karner et al., 2001). In the central equatorial Pacific, GDGTs are mainly produced in the thermocline layer (TL) (Turich et al., 2007). Recent case studies assumed that the $\text{TEX}_{86}^{\text{H}}$ -derived temperatures in EEP sediments reflect the temperature of the thermocline (30–50 m) rather than SSTs (Ho et al., 2011; Seki et al., 2012). Thaumarchaeota in marine environments have been recognized to be both heterotrophs (e.g., Ouverney and Fuhrman, 2000; Agogué et al., 2008; Zhang et al., 2009) and chemoautotrophic nitrifiers (e.g., Könneke et al., 2005; Hallam et al., 2006). Organic matter and NH_3 are produced by phytoplankton and by the decay of organic matter in surface and subsurface water, which explains why Thaumarchaeota are produced in both the surface mixed layer (SML) and TL. We thus assume that $\text{TEX}_{86}^{\text{H}}$ reflects a mixed temperature signal from the SML and TL (Fig. 3-5).

The production of Thaumarchaeota is fueled by the supply of organic matter and NH_3 . Both are more enhanced by phytoplankton production in upwelling periods. Yamamoto et al. (2012) observed that enhanced sinking flux of GDGTs is linked with phytoplankton bloom in the mid-latitude northwestern Pacific. GDGT abundance thus may reflect primary production and upwelling intensity.

$\text{TEX}_{86}^{\text{H}}$ showed higher temperatures than U_{37}^{K} during the some deglaciations (Fig. 3-4a), but this does not mean that the integrated SST of the SML and TL was higher than the SST of the SML. The calibration of $\text{TEX}_{86}^{\text{H}}$ to SST was conducted by comparing core-top $\text{TEX}_{86}^{\text{H}}$ with mean annual SST (Kim et al., 2010). If the phenomenon of $\text{TEX}_{86}^{\text{H}}$ recording both the SST and thermocline temperatures is common in tropical oceans, then calibration requires comparison between core top $\text{TEX}_{86}^{\text{H}}$ and integrated temperatures of the SML and TL; this calibration should give cooler estimates. The temperature reversal during the last deglaciation is thus attributed to the overestimation of $\text{TEX}_{86}^{\text{H}}$ -derived temperature.

3.4.2. GDGT/alkenone ratio and ΔT as upwelling indices

The relative abundance of isoprenoid GDGTs to alkenones (GDGT/alkenone ratio) was enhanced during the last five deglaciations (Fig. 2-6a), suggesting an enhanced production of GDGTs. When upwelling intensifies, GDGT production increases due to increasing NH_3 and organic matter. In contrast, when upwelling weakens, GDGT production decreases. The GDGT/alkenone ratio can thus be used as an index of upwelling intensity.

The difference between $\text{TEX}_{86}^{\text{H}}$ - and U_{37}^{K} '-derived temperatures (ΔT) was computed by subtracting U_{37}^{K} '-derived SST from $\text{TEX}_{86}^{\text{H}}$ -derived temperature ($\Delta T = \text{TEX}_{86}^{\text{H}} - \text{U}_{37}^{\text{K}}$). U_{37}^{K} ' reflects the temperature of the SML and $\text{TEX}_{86}^{\text{H}}$ reflects integrated temperatures from the SML and the TL. When upwelling intensifies, the temperature gradient between the SML and TL decreases (Fig. 3-5), and ΔT shifts in a positive direction. In contrast, when upwelling weakens, the temperature gradient between the SML and TL increases, and ΔT shifts in a negative direction. We thus assume that ΔT is a potential index of upwelling intensity.

ΔT varied between -6.2 and 4.1°C and showed maxima at 15, 50, 127, 213, 243, 260, 274, 310, 330, 340 and 427 ka. The maxima at 15, 127, 243, 340, and 427 ka correspond to glacial terminations (Fig. 3-6a). Minimal peaks of ΔT occurred at 33, 86, 179, 237, 289, and 386 ka. The variation in ΔT is very similar to that in the GDGT/alkenone ratio, although there are some mismatches in MIS 8 and MIS 11. This correspondence suggests that both are robust indices of upwelling intensity.

Positive ΔT and an elevated GDGT/alkenone ratio at the study site during deglaciations are associated with heavier $\delta^{18}\text{O}$ of subsurface-dwelling foraminifera (Pena et al., 2008) and increased export production (Pedersen, 1983; Lyle et al., 1988; Kienast et al., 2006) in the EEP. Pena et al. (2008) showed that thermocline water $\delta^{18}\text{O}$ ($\text{DT-}\delta^{18}\text{O}_{\text{sw}}$) at ODP Site 1240, reconstructed from the subsurface-dwelling foraminifera *Neoglobobulimina dutertrei*, was maximized during the last three deglaciations (Fig. 3-6d). This suggests intensified upwelling in those periods. Abrupt increases in organic carbon content during deglaciations were reported from sites P6 (Pedersen, 1983), V19-28 (Lyle et al., 1988), and ME0005A-24JC and 27JC (Kienast et al., 2006) in the EEP

(Fig. 3-6b), suggesting that export production was maximized during the last two deglaciations. The elevated ΔT and GDGT/alkenone ratio at the study site indicate not only the intensification of local upwelling, but also the intensification of regional upwelling associated with thermocline shoaling and enhanced export production in the EEP during deglaciations.

3.4.3. Hydrological evolution in the EEP

The ΔT record mirrors sedimentary $\delta^{15}\text{N}$ records from the Peru margin (Fig. 3-6c), which have been suggested to reflect the intensity of denitrification regulated by Peruvian coastal upwelling (Ganeshram et al., 2000). The trend in $\delta^{15}\text{N}$ at the Peru margin was slightly different from those in the EEP (Dubois and Kienast, 2011) and at the Mexican margin (Ganeshram et al., 2000) (Fig. 3-5c). The maxima of $\delta^{15}\text{N}$ at terminations are significant at the Peru margin but not in the EEP or at the Mexican margin, suggesting that $\delta^{15}\text{N}$ in the eastern Pacific margin was determined by the denitrification in the Peru margin and modified by local factors (Robinson et al., 2009). The correspondence between ΔT and the Peru margin $\delta^{15}\text{N}$ records suggests that the upwelling at the study site was closely linked with Peruvian coastal upwelling. The study site is located in a region influenced by the coastal upwelling system (Wrytki, 1981; Pennington et al., 2006; Talley et al., 2011). Because the southeast trade winds are a principal agent driving coastal upwelling along the west coast of South American continent (Wrytki, 1981; Kessler, 2006), it is highly likely that the southeast trade winds intensified during deglaciations owing to the stronger South Pacific High.

The paleo-position of the ITCZ was approximated using dust fluxes across the equator over the last 30 ka (McGee et al., 2007). The results of that analysis suggest that the ITCZ did not shift southward during the last deglaciation. Xie and Marcantonio (2012) precisely estimated the paleo-position of the ITCZ using neodymium isotopes (ϵ_{Nd}) derived from transect dust obtained by McGee et al. (2007). The average ϵ_{Nd} values from the last glacial and Holocene show similar gradients throughout the equatorial transect, but the latitudinal gradient was stronger, and a steeper interval was evident during the last deglaciation between 5°N and 7°N. This suggests more northerly mean position of the ITCZ.

Yamamoto et al. (2007) reconstructed the intensity of the California Current during the last 150,000 years and showed that the subtropical high-pressure cell in the North Pacific weakened during the last two deglaciations. Lyle et al. (2012) suggested that high precipitation in the Great Basin of the western United States during the last deglaciation was not caused by the southward shift of westerly storms, but instead by the northward transport of moist air masses from the tropical Pacific because of the weaker North Pacific High. This presumes that the northeast trade winds were not intensified under the condition of the weaker North Pacific High.

The stronger South Pacific High, combined with the weaker North Pacific High and northward shift of the ITCZ during the last deglaciation was an asymmetrical atmospheric phenomenon between the Northern and Southern hemispheres. This anti-phase variation in the subtropical high-pressure cells of both hemispheres was presumably caused by changes in the heat balance between the hemispheres (Fig. 3-7).

The ENSO model has been applied to understand hydrological evolution of the EEP (e.g., Lea et al., 2000; Koutavas et al., 2002; Koutavas and Lynch-Stieglitz, 2003; Martinez et al., 2003; Pena et al., 2008; Rincon-Martinez et al., 2010). Pena et al. (2008) proposed the deep thermocline seawater $\delta^{18}\text{O}$ (DT- $\delta^{18}\text{O}_{\text{sw}}$) based on *Neogloboquadrina dutertrei* $\delta^{18}\text{O}$ at Site 1240 and suggested that EEP hydrology was characterized by a La Niña-like condition during deglaciations. However, the zonal gradient of SST was inconsistent with a La Niña-like state during the last deglaciation (Fig. 3-6e). The DT- $\delta^{18}\text{O}_{\text{sw}}$ at ODP Site 1240 showed maximum peaks during deglaciations (Pena et al., 2008), but the Mg/Ca-SST, between the western and eastern Pacific did not show a large temperature gradient typical of La Niña (Lea et al., 2000). Also, the weaker North Pacific High evidenced during the last deglaciation (Yamamoto et al., 2007; Lyle et al., 2012) is not consistent with a La Niña-like state; a weaker North Pacific High is typical of the modern El Niño condition (Bogad and Lynn, 2001). We thus suggest that intensified upwelling shown by enhanced DT- $\delta^{18}\text{O}_{\text{sw}}$ at Site 1240 was not linked to a La Niña-like state, and an ENSO analogy cannot to be applied to explain hydrological conditions in the Pacific during the last deglaciation.

The intensification of upwelling in the EEP and the Peru margin during the last deglaciation coincided with intensification of upwelling in the Southern Ocean (Toggweiler et al., 2006; Anderson et al., 2009). Because upwelling in the Southern Ocean is regulated by the position of the southern westerlies (Russell et al., 2006; Toggweiler et al., 2006), the synchronous intensification of upwelling systems in the EEP, the Peru margin, and the Southern Ocean suggests that the reorganization of atmospheric circulation in the Southern Hemisphere induced the intensification of the subtropical

high-pressure cell, causing stronger southeast trade winds along the west coast of South America and southern westerlies over the Southern Ocean, enhancing upwelling in both regions.

The intensification of the South Pacific High caused southern westerlies to move poleward and the ITCZ to shift northward during deglaciations (Fig. 3-7). In response, the center of upwelling moved northward and cold tongue upwelling in the EEP area intensified. The stronger South Pacific High during the last deglaciation caused a drier climate in the Patagonia region of South America (de Porras et al., 2012), and the weaker North Pacific High caused a wetter climate in the Great Basin of the western United States (Lyle et al., 2012). This perspective is useful for understanding the hydrological and climatological evolution of the eastern Pacific region.

3.5 Conclusions

The abundance ratio of GDGTs to alkenone (GDGT/alkenone ratio) and difference between $\text{TEX}_{86}^{\text{H}}$ - and U_{37}^{K} '-derived temperature (ΔT) can be used as upwelling indices in the EEP. Our new data show that intensification of upwelling occurred in the EEP at each of the last five glacial terminations. The result suggests that the intensification of upwelling was a common phenomenon in the EEP at glacial terminations. The similar timing of intensified upwelling in the EEP, the Peru margin, and the Southern Ocean suggests an intensification of the South Pacific High during deglaciations. This new perspective can help explain the hydrological evolution of the eastern Pacific region during deglaciations.

CHAPTER 4: Nutricline shoaling in the eastern Pacific warm pool during the last two glacial maxima

4.1 Introduction

The EPWP is located just north of the eastern equatorial Pacific and is characterized by high SST ($>27.5^{\circ}\text{C}$) and low sea surface salinity (SSS) (<30 psu) (Fiedler and Talley, 2006). The eastern Pacific warm pool (EPWP) today is characterized by deep thermocline and nutricline and low primary production compared with the other areas of the eastern tropical Pacific (ETP) (Pennington et al., 2006). The nutricline depth is a key in regulating primary productivity in this region. However, little is known about the vertical water structure of the EPWP region in glacial-interglacial cycles.

Recent paleocenographic studies in the EPWP were devoted to understanding the environmental changes on millennial to ten million year time scales (e.g., Loubere, 1999; Koutavas and Lynch-Stieglitz, 2003, 2005; Benway et al., 2006; Groeneveld et al., 2006; Horikawa et al., 2006; Steph et al., 2006; Koutavas et al., 2008; Dubois et al. 2009; Kamikuri et al., 2009a, 2009b; Steph et al., 2010; Seki et al., 2010, 2012). The paleoceanographic conditions in this region have been reconstructed by various ways, including sea surface temperature (SST) (e.g., Pisias and Mix, 1997; Lea et al., 2000), salinity (e.g., Benway and Mix, 2004) and primary productivity (e.g., Chavez and Barber, 1987; Loubere, 1999) reconstructions.

The glacial-interglacial SST difference in the EPWP is controversial. Foraminiferal Mg/Ca ratio indicated larger temperature difference (e.g., Koutavas and Lynch-Stieglitz, 2003), whereas $U^{K}_{37'}$ and Radiolarian assemblage showed a smaller temperature difference (e.g., Dubois et al., 2009; Pisias and Mix, 1997). The interaction

between regional paleoceanographic dynamics with the ecological behavior of phytoplankton and zooplankton was assumed to have an effect on SST records with a strong seasonal imprint in the geological record (e.g., Leduc et al., 2010). The reliability of paleotemperature proxies in this region has been discussed (e.g., Dubois et al., 2009). Thus, application of new temperature proxy will provide a clue for the discrepancy of SST records obtained by various temperature proxies and a better understanding of the hydrological evolution of the EPWP.

In this study, we investigated paleotemperature changes derived from $\text{TEX}_{86}^{\text{H}}$ and U_{37}^{K} and the paleoproductivity based on glycerol dialkyl glycerol tetraether (GDGT) and alkenone concentrations in Ocean Drilling Program (ODP) Site 1241 during the last 148 kyrs to discuss the cause of SST discrepancy reconstructed by various temperature proxies, and changes in paleoproductivity and nutricline depth in the EPWP.

4.2 Modern physical oceanography

The surface current system in the eastern tropical Pacific (ETP) consists of eastward- and westward-flowing currents (Fig. 4-1). The main eastward current is the NECC centered at about 5°N (Wyrski, 1967; Talley et al., 2011). This current transports warmer surface water from the WPWP to the ETP region. There are two prominent westward currents; the North Equatorial Current (NEC; 8°N and 20°N) and the South Equatorial Current (SEC; 3°N to 10°S) (Kessler, 2006). Both currents transport colder water from higher latitudes to the ETP region.

The major subsurface current in this region is the Equatorial Undercurrent (EUC) that flows eastward beneath the SEC. The EUC flows within the equatorial thermocline

and shoal as it approaches the Galapagos Islands (Kessler, 2006). When it reaches the Galapagos Islands, it splits into two branches (Steger et al., 1998) with the main branch flowing southward to merge with the Peruvian Undercurrent (Brink et al. 1983), and the other branch continues to flow eastward, merging with NECC (Wyrski, 1967; Fieldler and Tally, 2006; Kessler, 2006).

The study area is covered by NECC water. The NECC is a geostrophic flow which is driven by distinct meridional wind-stress curl forcing along the equator (Yu et al. 2000). The NECC flows between the NEC and SEC in the region where the opposing surface trade winds are weak. The strength of the NECC seasonally responds to the seasonal migration of the intertropical convergence zone (ITCZ). The ITCZ migrates north during boreal summer and south during boreal winter (Waliser and Gautier, 1993). This seasonal migration causes NECC flow to be strongest in boreal fall and weak or absent in boreal spring (Kessler, 2006). Interannually, the NECC is stronger during El Niño events and the zonal tilt of the equatorial thermocline flattens in the ETP, causing the penetration of this current into the coastal boundary region (Kessler, 2006).

The Antarctic intermediate water (AAIW) is an important subsurface water mass in the tropical Pacific region. The AAIW is formed through the interaction between the Antarctic circumpolar current and wind-driven upwelling in the Southern Ocean (Taft, 1963) and is transported northward into the Pacific Ocean along the subtropical gyres. The AAIW can extend northward as far north as 20°N. The water travels at a depth of 600–900 m (Wyrski, 1967), and has been defined as the densest class of the Subantarctic Mode Water (SAMW) (McCartney, 1977), with which it shares similar dynamics (Drijfhout et al., 2005). This water mass blends with subducted subtropical waters to

form the subthermocline waters in the tropical Pacific (Pierrehumbert, 2000).

Modern oceanographic data shows a small seasonal variation ($\sim 2^{\circ}\text{C}$) in the upper water column at the study site (Fig. 4-2a). Seasonally, higher SST and lowest nitrate concentrations were recorded at the study site during boreal spring (April–June), and the lowest SST and highest nitrate concentrations were recorded in the boreal fall (October–December) (Fig. 4-2b and 4-2c). Interannually, the SST is higher during El Niño Southern Oscillation (ENSO) events than normal years (Fig. 4-2a). Changes in modern nutricline and thermocline depth in the EPWP is significantly correlated with changes in surface water temperature and primary productivity (Forsbergh, 1969; Pennington et al., 2006). When the ITCZ is at its southern position during boreal winter and spring, the northeasterly winds over the Panama basin are strongest, causing the thermocline rises to a depth of 10 m or less, and extensive upwelling of nutrient-rich waters in the Panama Basin (Thunell and Reynolds, 1984; Honjo et al., 1982). The surface chlorophyll concentration appears to be slightly higher in boreal winter and spring (Forsbergh, 1969; Honjo et al., 1982; Marra et al., 1987; Pennington et al., 2006). In contrast, when the ITCZ is at its north position during boreal summer and fall, the thermocline is deepest (50–60 m) (Thunell and Reynolds, 1984). The surface chlorophyll concentration is lower in boreal summer and fall.

4.3 Results

4.3.1 Oxygen isotopes and age-depth model

The $\delta^{18}\text{O}$ of planktonic foraminifera *G. ruber* in ODP Site 1241 ranges from -0.65 to -2.81‰ with an average value of -1.64‰ (Fig. 4-4). The changing pattern and

amplitude in the variation are similar to the LR04 stacked $\delta^{18}\text{O}$ record of benthic foraminifera (Lisiecki and Raymo, 2005), suggesting that the *G. ruber* $\delta^{18}\text{O}$ variation at the study site is governed principally by global ice volume change. We thus created the age-depth model for the studied interval of Site 1241 by orbital tuning of the $\delta^{18}\text{O}$ record of *G. ruber* to the benthic $\delta^{18}\text{O}$ of LR04 stack (Fig. 4-4) (Lisiecki and Raymo, 2005) using the *AnalySeries* software (Paillard et al., 1996).

4.3.2 GDGTs and TEX₈₆

Isoprenoid and branched GDGTs were detected in Site 1241 sediments. Crenarchaeol and caldarchaeol (GDGT-0) dominate followed by GDGT-1, GDGT-2, GDGT-3, crenarchaeol regioisomer and branched GDGTs. The total concentration of isoprenoid GDGTs varied between 0.3 to 4.5 $\mu\text{g g}^{-1}$ (Fig. 4-5a). Isoprenoid GDGTs were abundant in marine isotope stage (MIS)-6 and MIS-2, and were also elevated in MIS-5d, MIS-5b and mid MIS-3 (Fig. 4-5a). The branched and isoprenoid tetraether (BIT) index (Hopmans et al., 2004) varied between 0.02 and 0.12 (Fig. 4-4b). Weijers et al. (2006) noted that samples with high BIT values (> 0.4) may show anomalously high TEX₈₆-derived temperatures because soil organic matter also contains GDGTs 1–3. This concern is, however, not relevant for the samples used in this study.

TEX₈₆^H-derived temperature ranged from 20.5 to 28.4°C with an average of 23.8°C (Fig. 4-5c). The lowest TEX₈₆^H-derived temperature was recorded during MIS-6 and considerably increased to ~27°C during MIS-5e. After the rapid warming, there was a gradual cooling to ~22°C between 110 and 90 ka (Fig. 4-5c). After this cooling trend, the TEX₈₆^H-derived temperature increased again to 26°C at 85 ka. The TEX₈₆^H-derived

temperature were fluctuated between 80 and 24 ka. An abrupt temperature increase by 4°C was observed again at MIS 2/1 boundary, and then, the TEX₈₆^H-derived temperature increased continuously to the maximum at the core-top sediment.

4.3.3 Alkenones and U₃₇^K'

The total concentration of alkenones varied between 0.5 and 6.5 µg g⁻¹ with an average of 2.9 µg g⁻¹ (Fig. 4-5a). The U₃₇^K' of the studied intervals is close to the upper saturation level (U₃₇^K'=1). Interglacial periods of MIS-1, MIS-5c and MIS-5e exhibit low alkenone concentrations, whereas MIS-6 and MIS-2 showed higher concentrations.

The U₃₇^K'-derived temperature at ODP Site 1241 ranged between 25.2 and 27.8°C with an average 26.5°C (Fig. 4-5c). The U₃₇^K' did not display a significant glacial-interglacial variation.

4.4 Discussion

4.4.1 Glacial cycles in GDGT and alkenone productions

The abundances of GDGTs and alkenones were maximized during glacial maxima in MIS-2 and MIS-6 (Fig. 4-5). GDGT concentration showed a good correlation with alkenone concentration ($r = 0.68$). Alkenone production is likely proportional to primary production in the EPWP because haptophytes are a major blooming phytoplankton in the EPWP (Steinmetz, 1991), and *Gephyrocapsa oceanica* (alkenone producer) is one of the major haptophytes in the NECC water (>30 %) (Okada and Honjo, 1973). GDGT production is also likely proportional to primary production because Thaumarchaeota (GDGT producer) assimilates organic matter and NH₃ (Francis et al., 2005). Higher

GDGTs in sediment thus reflects the increase of primary production. Horikawa et al. (2006) suggested that higher alkenone concentration in glacial maxima in core HY04 reflects higher primary production owing to a good correlation with organic carbon content in the ETP. Enhanced primary production during the last two glacial maxima was reported in the EPWP based on increased abundance of benthic foraminifera *Uvigerina spp* at site GS7202-9 (Loubere, 1999) and elevated organic carbon, alkenone and CaCO_3 contents during the last two glacial maxima in core HY04 (Fig. 3-5d) (Horikawa, 2006).

Nutricline shoaling is a potential cause enhancing primary production (Forsbergh, 1969; Pennington et al., 2006; Chavez et al., 2011) in the ETP. Nutricline shoaling should enhance nutrient supply to the euphotic zone, which increased primary production in glacial maxima. This perspective also can account for unchanged $U^{K}_{37'}$ during interglacial-glacial cycles, as discussed in section 4.5.3.

4.4.2 Glacial and interglacial variations in $\text{TEX}_{86}^{\text{H}}$

The amplitude in $\text{TEX}_{86}^{\text{H}}$ variation is larger and more fluctuated than that in $U^{K}_{37'}$ over the last 150 ka (Fig. 4-4c). Ho et al. (2011) showed that the TEX_{86} -derived temperature at the core-top sample from sites located in the EPWP was $\sim 3.5^\circ\text{C}$ lower than the mean annual SST. Seki et al. (2012) assumed that $\text{TEX}_{86}^{\text{H}}$ in ODP Site 1241 sediments reflects the temperature of thermocline depth (30–50 m) because $\text{TEX}_{86}^{\text{H}}$ -derived temperatures agree with the temperature derived from Mg/Ca ratio of subsurface dwelling *Neogloboquadrina dutertrei*. Francis et al. (2005) reported that the production of Thaumarchaeota is enhanced by the supply of organic matter and NH_3 . In this region, the maximum NH_3 concentration was found in the upper thermocline (Bishop et al. 1986).

This may support the production of Thaumarchaeota in subsurface water. In this study, we assume that GDGTs are produced in both surface and subsurface waters because organic matter and NH_3 are more available in these depth ranges, and that $\text{TEX}_{86}^{\text{H}}$ reflected an integrated temperature from surface to thermocline water (Fig. 4-7).

4.4.3 Unchanged U_{37}^{K} during glacial cycles

In contrast to $\text{TEX}_{86}^{\text{H}}$ and Mg/Ca ratio, U_{37}^{K} did not vary in response to glacial-interglacial cycles (Fig. 4-5). Horikawa et al. (2006) noted a minor change in U_{37}^{K} in core HY04 during glacial-interglacial (Fig. 4-5), but they did not explain the reason. This phenomenon is potentially attributed to either the physiological limitation of U_{37}^{K} to temperature in warm water (Bentaleb et al., 2002), lateral advection of alkenones (Rühlemann and Butzin, 2006; Conte et al., 2006) or changes in the production depth of alkenones. Firstly, Bentaleb et al. (2002) pointed that U_{37}^{K} is not sensitive to temperature change in warm surface waters of $>26.4^\circ\text{C}$. The U_{37}^{K} -derived temperature at the study site ranged between 25.2 and 27.8°C ; half of the samples belong to the range above 26.4°C (Fig. 4-5). The estimated temperatures are constantly higher than 26.4°C before 60 ka. The unchanged pattern in this interval may be attributed partly to the insensitive response of U_{37}^{K} to temperature change. Secondly, in some regions, the lateral advection of allochthonous alkenones by strong surface currents alters the alkenone signal (Rühlemann and Butzin, 2006; Conte et al., 2006). Intensified NECC can induce warm-bias of U_{37}^{K} -derived temperatures. However, intensified NECC during glacials is less likely because higher primary production in glacials, as shown in this study, is not consistent with intensified NECC. We thus conclude that lateral advection was not a

major factor determining U_{37}^K variation at the study site. Lastly, U_{37}^K is responsible to the production depth of alkenones. In the previous studies, U_{37}^K was assumed to reflect the mean annual SST in the ETP (e.g., Horikawa et al., 2006; Koutavas et al., 2008; Dubois et al. 2009; Rincon-Martinez et al. 2010; Kienast et al., 2012; Seki et al., 2012). Dubois et al. (2009) and Kienast et al. (2012) showed that the U_{37}^K in the eastern Pacific Ocean core-top sediments roughly corresponded to the mean annual SSTs. Detailed inspection, however, indicated that U_{37}^K -derived temperature in the core-top sediment were lower than the SSTs in the region north of the study site. In fact, the core-top U_{37}^K -derived temperature at the study site was lower than the SST, suggesting that U_{37}^K reflects the subsurface temperature at the study site. Alkenone producers were abundant in subsurface water near nutricline in the WPWP (Hagino et al., 2000) and the central North Pacific (Reid, 1980; Cortés et al., 2001). It is thus highly likely that alkenones are produced near nutricline in stratified warm pool regions. In interglacials nutricline and the production depth of alkenones were deeper, and in glacials they were shallower, resulting in unchanged U_{37}^K (Fig. 4-6). Changes in nutricline depth was a major factor determining U_{37}^K at the study site.

U_{37}^K at MD02-2529 located in the coastal boundary of the central America (Fig. 4-1) showed larger variation than ODP Site 1241 and HY04 (Fig. 4-6). Sites 1241 and HY04 are situated under the influence of the NECC with deeper nutricline of ~75m (Pennington et al. 2006), but Site MD02-2529 has shallower nutricline and suffers less influence of the NECC. The NECC penetrates the coastal boundary region only when the El Niño was intensified (Kessler, 2006). The difference between Sites MD02-2529, ODP

Site 1241 and HY04 thus suggests that unchanged $U^{K}_{37'}$ is a characteristic of the central EPWP which has deep nutricline.

The range of alkenone production depth is narrow, and the production depth of this compound corresponds to nutricline because alkenone producers (*Gephyroxcapsa* and *E. huxleyi*) as photosynthetic organisms required nutrients for the production. In contrast, *Thaumarchaeota* and foraminifera do not strictly depend on nutrient for the production, thus, both species grow independently of nutrient (e.g., Karner et al., 2001, for GDGT, Arnold and Parker, 1999; Hansen, 1999; Schiebel and Hemleben., 2005, for foraminifera). In the tropical Pacific, the different dwelling foraminifera species grow at distinctive depths, e.g., *G.ruber* in surface mixed layer and *N.dutertrei* in thermocline layer (Fairbanks et al., 1982). Although, changes in nutricline affect the foraminifera assemblages, but it does not affect the Mg/Ca ratio of single species. The difference in the behavior of haptophytes, *Thaumarchaeota* and foraminifera caused different responses of recorded temperature to different depths.

4.4.4 Paleocceanographic implications

Different temperature proxies yield different conclusions about the glacial-interglacial environmental changes in this region (Fig. 4-8). The Mg/Ca ratio and $\delta^{18}O$ from planktonic foraminifera indicated a large glacial cooling (Lea et al. 2000; Koutavas and Lynch-Stieglitz; 2003; Benway et al., 2006; Dubois et al., 2009), whereas $U^{K}_{37'}$ indicated a small SST drop in glacial periods (Horikawa et al., 2006). This discrepancy can be fully explained by the shift of alkenone production depth in glacial-interglacial cycles. We thus do well to use TEX_{86}^H and Mg/Ca ratio rather than $U^{K}_{37'}$ for the

discussion of glacial-interglacial temperature contrast in the EPWP.

Higher abundance of GDGTs and alkenones during glacial maxima was attributed to shallow nutricline in the EPWP in this study. Why was nutricline shallower in glacial maxima? There are three possible mechanisms to account for the shoaling of nutricline. Firstly, in modern condition, stronger northeasterly trade winds induce upwelling in the coastal boundary region and weakens the NECC, resulting in shallower thermocline and nutricline in the EPWP (Forsbergh, 1969; Fiedler and Talley, 2006; Kessler, 2006). There is, however, no concrete evidence of stronger northeasterly trade winds in glacial maxima. The paleo-position of the ITCZ in the ETP was approximated using dust fluxes across the equator over the last 30 ka (McGee et al., 2007), suggesting that the ITCZ did not shift southward during the LGM. Xie and Marcantonio (2012) estimated the paleo-position of the ITCZ using neodymium isotopes (ϵ_{Nd}). Nd isotope data showed a similar latitudinal trends in the ϵ_{Nd} values in the LGM and the Holocene, with more radiogenic values further south and less radiogenic values further north, suggesting that the position of the ITCZ in the LGM was the same as that in the Holocene. These results contradict with intensified northeasterly trade winds in the LGM, and it is thus less likely that stronger northeasterly trade winds induced shallower nutricline in glacial maxima. Second, by the analogy of the ENSO, stronger Walker circulation can decrease thermocline depth in the EPWP. However, Sagawa et al. (2012) indicated shallower thermocline in the WPWP in the LGM than in the Holocene. This indicates that the shoaling of thermocline and nutricline during the LGM was synchronous in both WPWP and EPWP, suggesting that the shoaling of nutricline is a phenomenon of Pacific basin scale. It is thus less likely that stronger Walker circulation caused shallower nutricline in the EPWP in glacial maxima.

Lastly, the formation of the AAIW can decrease the depth of thermocline and nutricline in the Pacific basin because the cooled AAIW blends with subducted subtropical waters to form the subthermocline waters that are trapped by a combination of upwelling and vertical mixing in the tropical Pacific (Pierrehumbert, 2000). The increasing ventilation and production of the AAIW during the LGM were supported by sediment core studies (e.g., Matsumoto et al., 2002; Nameroff et al., 2004; Pahnke and Zahn, 2005; Muratli et al., 2010). The increasing production of the AAIW may have caused upward expansion of intermediate waters during LGM over the Pacific Ocean. Shallower nutricline in the EPWP in glacial maxima was most likely linked to the enhanced production of the AAIW.

4.5 Conclusions

$\text{TEX}_{86}^{\text{H}}$ is used as a proxy to indicate the integrated temperature from the surface to thermocline. Unchanged U_{37}^{K} during glacial-interglacial cycles most likely resulted from the shift of alkenone production depth. Elevated alkenone and GDGT concentrations during glacial maxima are attributed to enhanced primary production caused by nutricline shoaling. Nutricline shoaling at the study site during glacial maxima presumably reflected thermocline and nutricline shoaling on a Pacific basin scale caused by intense formation of the AAIW.

CHAPTER 5: Intensified upwelling in the Peru margin during the last deglaciation

5.1 Introduction

The Peruvian coastal region is characterized by strong and persistent coastal upwelling. The most important aspect of the modern Peru margin is its high biological productivity, which makes this region one of the most prominent high production regions in the world ocean (Berger et al., 1987).

The paleoceanographic study of the Peruvian coastal upwelling regime has been subject to very diverse goals, which was more focused on the glacial-interglacial interval (e.g., Pisias and Mix, 1997; Ganeshram et al., 2000; Galbraith et al., 2004). The hydrological evolution in this region has been reconstructed by various studies, including sea surface temperature (SST) (e.g., Feldberg and Mix, 2002; Rein et al., 2005; Prahl et al., 2006) and primary productivity (e.g., Suess et al., 1988; Ganeshram et al., 2000) reconstructions. The deglaciation is an important periods due to the abrupt change of the global hydrological and atmospheric circulation and the opposite response between northern and southern hemisphere to the orbital forcing (Imbrie et al., 1992). However, little is known about the hydrological changes of the Peru margin during deglaciations.

In this study, we established the age-depth model and generated TEX₈₆ and U^K_{37'} records from the Ocean Drilling Program (ODP) Site 1237 sediments during the last 90,000 years. The records from Site 1237 (Peru margin) were compared with the SST records from Sites 1241 (off Panama) and 1239 (off Ecuador). The TEX₈₆ was applied in this study because the study on TEX₈₆ is very limited in the eastern Pacific Ocean (e.g., Ho et al., 2011, Seki et al., 2012; Shaari et al., 2013). There is also no comparison study

of the estimated temperatures between both proxies in this region during the late Pleistocene. Our goal is to understand the hydrological changes and discuss the intensity of the Peru-Chile Current (PCC) during the last 90 ka.

5.2 Modern physical oceanography

The Peru current system consists of a strong equatorward surface and poleward subsurface currents (Fig. 5-1). The PCC is an eastern boundary current that flows northwestward along the west coast of South America from the southern Chile to northern Peru, carrying cold and less saline water to the ETP and being associated with the coastal upwelling. This current feeds the South Equatorial Current (SEC), forming the equatorial cold tongue. Below a shallow upper layer (~20 m) of the equatorward PCC, the Peru Chile Undercurrent (PCUC) flows poleward over the slope (Brink et al., 1983). The PCUC is fed by the lower part of the Equatorial undercurrent and becomes a major source of the Peru coastal upwelling water (Wyrski, 1963; Brink et al., 1983). The PCUC dominates within the first 180 km from the coast (Fonseca, 1989), and extends to 600–700 m deep (Wyrski, 1963). It transports salty, nutrient-rich and oxygen-deficient water (Fonseca, 1989).

Modern oceanographic data from January 1982 to December 2011 show a seasonal variation in water temperature at Site 1237 (Fig 5-2). Seasonal variation is more dominant than interannual variation in the Peru margin. Higher SST is recorded during austral fall (April–June), and the lowest SST is recorded in the austral spring in Site 1237 (Fig. 5-2). The thermocline water shoals to <40 m and very often breaks the surface, resulting in very low SST in this region (Fiedler and Talley, 2006; Pennington et al.,

2006). The highest level of chlorophyll and primary production is recorded during the austral summer and fall in the Peru margin (e.g., Chavez, 1995; Pennington et al., 2006). This is inconsistent with intensified upwelling during austral winter and spring. Pennington et al. (2006) suggested that the strong offshore advection and mixing may dilute phytoplankton faster than it can grow during peak summer and fall upwelling and causing suppress production in the winter. The thermocline is deepened in until a maximum depth of 250 m response to the El Niño-Southern Oscillation (ENSO) (Wrytki, 1975). In normal years, the thermocline depth ranges between 50 to 100 m along the coast off Peru.

5.3 Results

5.3.1 Oxygen isotopes and age-depth model

The identification of intact planktonic or benthic foraminifera shells was difficult in Site 1237 because this site is located beneath the lysocline. Instead, we analyzed the $\delta^{18}\text{O}$ of bulk sediment samples. The bulk sediment $\delta^{18}\text{O}$ ranges from -0.65 to -2.81‰ with an average value of -1.64‰ over the study period. The profile is comparable to global LR04 oxygen isotope curve (Fig. 5-4). We thus created the age-depth model of Site 1237 by orbital tuning of the $\delta^{18}\text{O}$ record of bulk sediment to the benthic $\delta^{18}\text{O}$ of LR04 stack (Fig. 5-4) (Lisiecki and Raymo, 2005) using the *AnalySeries* software (Paillard et al., 1996). However, we considered the ages in the periods between 90 and 130 ka as tentative ones owing to unstable $\delta^{18}\text{O}$ values. Carbonate content within this interval was incredibly low compared to other intervals (Fig. 5-4), causing a noisy pattern.

5.3.2 GDGTs and TEX₈₆^H temperature

Both isoprenoid and branched GDGTs were detected in sediment samples in Site 1237 over the past 90 ka (Fig. 5-5). Crenarchaeol and caldarchaeol were the most abundant GDGTs followed by the combination of GDGT 1-3, and brGDGTs were detected in trace. The concentrations of GDGTs in Site 1237 varied from 1.2 to 14.4 µg g⁻¹ (Fig. 5-5). GDGTs were abundant in marine isotope stage (MIS)-3 and MIS-2 (Fig. 5-5).

The TEX₈₆^H-derived temperatures in Site 1237 are more fluctuated than U^K_{37'}-derived temperatures over the last 90 ka (Fig. 5-5b). The TEX₈₆^H-derived temperatures varied between 14.9°C and 24.2°C with an average of 18.3°C. The last deglaciation is marked by an increased in TEX₈₆^H temperatures from 15.1 to 24.2°C. TEX₈₆^H temperatures fluctuated between 90 and 79 ka. Lower branched and isoprenoid tetraether index (BIT) values (Hopmans et al., 2004) at the study sites (< 0.12) suggest that the terrestrial organic matter is not high enough to influence the interpretation of the TEX₈₆^H index (Weijers et al., 2006).

5.3.3 Alkenones and U^K_{37'} temperature

The total concentration of C₃₇-C₃₉ alkenones in Site 1237 ranged from 3.4 to 11.9 µg g⁻¹ during the last 90 ka (Fig. 5-5a). The alkenones concentration does not show a uniform trend within the studied intervals. The U^K_{37'} temperature in Site 1237 was minimal at 35 ka of 16.4°C and maximal during 11 ka of 21.1°C (Fig. 5-5b). U^K_{37'}-derived temperatures gradually decreased from MIS-5b to MIS-4 and achieved the lowest value at 35 ka of 16.4°C. The U^K_{37'} started to rise at 45 ka toward the Holocene. This

warming trend is continuing until 12 ka, $U^{K}_{37'}$ -derived temperatures fluctuated around 20°C during the Holocene. The $U^{K}_{37'}$ -derived temperatures at core-top sample in Site 1237 (19.9°C) is in a good agreement with the modern SST (19.7°C, Locarnini et al., 2010).

5.4 Discussion

5.4.1 Proxy responses in the Peru margin

The TEX_{86}^H - and $U^{K}_{37'}$ -derived temperatures showed a similar changing pattern in Site 1237, although the amplitude variation in TEX_{86}^H more fluctuated than did $U^{K}_{37'}$. The larger variation in TEX_{86}^H than $U^{K}_{37'}$ was often reported in marine records (e.g., Huguet et al., 2006; Shintani et al., 2011; Nakanishi et al., 2012). GDGTs are generally produced in both surface and subsurface water (e.g., Sinninghe Damste et al., 2002; Turich et al., 2007), while alkenones was suggested to be produced mainly in surface water in the ETP (Dubois et al., 2009; Kienast et al., 2012). Recent case studies in the ETP assumed that the TEX_{86}^H -derived temperatures in ETP sediments reflect the temperature of the thermocline (30–50 m) rather than SSTs (Ho et al., 2011; Seki et al., 2012; Shaari et al., 2013). If the subsurface production of GDGTs increases, TEX_{86}^H records cooler subsurface water temperature. In Site 1237, cooler spikes corresponded to peaks of GDGT concentration (Fig. 5-5). Primary production in this region was increased after intense upwelling season (e.g., Chavez, 1995; Pennington et al., 2006; Echevin et al., 2004, 2008). Organic matter and NH_3 are highly produced by phytoplankton and by the decay of organic matter owing to the shoaling thermocline (Pennington et al., 2006). This

correspondence suggests that the fluctuation of $\text{TEX}_{86}^{\text{H}}$ was caused by changes in subsurface production, presumably due to the shoaling of nutrient-rich upwelled water.

5.4.2 Latitudinal temperature gradient

The U_{37}^{K} at three different sites showed a latitudinal SST gradient throughout the last 90 ka (Fig. 5-6). The U_{37}^{K} temperature decreases in the order from Site 1241, Site 1239 and Site 1237. This trend is in agreement with the modern latitudinal SST gradient in the eastern Pacific Ocean (Locarnini et al., 2010).

We observed a different response of the U_{37}^{K} in non-upwelling and coastal upwelling region. At Site 1241, U_{37}^{K} reflected thermocline layer (Chapter 4). At Site 1239, U_{37}^{K} reflected surface mixed layer (Chapter 3). Because the Peru margin is closely linked with the EPP, the response of U_{37}^{K} in the upper water column at Site 1237 is similar to that in Site 1239. Thus, the U_{37}^{K} also reflected surface mixed layer. The behavior of U_{37}^{K} -derived temperatures in the ETP is governed by oceanographic setting (Table 1-1). At site 1241, the depth of nutricline is a key factor determining the behavior, but in Sites 1239 and 1237, upwelling is a key factor (Table 1-1).

The U_{37}^{K} in Sites 1237 and 1239 is a robust SST proxy. The U_{37}^{K} temperatures of core-top sample at both sites show a good agreement with the modern SSTs in the Peru margin and the EEP (Locarnini et al., 2010). The U_{37}^{K} in Sites 1239 and 1237 showed a systematic glacial-interglacial variation. In comparison to Sites 1237 and 1239, cooler temperature at Site 1241 in MIS-1 was attributed to the deeper production of alkenones owing to the deeper thermocline (Chapter 4). In the EPWP, alkenone producers were

suggested to be abundant in subsurface water near nutricline. Thus, the U_{37}^K at Site 1241 in the Holocene did not reflect the SST but thermocline temperature.

5.4.3 Intensified PCC during the last deglaciation

In modern oceanographic setting smaller temperature gradient between the EEP and the Peru margin reflects the intensification of the PCC and vice versa (Pennington et al., 2006). The SST difference between Sites 1237 and 1239 was minimum during the last deglaciation (Fig. 5-6). Because both two sites are located under the influence of the PCC (Wyrski, 1963), this suggests that the PCC intensified during the last deglaciation. During the last deglaciation, sediment $\delta^{15}\text{N}$ showed a maximum, suggesting intensified anoxia in the intermediate water presumably due to enhanced upwelling (Ganeshram et al., 2000). In the EEP, intensified upwelling was suggested by the elevated ΔT and the GDGTs/ alkenone ratio (Chapter 3). The coincidence of the intensification of the PCC with the intensified anoxia in the Peru margin and the intensified upwelling in the EEP suggests the intensification of the PCC and the EEP-Peru coastal upwelling system during the last deglaciation.

Modern observation demonstrated that the PCC intensity is linked to the formation of the eastern Pacific cold tongue and northward shift of the equatorial front (e.g., Kessler, 2006; Pennington et al., 2006). Based on the $\delta^{13}\text{C}$ of benthic foraminifera and export production derived from inorganic element composition, Loubere et al. (2003) suggested that primary production in the EEP region was well correlated with the Peru coastal region. Southeast trade winds are the principal agent driving the PCC and coastal upwelling along the west coast of the South American continent (Wyrski, 1981; Kessler,

2006). Shaari et al. (2013) suggested the intensification of southeast trade winds over this region during the deglaciation owing to the intensified South Pacific High. The stronger South Pacific High during the last deglaciation can explain a drier climate in the Patagonia region of South America (de Porras et al., 2012). Concentration of GDGTs and alkenones was higher (this study), and $\delta^{15}\text{N}$ was higher (e.g., Ganeshram et al., 2000; Martinez and Robinson, 2010) in the Peru margin during the last deglaciation (Fig. 5-7). Denitrification was maximized in this region during the last deglaciation, suggesting an enhancement of primary production and export production (Ganeshram et al., 2000; Martinez and Robinson, 2010).

5.5 Conclusions

The latitudinal temperature gradient between Sites 1237 and 1239 indicates the intensity of PCC, suggesting that the PCC intensified during the last deglaciation. The PCC intensification coincided with the intensification of upwelling in both the Peru margin and the EEP. This suggests the intense subtropical gyre circulation in the South Pacific during the last deglaciation.

CHAPTER 6: General summary

In this study, we tried to understand the hydrological evolution in the ETP during glacial-interglacial cycles. We investigated GDGTs and alkenones for sediment samples retrieved from ODP Sites 1241, 1239 and 1237.

In Chapter 3, the upwelling in the EEP was investigated using newly proposed upwelling indices based on the difference between $\text{TEX}_{86}^{\text{H}}$ - and $\text{U}_{37}^{\text{K}'}$ -derived temperatures (ΔT) and the abundance ratio of GDGTs to alkenones (GDGT/alkenone ratio) at Site 1239. The GDGT/alkenone ratio and ΔT were maximal during the last five deglaciations. This suggests that upwelling was intensified in the EEP during deglaciations.

In Chapter 4, we investigated changes in nutricline depth using the concentrations of GDGTs and alkenones, $\text{TEX}_{86}^{\text{H}}$ and $\text{U}_{37}^{\text{K}'}$ at Site 1241 in the EPWP. Higher GDGTs and alkenone concentrations in MIS 2 and MIS 6, and unchanged $\text{U}_{37}^{\text{K}'}$ reflected shallow nutricline in the EPWP during glacial maxima, presumably resulted from the intense formation of Antarctic intermediate water.

In Chapter 5, we report the $\text{U}_{37}^{\text{K}'}$ and $\text{TEX}_{86}^{\text{H}}$ at Site 1237 in the Peru margin and discussed changes in the PCC based on SST gradient along Peru-Ecuador margin during the last 90 ka and indicated that the PCC intensified during the last deglaciation.

Enhanced upwelling in the EEP and the intensification of the PCC, along with other evidence from published records, suggest the intensification of the South Pacific subtropical gyre circulation during deglaciations (Chapters 3 and 5). In the EPWP, thermocline shoaled in glacial maxima, likely reflected the intense formation of the

AAIW (Chapter 4). The new and original insight of this study can explain well both atmospheric and oceanic patterns in South and North America continents during the last deglaciation.

The behavior of U_{37}^K was different between non-upwelling and upwelling regions. In the non-upwelling region (Site 1241), U_{37}^K reflected the temperature of nutricline, but in upwelling region (Sites 1239 and 1237), U_{37}^K reflected the temperature of the surface mixed layer (Table 1-1). TEX_{86}^H reflected the integrated temperature of the surface mixed and thermocline layers both in both non-upwelling and upwelling regions (Table 1-1). This insight is useful when U_{37}^K and TEX_{86}^H are applied to paleoceanographic reconstruction in the ETP region.

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Table

Table 1-1. Showing the overview of U_{37}^K - and TEX_{86}^H -derived temperatures at different study sites.

Study Sites	U_{37}^K	TEX_{86}^H	Key factors
1241	TL	Integrated SML and TL	Depth of nutricline
1239	SML	Integrated SML and TL	Upwelling
1237	SML	Integrated SML and TL	Upwelling

* SML= Surface Mixed Layer, TL = Thermocline layer.

Figures

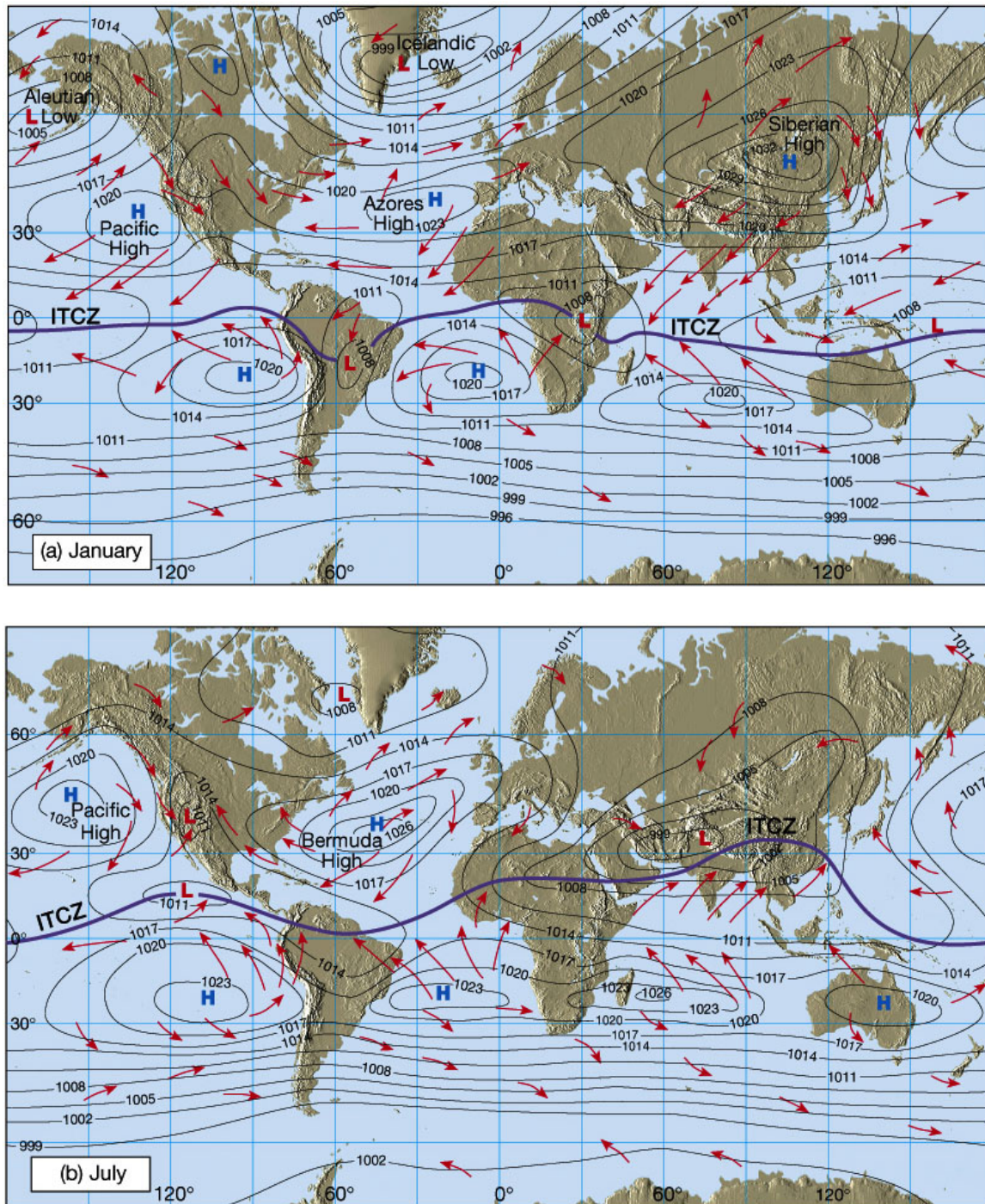
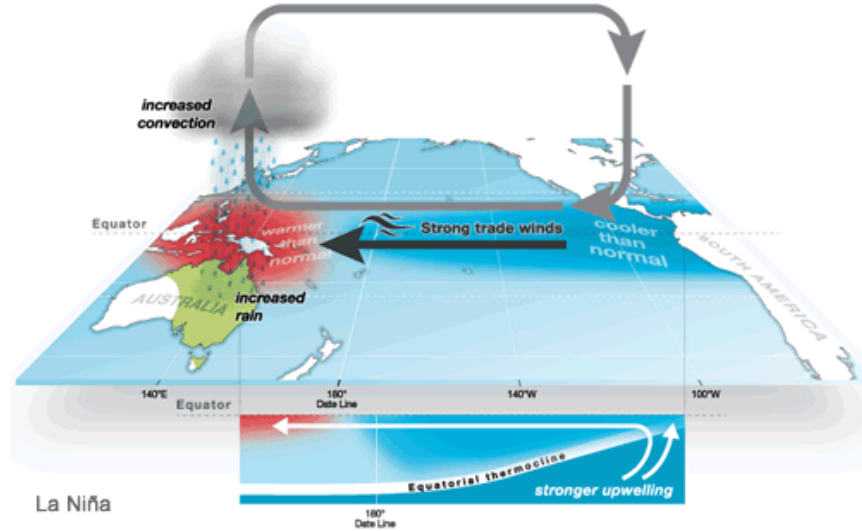


Figure 1-1. Seasonal migration of the Intertropical convergence zone (ITCZ) during (a) January and (b) July (Lutgens and Tarbuck, 2001).

a.



b.

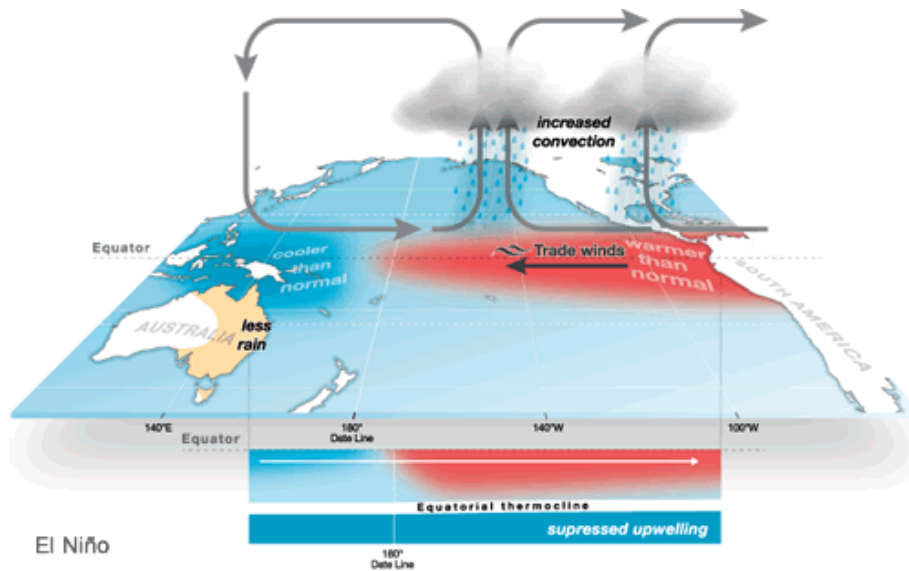


Figure 1-2. Atmospheric and oceanic condition during (a) La Niña and (b) El Niño (<http://www.bom.gov.au/climate/enso/history/ln-2010-12/three-phases-of-ENSO.shtml>)

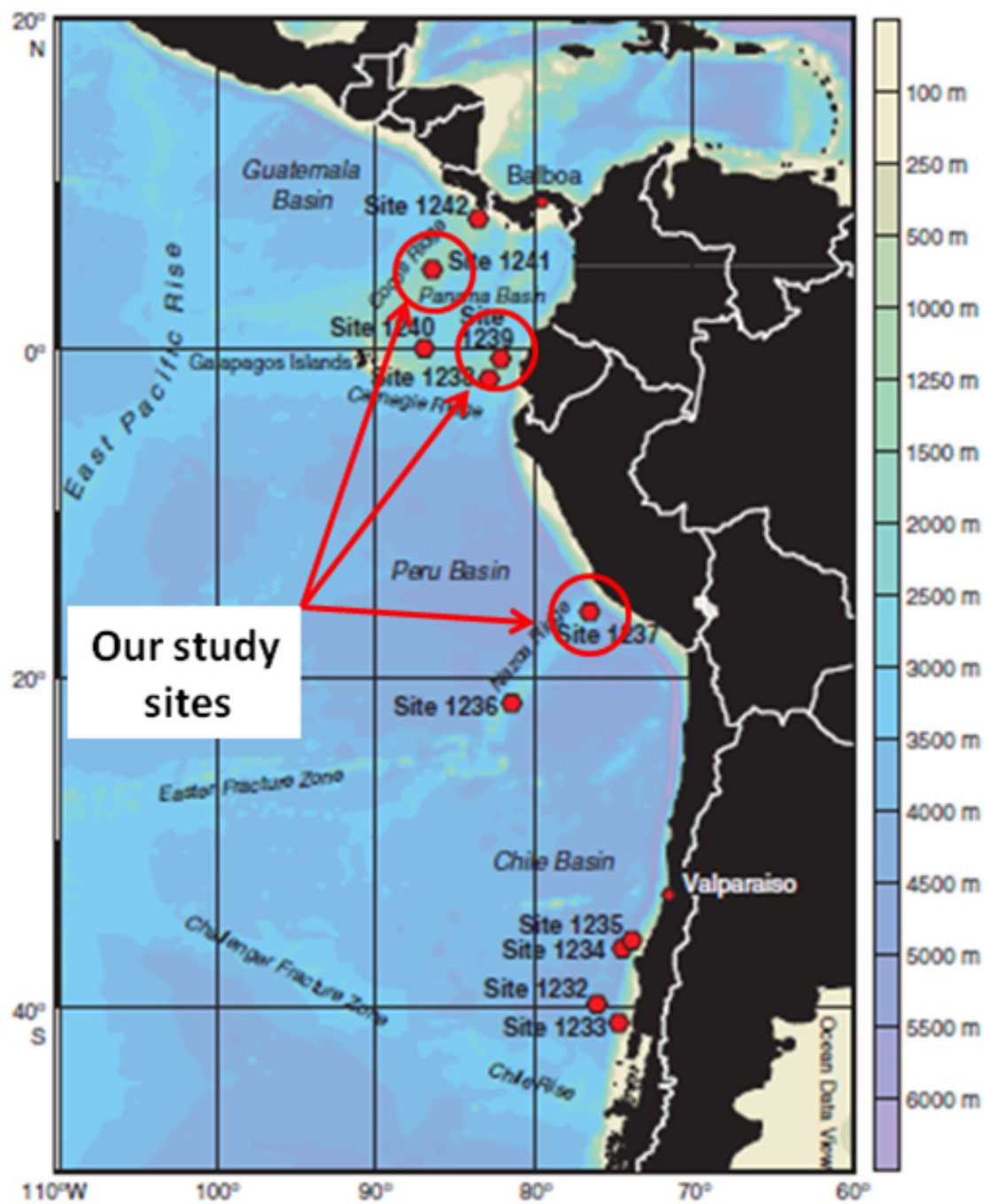


Figure 1-3. Map of Ocean Drilling Program (ODP) Leg 202 Sites

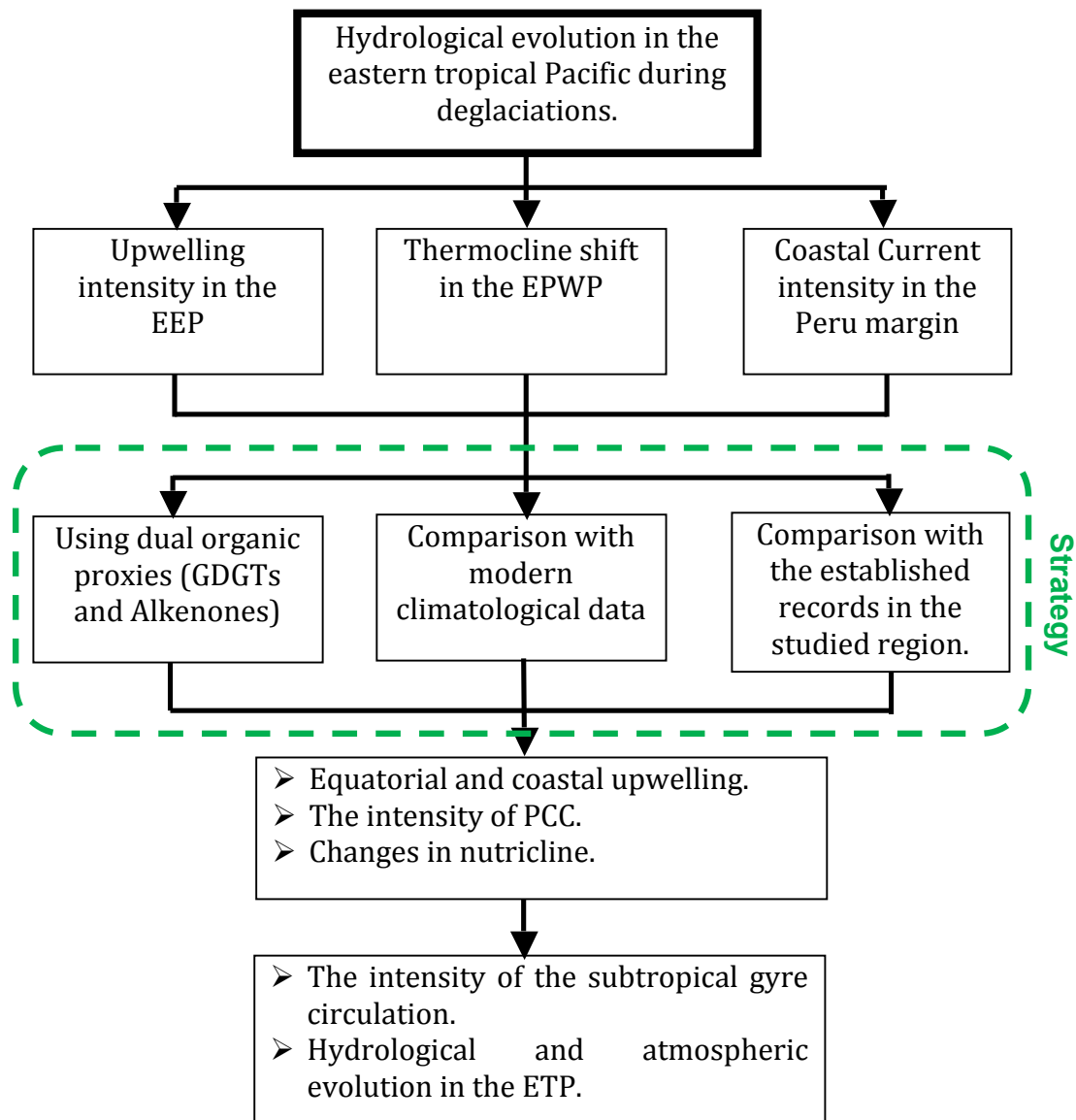


Figure 1-4. Flow chart showing the outline of this study.

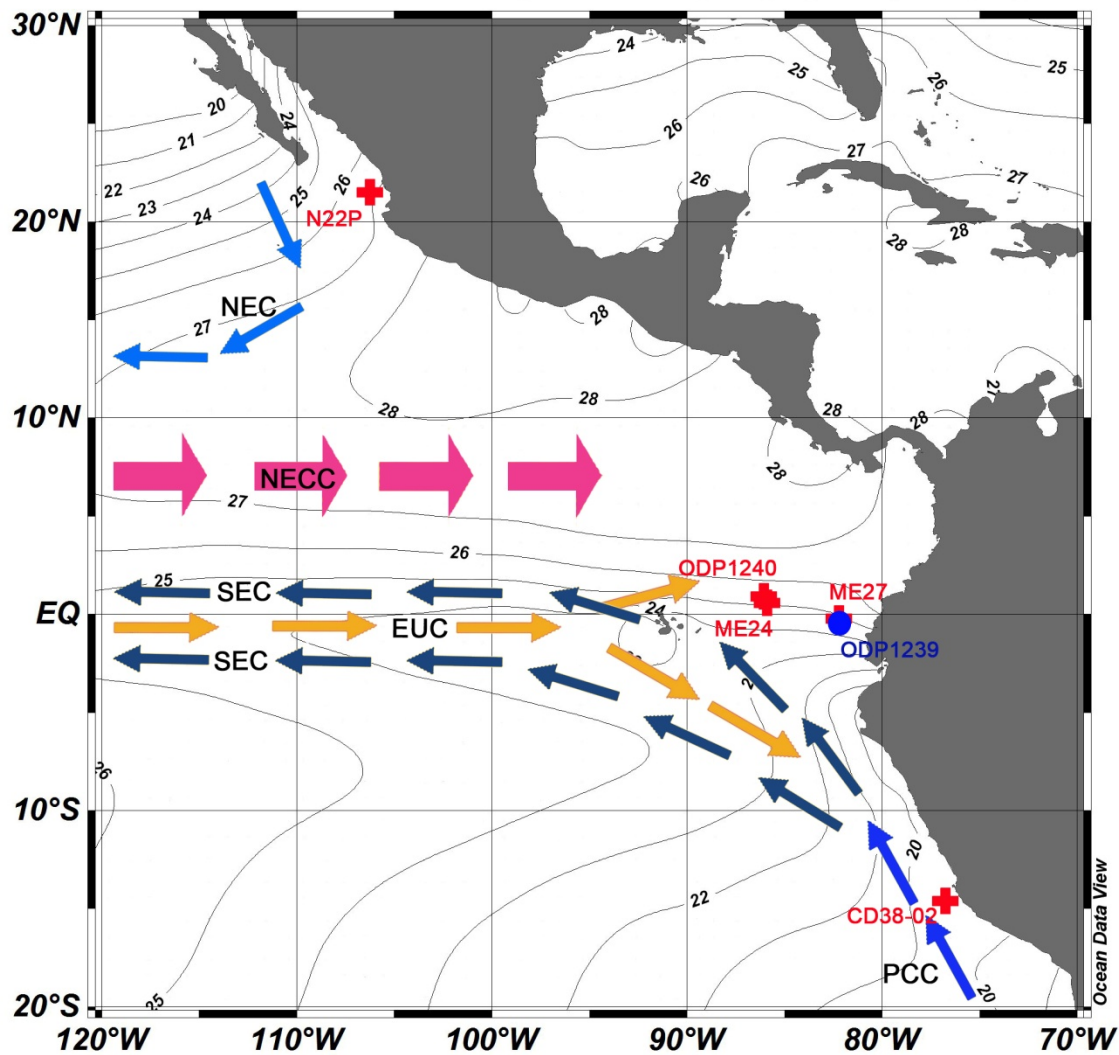


Figure 3-1. Map showing mean annual SST (Locarnini et al., 2010), the location of ODP Site 1239 (this study), Sites 1240, ME24, ME27, N22P, CD38-02 and the surface and subsurface ocean currents in the EEP. SEC = South Equatorial Current, NEC = North Equatorial Current, EUC = Equatorial Undercurrent, NECC = North Equatorial Countercurrent; modified after Kessler (2006) and Pennington et al. (2006).

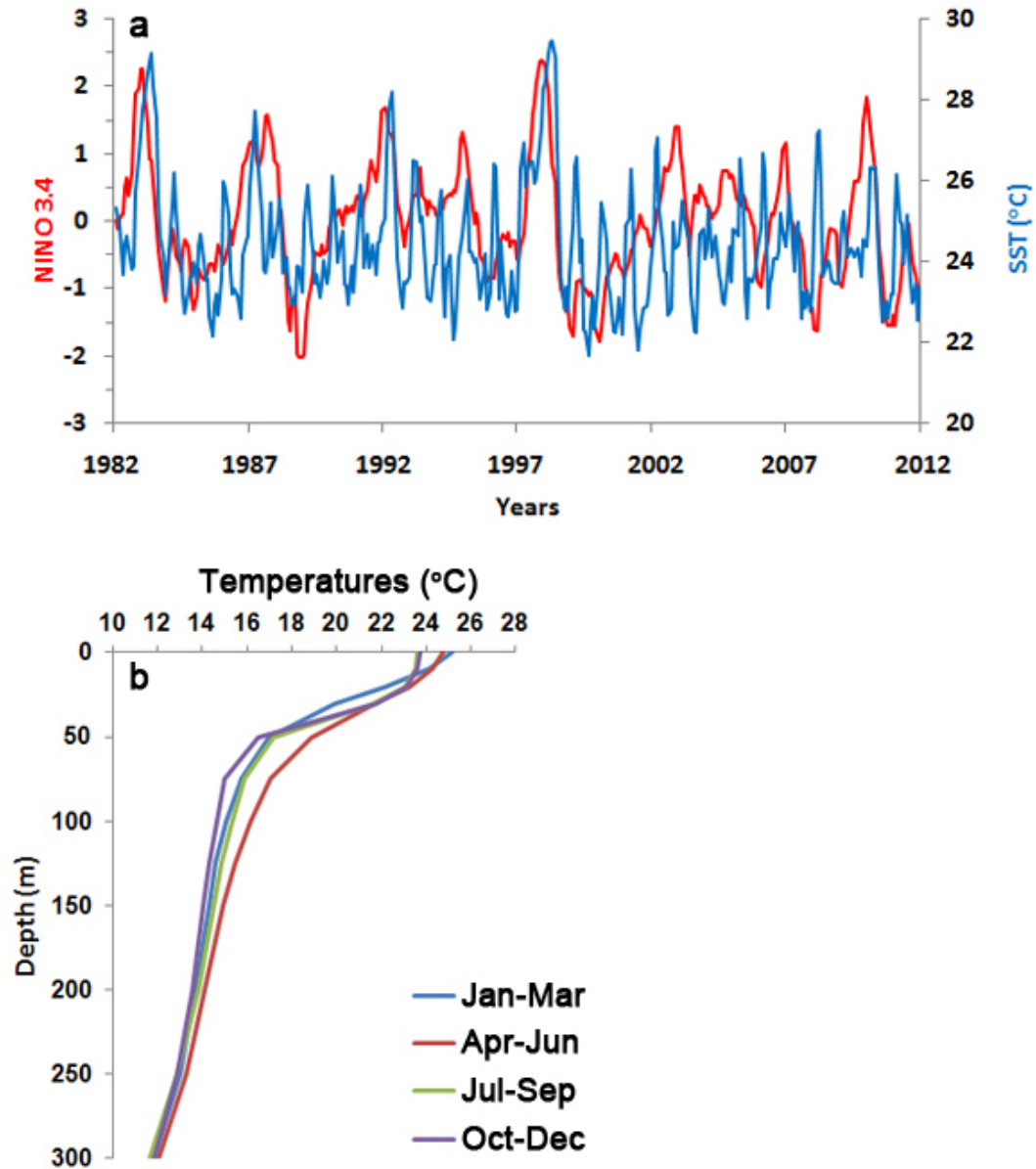


Figure 3-2. Records of (a) Niño 3.4 index (averaged SST anomaly in the region 170°W-120°W, 5°S-5°N) (Trenberth, 1997) and monthly SST at 0.5°S, 82.5°W (Reynolds et al., 2002) from January 1982 to December 2011 (see online data at http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP/.EMC/.CMB/.GLOBAL/.Reyn_SmithOIv2/.monthly/ for detail); (b) Seasonal vertical water structure at 0.5°S, 82.5°W (see online data at <http://iridl.ldeo.columbia.edu/SOURCES/.LEVITUS94/.MONTHLY/.temp/>).

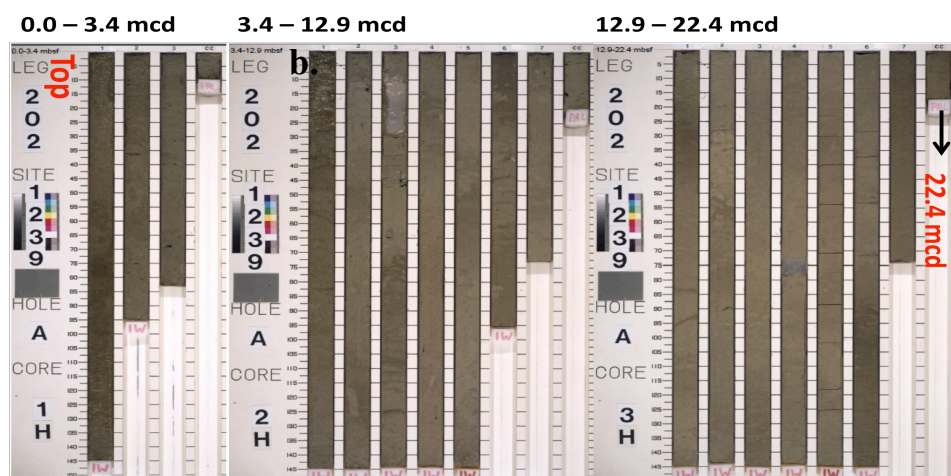


Figure 3-3. Photograph of down-core sediments from 0 – 22.4 mcd of ODP Site 1239.

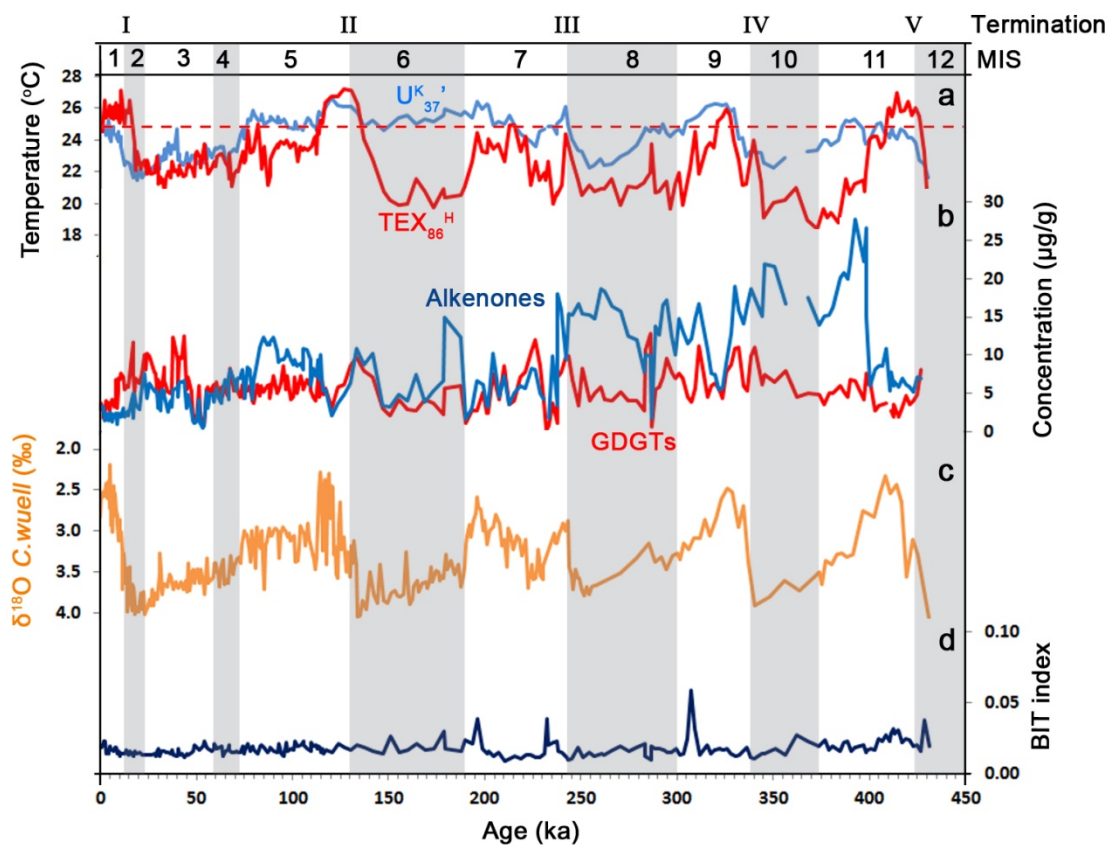


Figure 3-4. Variations in (a) $\text{TEX}_{86}^{\text{H}}$ - and $\text{U}^{\text{K}}_{37'}$ -derived temperatures; (b) the concentration of alkenones and isoprenoid GDGTs; (c) $\delta^{18}\text{O}$ of the benthic foraminifera *C. wuellerstorfi* at the study site (Rincon-Martinez et al., 2010); (d) branched isoprenoid tetraether (BIT) index.

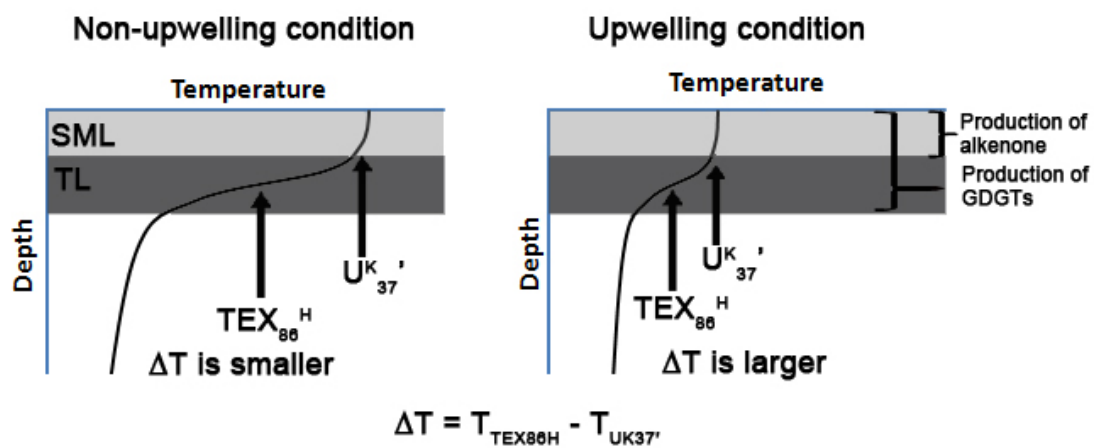


Figure 3-5. Conceptual model of ΔT in upwelling and non-upwelling conditions.

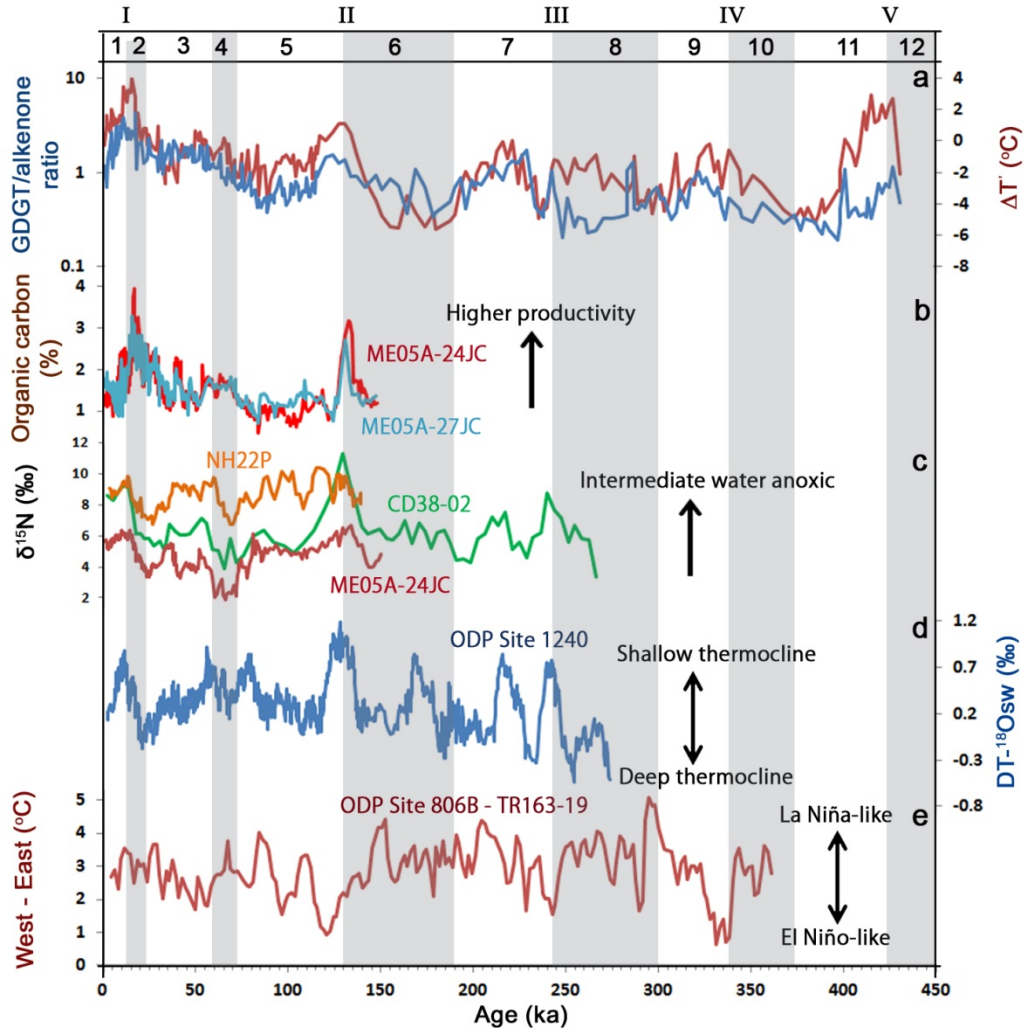


Figure 3-6. Variation in (a) the difference between $\text{TEX}_{86}^{\text{H}}$ and U_{37}^{K} temperatures (ΔT) and the abundance ratio of GDGTs to alkenones (GDGT/alkenone); (b) organic carbon content at ME0005A-24JC and ME0005A-27JC (Dubois and Kienast, 2011); (c) $\delta^{15}\text{N}$ of bulk sediments from cores CD38-02 and NH22P at the Peru and Mexican margins, respectively (Ganeshram et al., 2000) and core ME0005A-27JC in the EEP (Dubois and Kienast, 2011); (d) $\text{DT}-\delta^{18}\text{O}_{\text{sw}}$ at ODP Site 1240 (Pena et al., 2008); (e) Mg/Ca-derived temperature difference (smoothed; west-east) between the western equatorial Pacific (ODP Site 806B; Medina-Elizalde and Lea, 2005) and the EEP (core TR163-19; Lea et al., 2000).

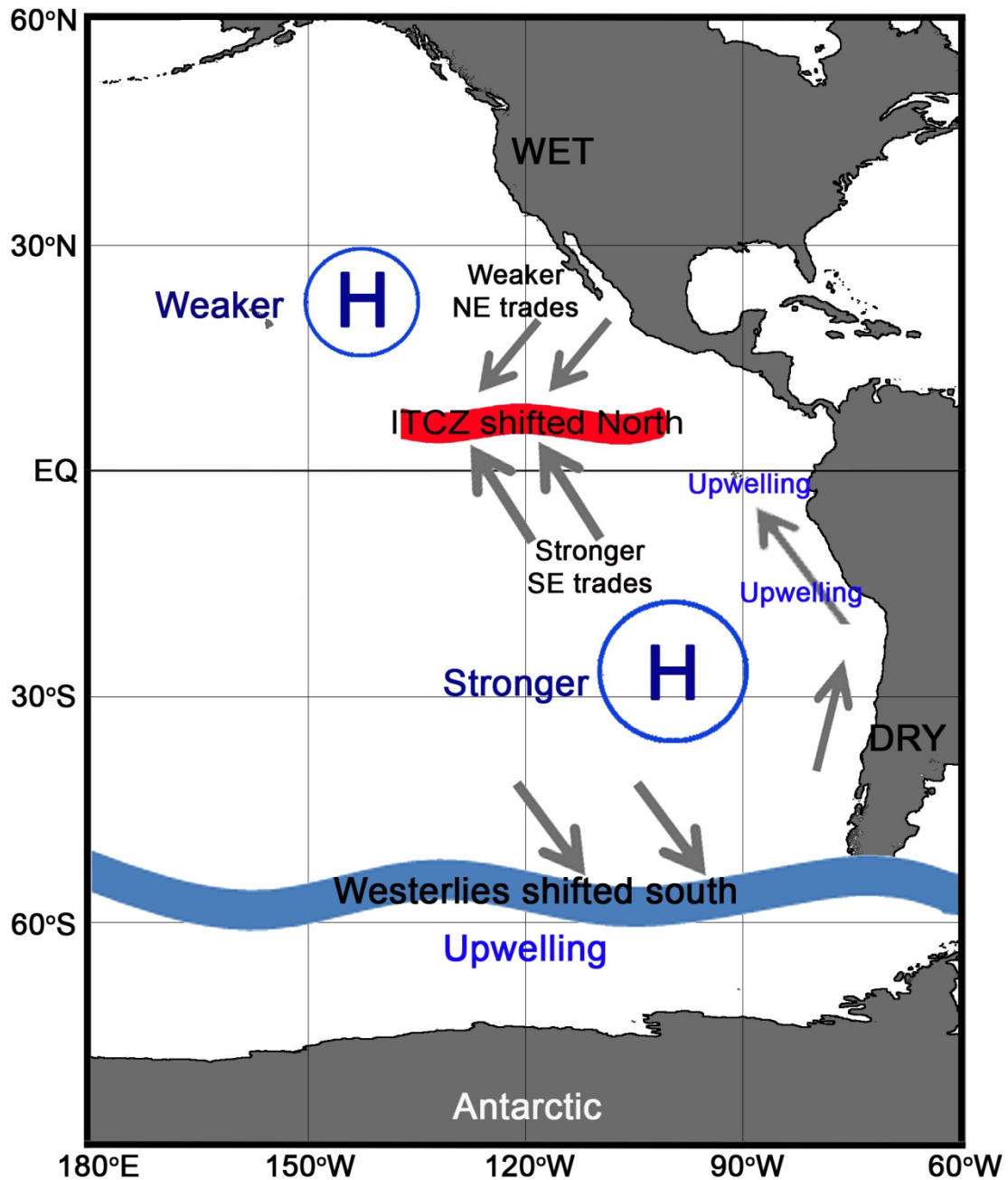


Figure 3-7. Ocean and atmospheric conditions in the eastern Pacific region during deglaciations. The weaker North Pacific High and the stronger South Pacific High resulted in the northward shift of the ITCZ, the southward shift of the southern westerlies and the intensification of upwelling in the EEP, the Peru margin and the Southern Ocean.

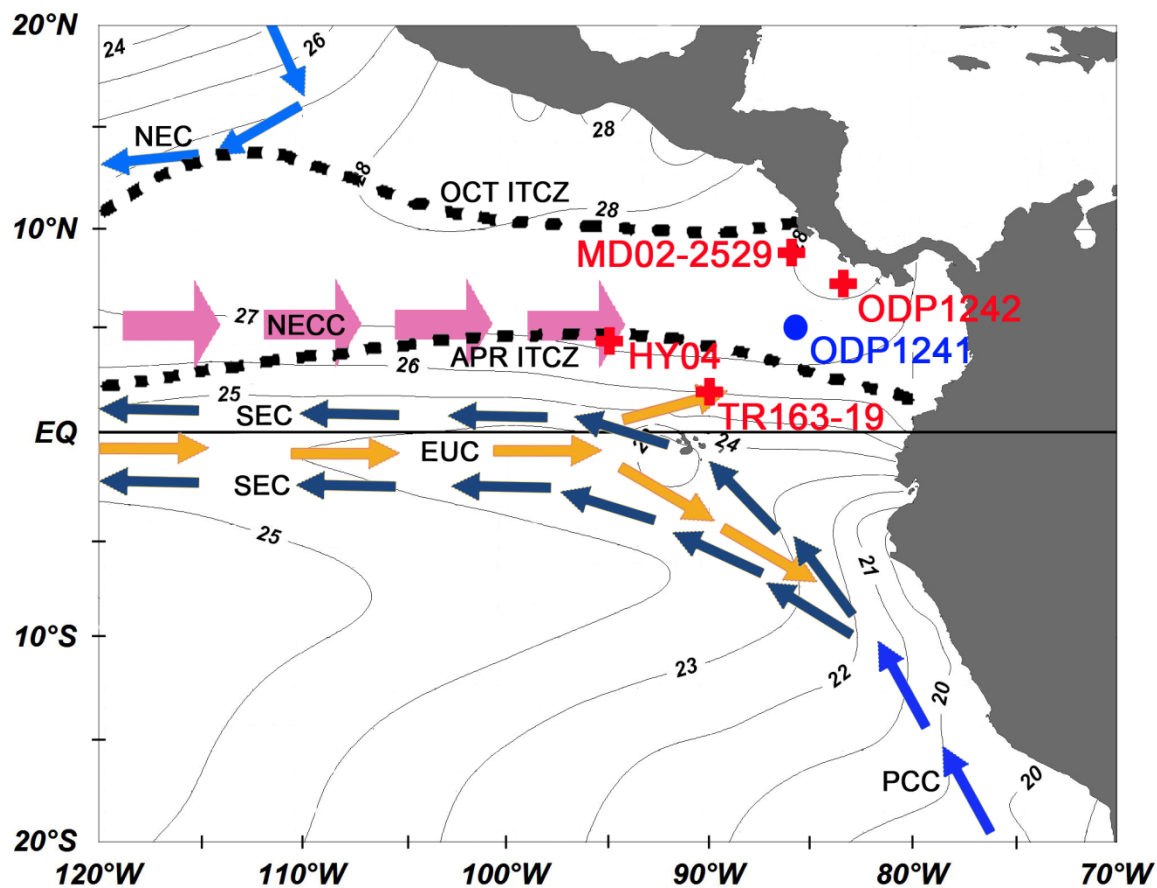


Figure 4-1. Map showing the location of ODP Site 1241 (this study), Site 1242 (Benway et al., 2006), HY04 (Horikawa et al., 2006) and MD02-2529 (Rincon-Martinez et al., 2010), mean annual SST (Locarnini et al., 2010), and surface and subsurface ocean currents in the EEP. SEC = South Equatorial Current, NEC = North Equatorial Current, EUC = Equatorial Undercurrent, NECC = North Equatorial Counter Current. Modified after Kessler (2006) and Pennington et al. (2006). The seasonal location of the intertropical convergence zone (ITCZ) is marked by a dashed line.

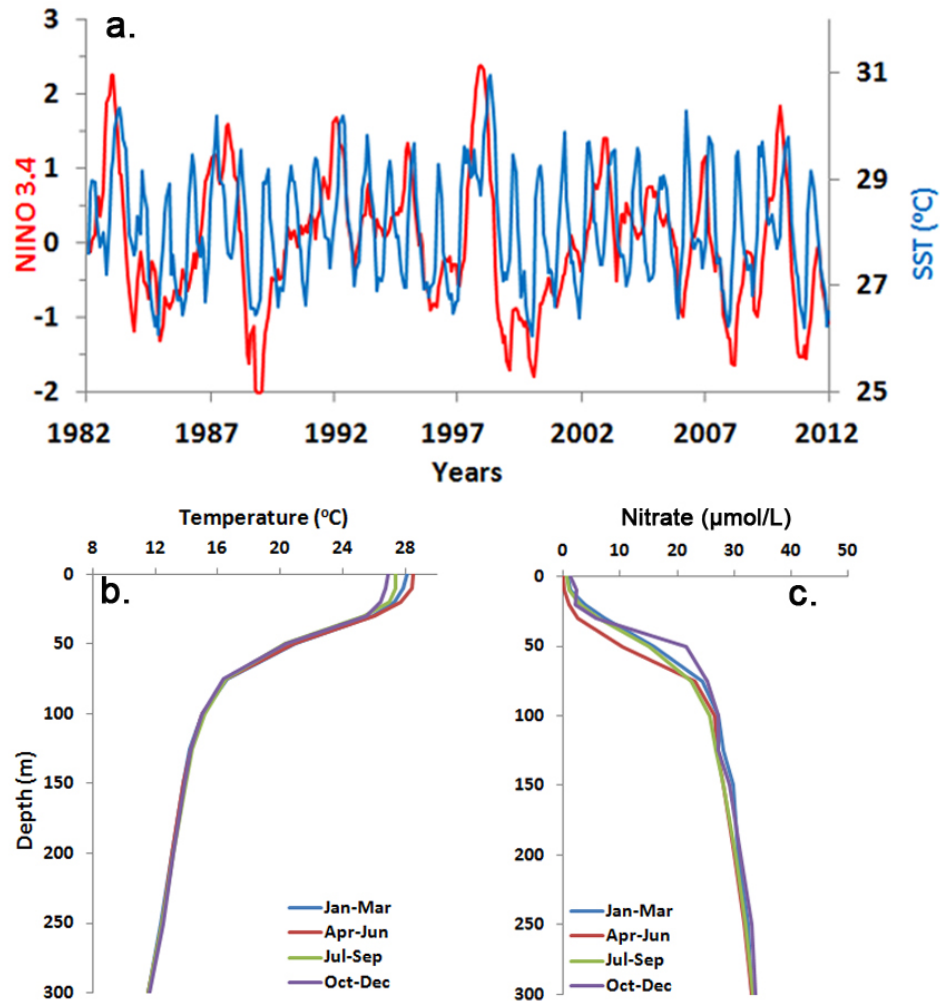


Figure 4-2. Changes in (a) Niño 3.4 index (averaged SST anomaly in the region 170°W–120°W, 5°S–5°N) (Trenberth, 1997) and monthly SST at 5.5°N, 86.5°W (Reynolds et al., 2002) from January 1982 to December 2011s (see online data at http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP/.EMC/.CMB/.GLOBAL/.Reyn_SmithOIv2/.monthly/ for detail); (b) Depth profile of water temperatures in different seasons at 5.5°N, 86.5°W (see online data at <http://iridl.ldeo.columbia.edu/SOURCES/.LEVITUS94/.MONTHLY/.temp/>); (c) Depth profile of nitrate concentrations in different seasons at 5.5°N, 86.5°W (see online data at <http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NODC/.WOA98/.SEASONAL/.analyzed/.nitrate/>)

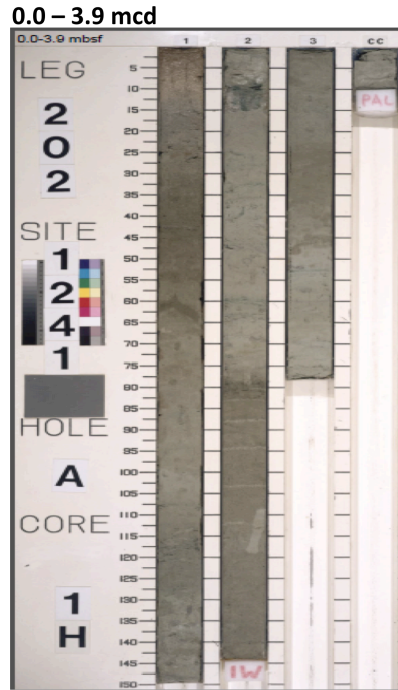


Figure 4-3. Photograph of down-core sediment from 0 – 3.9 mcd of ODP Site 1241.

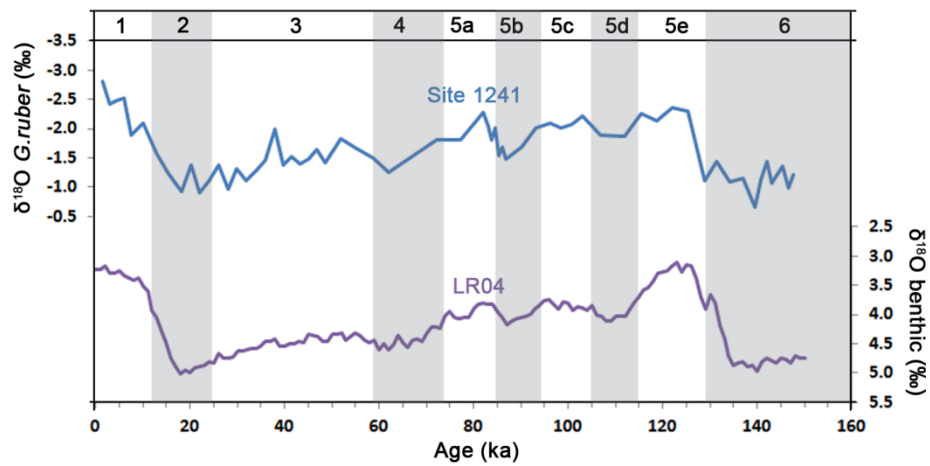


Figure 4-4. Oxygen isotope stratigraphy for ODP Site 1241. (a) $\delta^{18}\text{O}$ of planktonic foraminifera *Globigerinoides ruber* in Site 1241 and global stack LR04 $\delta^{18}\text{O}$ of benthic foraminifera (Lecieski and Raymo, 2005); (b) the age depth model at Site 1241. Shading highlights glacial and stadial marine isotopic stages.

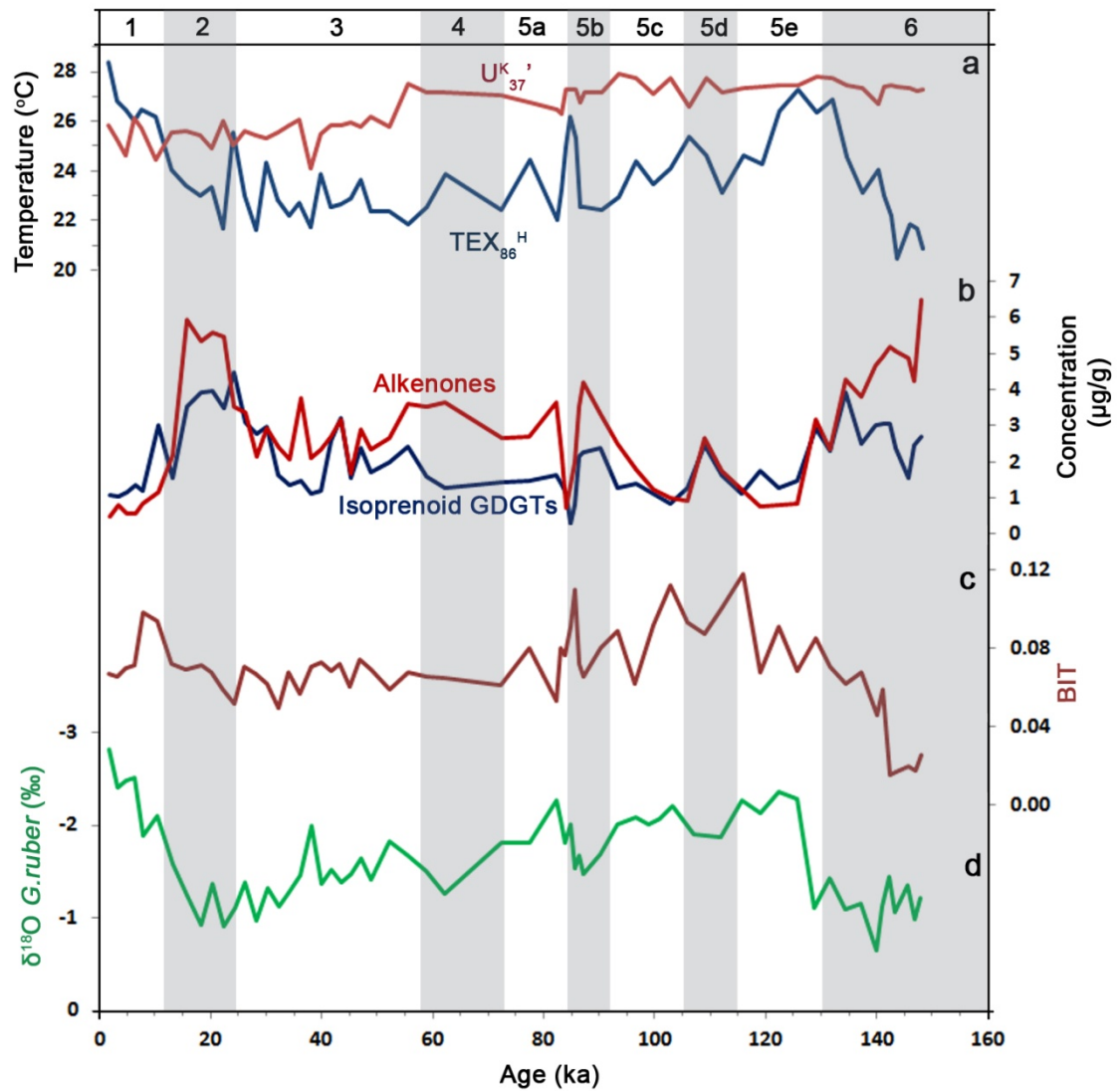


Figure 4-5. Variations in (a) $\text{TEX}_{86}^{\text{H}}$ - and $\text{U}^{\text{K}}_{37}'$ -derived temperatures; (b) the concentrations of alkenones and isoprenoid GDGTs; (c) BIT value; (d) the $\delta^{18}\text{O}$ of planktonic foraminifera *Globigerinoides ruber*.

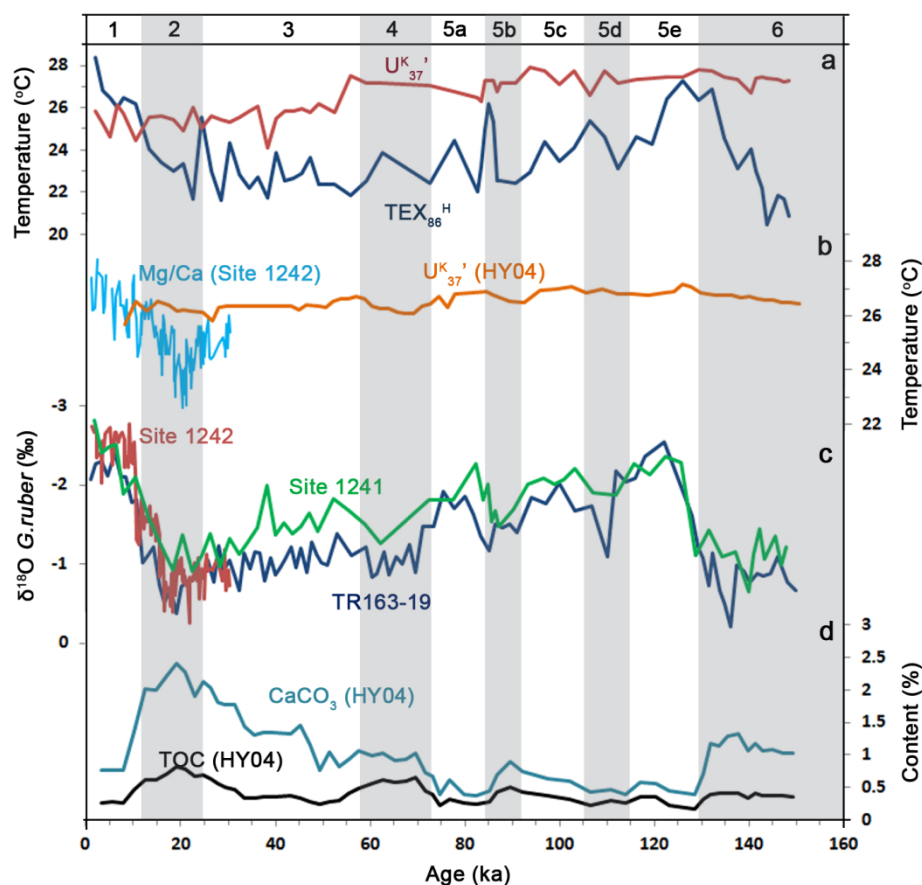


Figure 4-6. Variations in (a) TEX₈₆^H- and U₃₇^{K'}-derived temperatures (this study); (b) Mg/Ca-derived temperatures at ODP Site 1242 (blue line; Benway et al., 2006), U₃₇^{K'}-derived temperatures in core HY04 (orange line; Horikawa et al., 2006) and U₃₇^{K'}-derived temperatures in core MD02-2529 (Rincon-Martinez et al., 2010); (c) the δ¹⁸O of planktonic foraminifera *Globigerinoides ruber* at ODP Site 1241 (this study), and 1242 (red line; Benway et al., 2006) and in core TR163-19 (dark blue line; Lea et al., 2000); (d) total carbon organic (TOC) and CaCO₃ at Site HY04 (Horikawa, 2006). Calculation of U₃₇^{K'}-derived temperature used a calibration equation of Prahl et al. (1988).

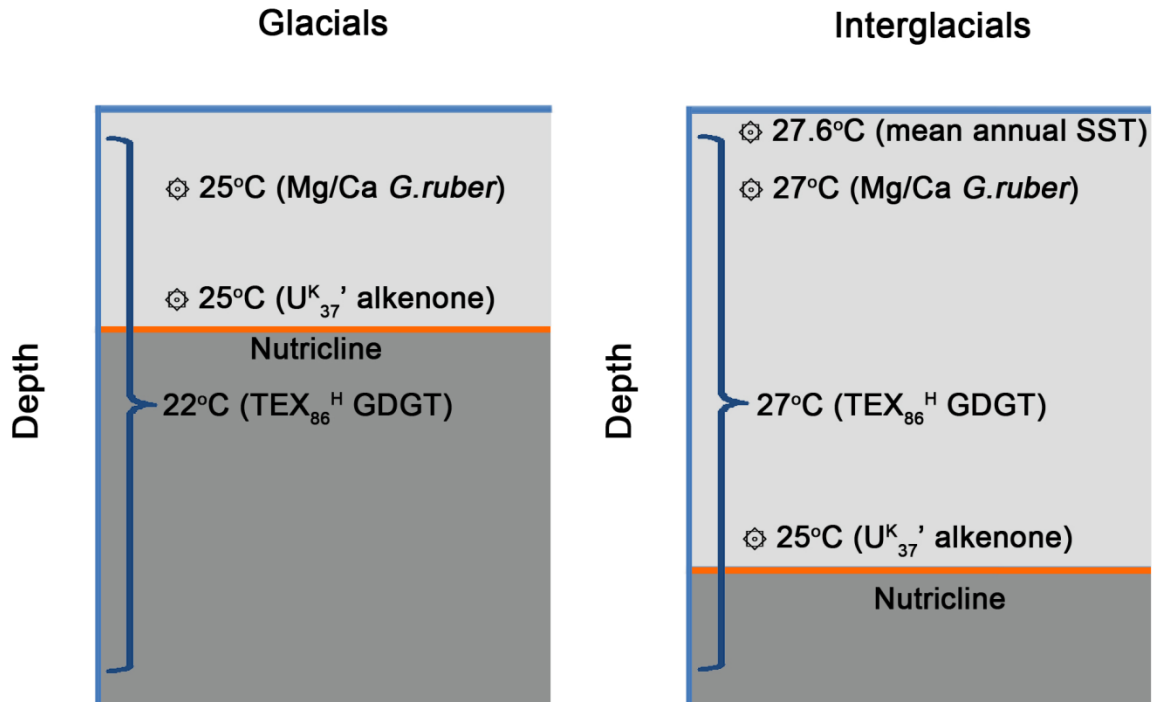


Figure 4-7. Conceptual model of temperature proxies during glacial and interglacials in the EPWP. Modern mean annual SST (Locarnini et al., 2010), Mg/Ca temperature derived from planktonic foraminifera *G.ruber* at ODP Site 1242 (Benway et al., 2006), and TEX_{86}^H - and $U^{K}_{37'}$ -derived temperatures at ODP Site 1241 (this study).

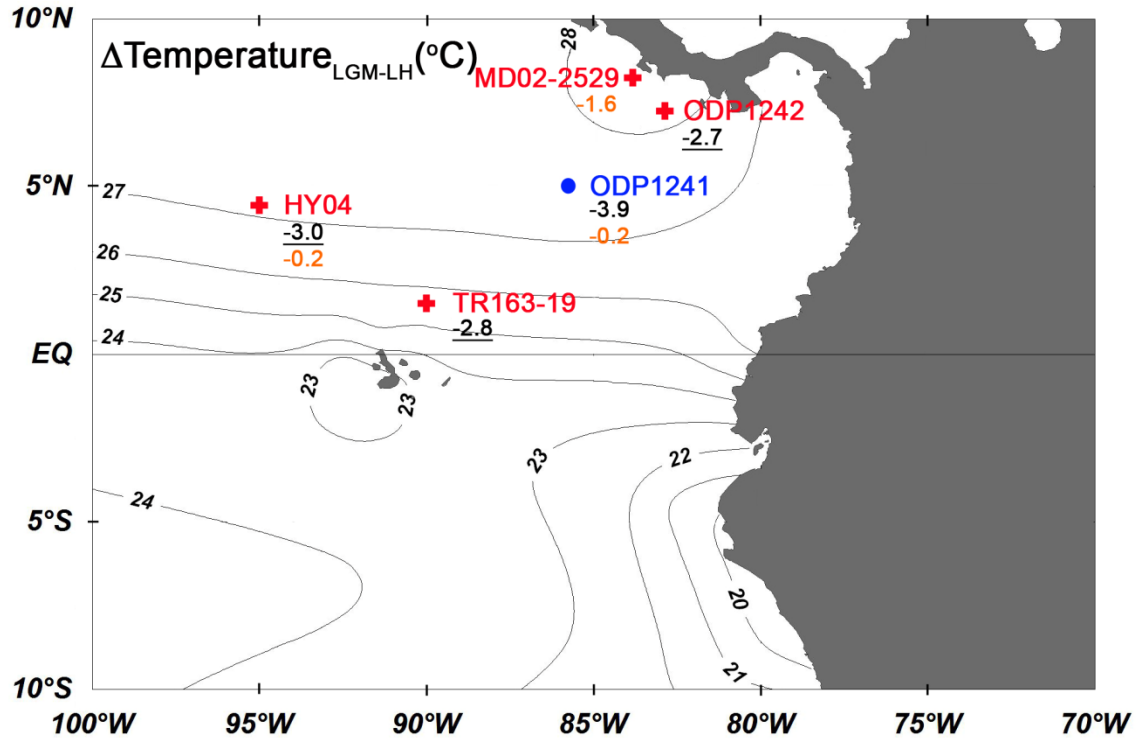


Figure 4-8. LGM-Late Holocene temperature differences ($\Delta\text{Temperature}_{\text{LGM-LH}}$) calculated from $\text{TEX}_{86}^{\text{H}}$ -, U_{37}^{K} - and Mg/Ca-derived temperature. $\Delta\text{Temperature}$ of $\text{TEX}_{86}^{\text{H}}$ in ODP 1241 (number in black, this study), $\Delta\text{Temperature}$ of U_{37}^{K} in ODP 1241 (this study), HY04 (Horikawa et al., 2006) and MD02-2529 (Rincon-Martinez et al., 2010) are numbered in orange, and $\Delta\text{Temperature}$ of Mg/Ca derived from *G.ruber* in TR163-19 (Lea et al., 2000) and ODP 1242 (Benway et al., 2006) are underlined. Negative values indicate cooling during the LGM. The background contours show the modern annual mean SST (Locarnini et al., 2010).

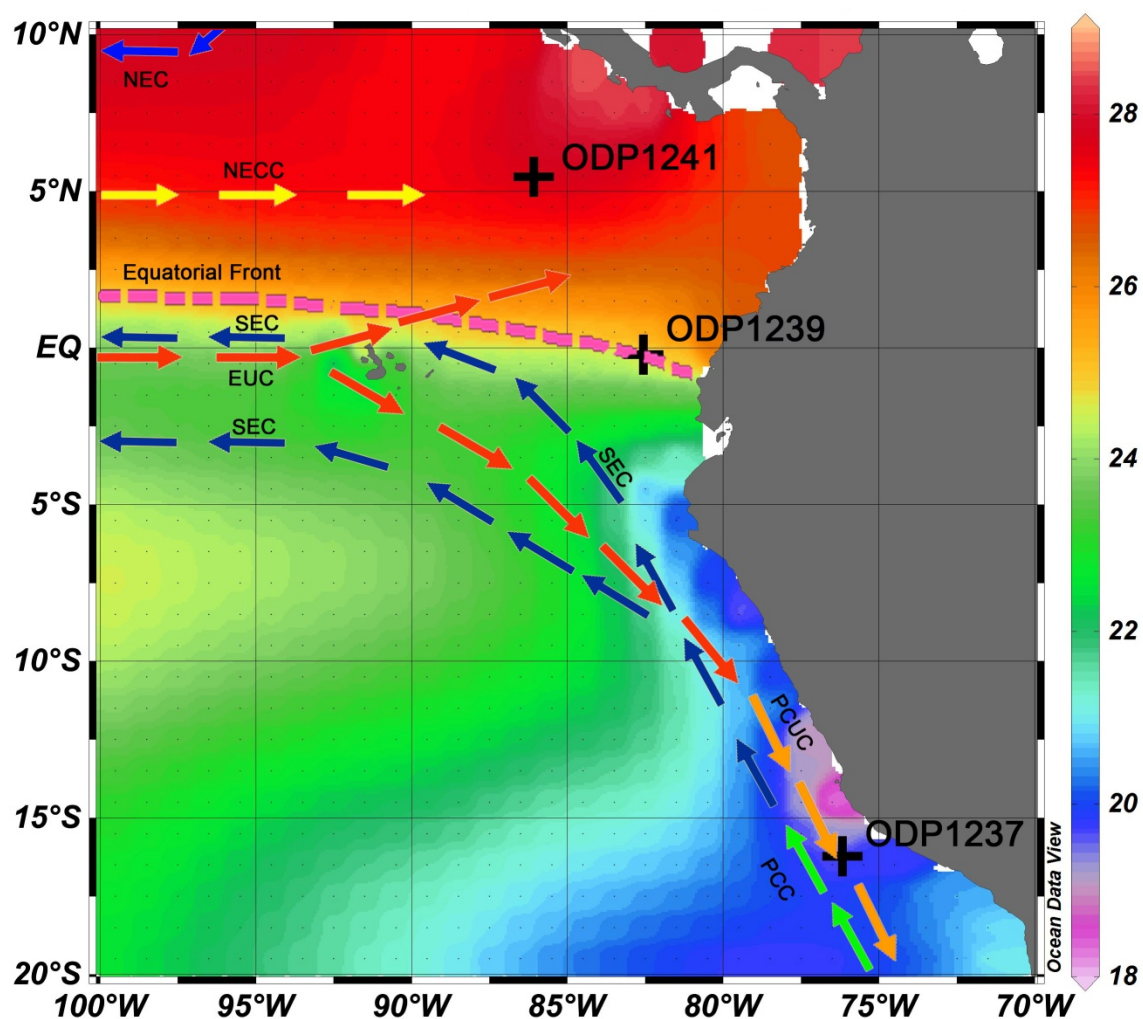


Figure 5-1. Schematic diagram of annual sea surface temperatures (SSTs) gradient from World Ocean Atlas 2009 (WOA09), the location of Ocean Drilling Program (ODP) Sites 1241, 1239, 1237 and currents in the eastern equatorial Pacific, SEC= South Equatorial Current, NEC=North Equatorial Current, EUC= Equatorial Undercurrent, NECC= North Equatorial Countercurrent, PCC= Peru Chile Current, PCUC= Peru Chile Undercurrent (Modified after Kessler, 2006 and Penington et al., 2006).

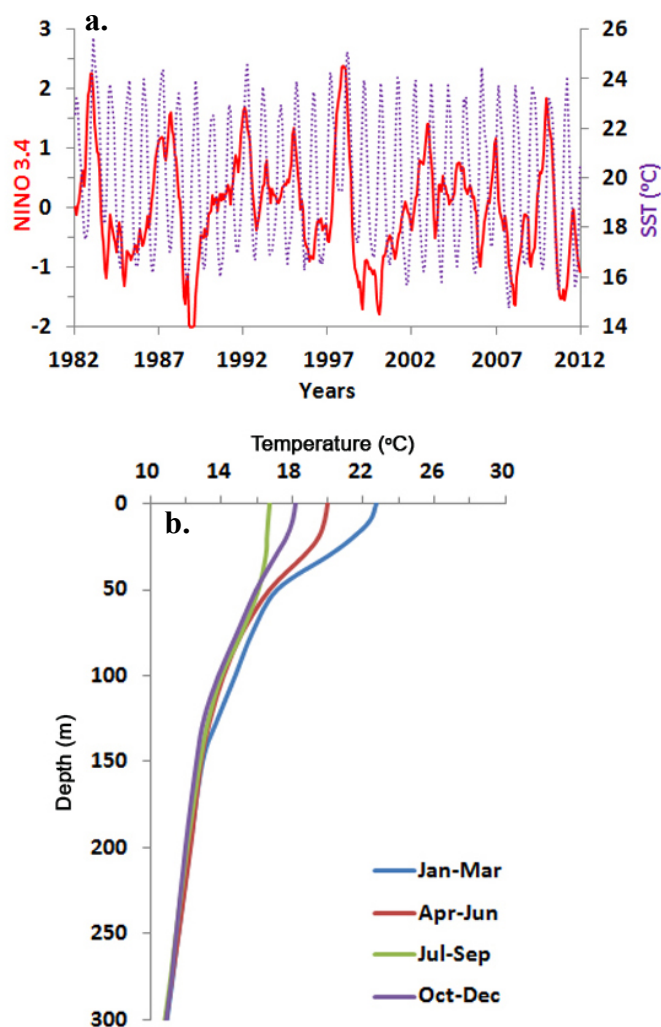


Figure 5-2. The variation of (a) monthly average SST at the nearest point to the study Site 1237 (16.5°S 76.5°W) from January 1982 to December 2011 (Reynold et al., 2002) (see http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP/.EMC/.CMB/.GLOBAL/.Reyn_SmithOIv2/.monthly/) and Niño 3.4 index (averaged SST anomaly in the region 170°W-120°W, 5°S-5°N) (Trenberth, 1997); (b) Depth profile of water temperatures in different seasons at the nearest point to the study Site 1237 (16.5°S 76.5°W) (see online data at <http://iridl.ldeo.columbia.edu/SOURCES/.LEVITUS94/.MONTHLY/.temp/>).

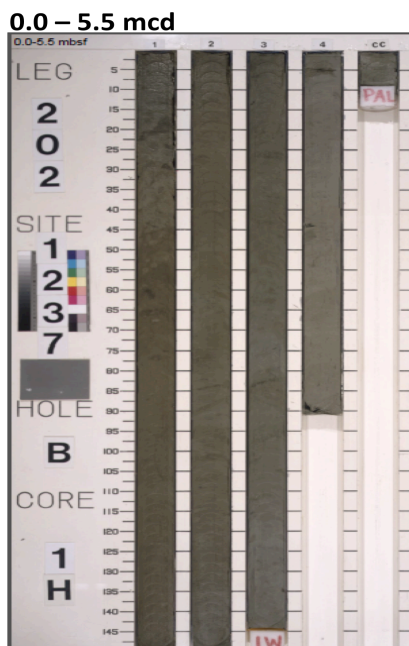


Figure 5-3. Photograph of down-core sediments from 0 – 5.5 mcd of ODP Site 1237.

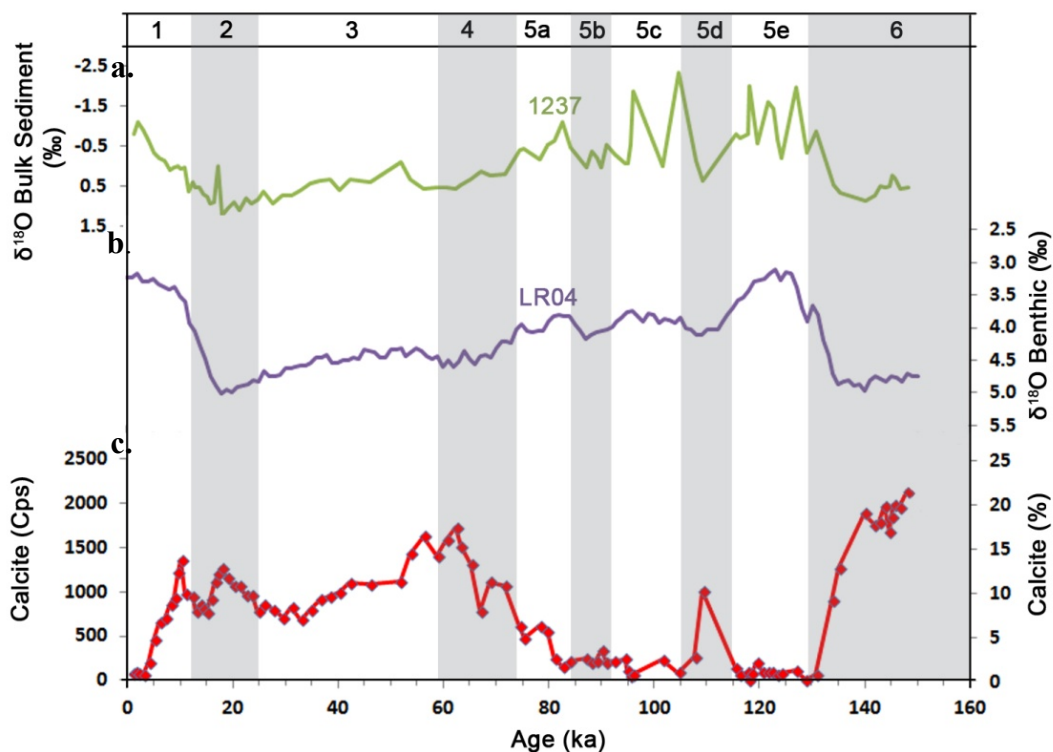


Figure 5-4. The record of (a) the bulk sediment $\delta^{18}\text{O}$ from the ODP Site 1237 (green line), (b) a benthic oxygen isotope stack (purple line) from Lisiecki and Raymo (2005), (c) calcite content from ODP Site 1237 (red line) in count per second (Cps) and percentage.

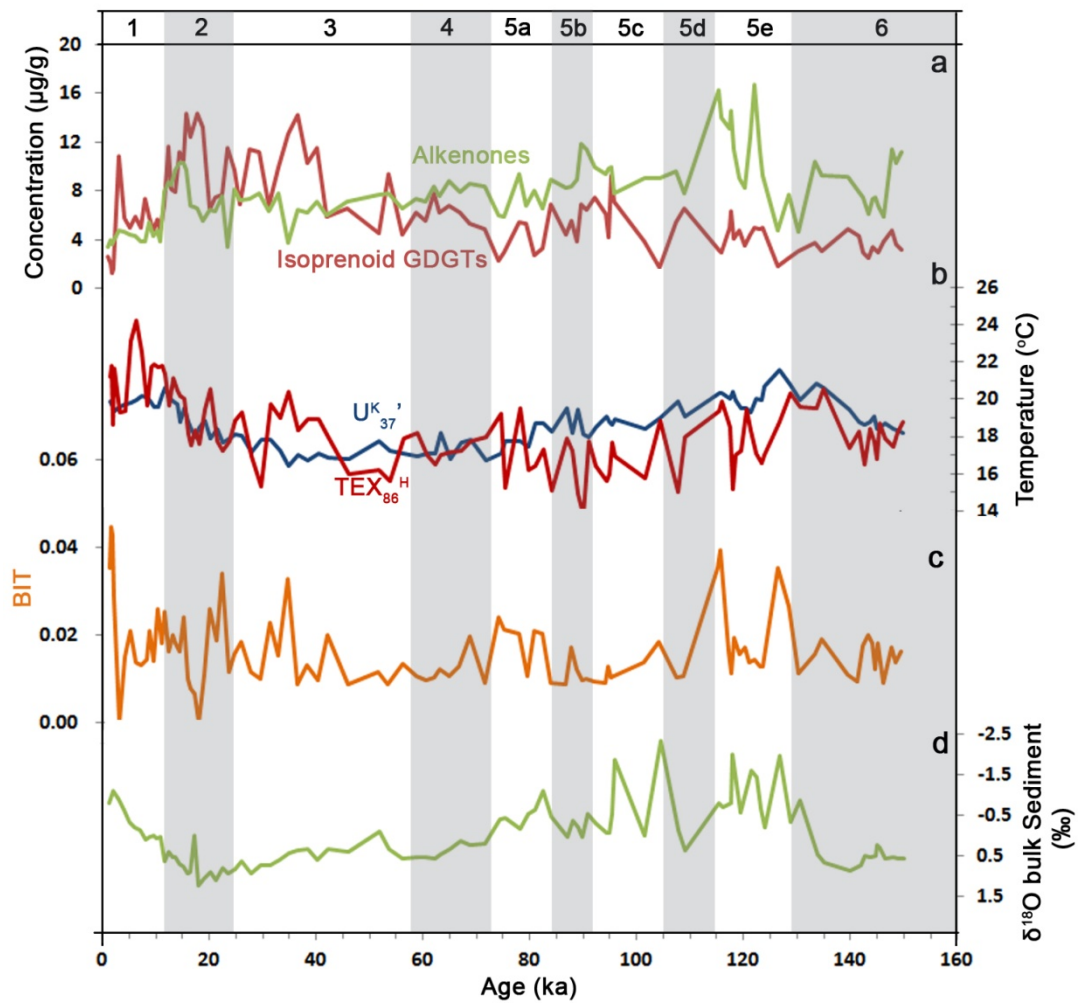


Figure 5-5. Variations in (a) the concentrations of total alkenones and total isoprenoid GDGTs, (b) $\text{TEX}_{86}^{\text{H}}$ - and $\text{U}^{\text{K}}_{37}'$ -derived temperatures, (c) BIT value, and (d) bulk sediment $\delta^{18}\text{O}$ from the ODP Site 1237.

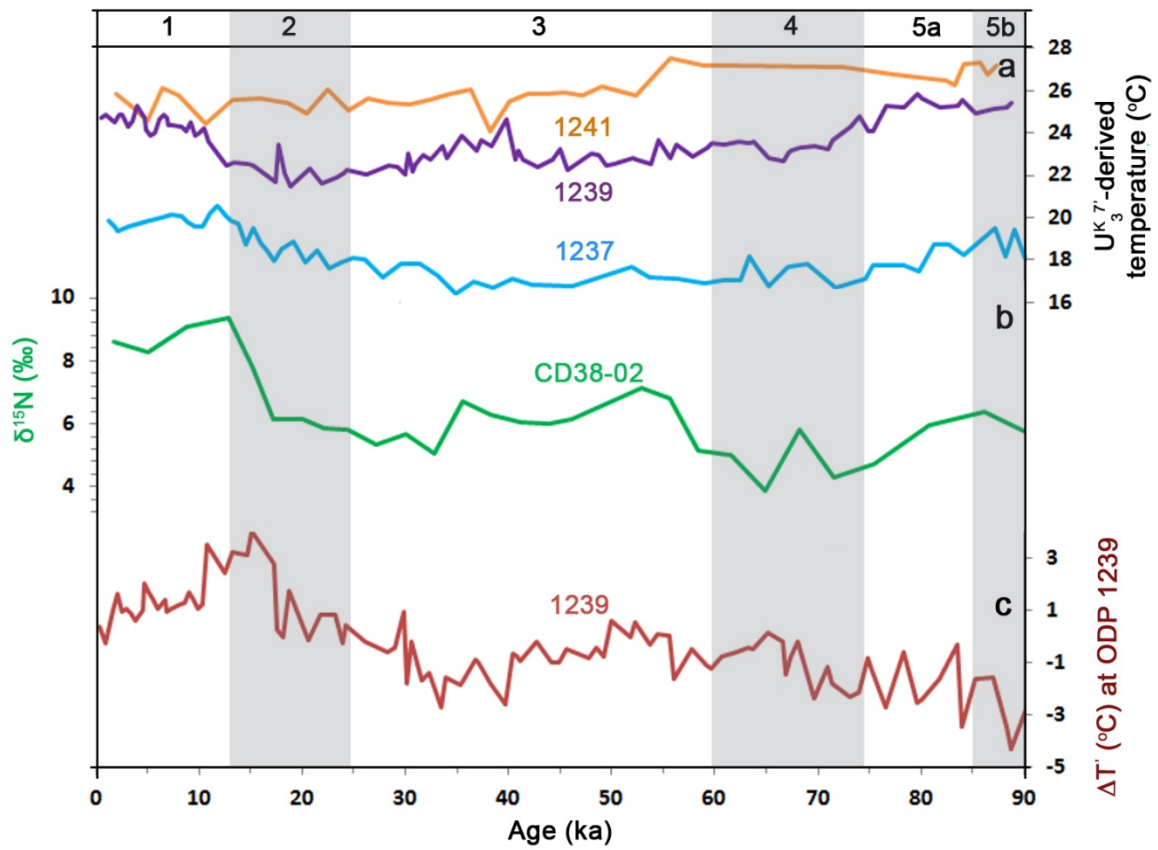


Figure 5-6. The variability of (a) U^{K}_{37} -derived temperatures gradient at Sites 1241, 1239 and 1237, (b) $\delta^{15}N$ of bulk sediments from core CD38-02 the Peru margin (Ganeshram et al., 2000), and (c) the difference between TEX_{86}^H - and U^{K}_{37} -derived temperatures (ΔT) at ODP 1239 in the EEP (Shaari et al., 2013).

Appendices

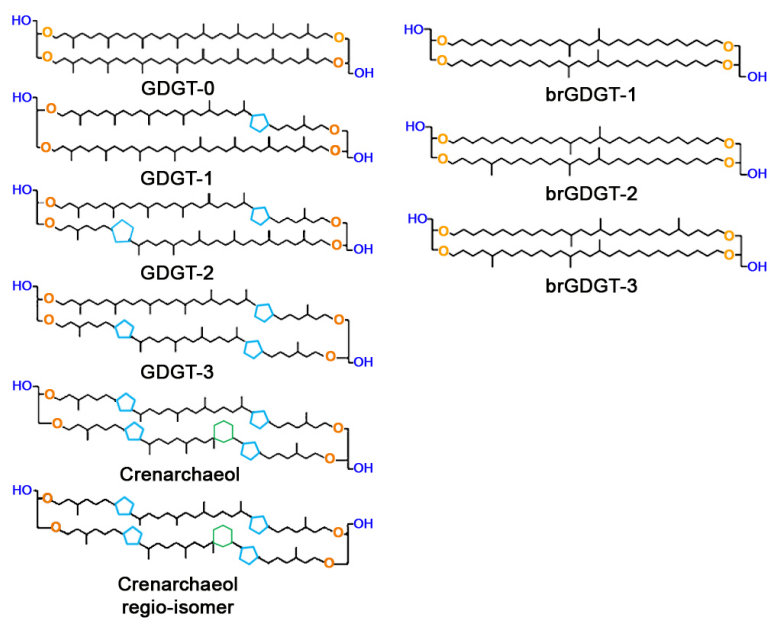


Fig. 1. Structure of isoprenoid GDGT (isoGDGTs) synthesized by marine Thaumarchaeota and branched GDGT (brGDGT). GDGT-0 (caldarchaeol) and crenarchaeol are the most abundant membrane lipids and are accompanied by smaller amounts of other isoprenoidal GDGTs (1, 2, 3 and region-isomer crenarchaeol), which is used to determine TEX₈₆ value.

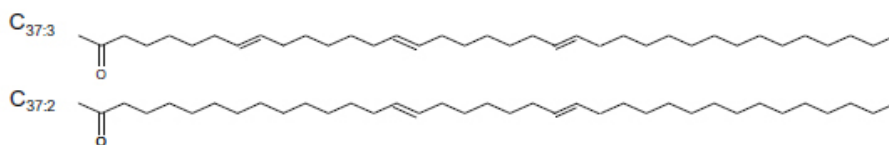


Fig. 2. Structure of unsaturated long-chain alkenone synthesized by marine Haptophyte algae (*Emiliania huxleyi* and *Gephyrocapsa oceanica*)

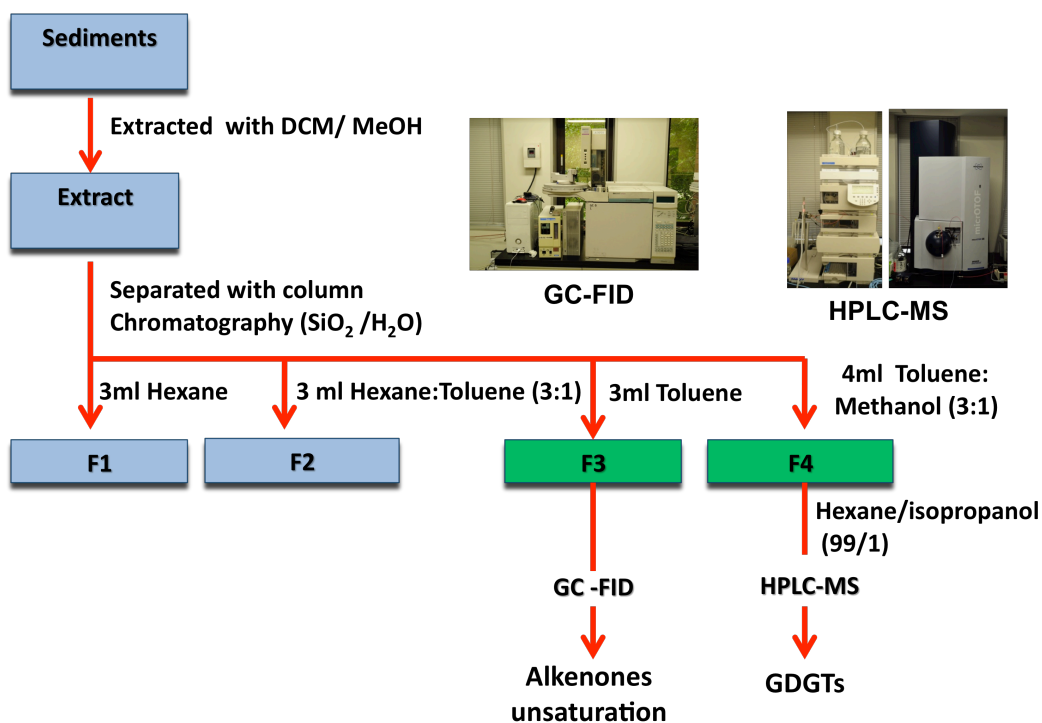


Fig. 3. Analytical scheme for lipids extraction and separation

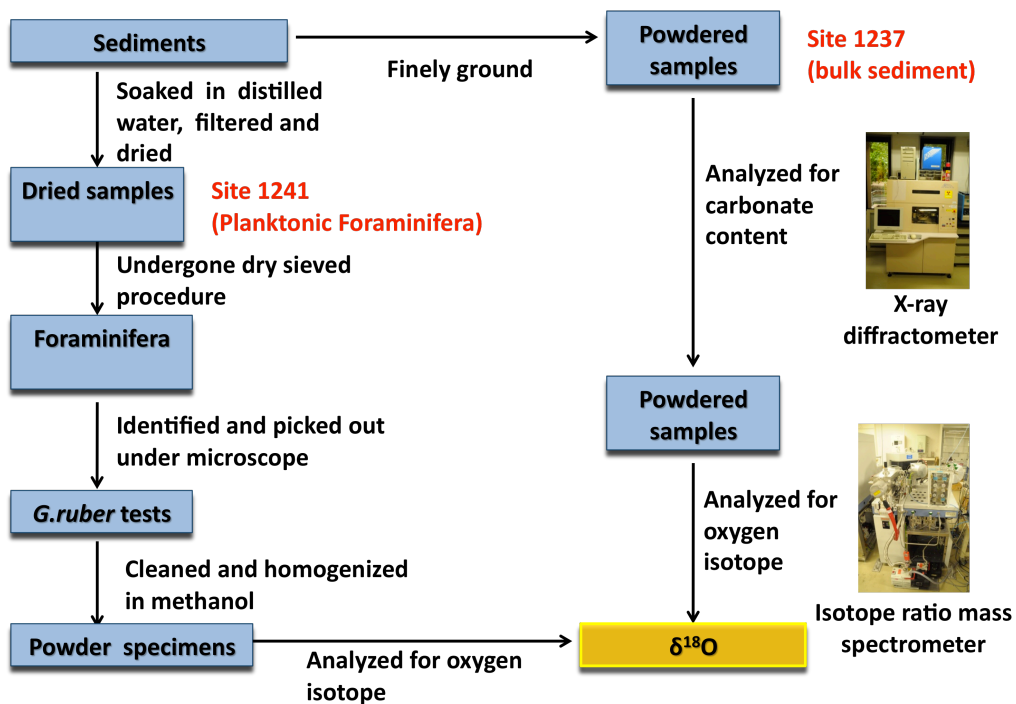


Fig. 4. Analytical scheme for $\delta^{18}\text{O}$ analysis

Table 1-3. GDGTs and TEX₈₆^H-derived temperature at ODP Site 1241 (EPWP)

Depth (mcd)	Age (ka)	GDGT-0 (ng/g)	GDGT-1 (ng/g)	GDGT-2 (ng/g)	GDGT-3 (ng/g)	Cren (ng/g)	Cren* (ng/g)	isoGDGTs (ug/g)	brGDGTs (ug/g)	BIT	TEX86	Temp. (°C)
0.1	1.8	316.9	58.1	84.9	11.9	534.4	45.2	1.1	0.04	0.1	0.7	28.4
0.1	3.3	311.0	73.0	96.2	11.6	466.5	44.0	1.0	0.03	0.1	0.7	26.8
0.2	4.8	341.7	80.2	98.1	11.8	555.8	51.1	1.2	0.04	0.1	0.7	26.5
0.2	6.4	424.5	90.1	105.7	11.4	634.3	55.0	1.4	0.05	0.1	0.7	26.0
0.3	7.9	341.9	85.7	103.6	12.4	528.4	53.6	1.2	0.06	0.1	0.7	26.5
0.3	10.5	912.8	234.8	297.1	32.3	1287.4	121.8	3.0	0.13	0.1	0.7	26.2
0.4	13.1	498.8	134.9	135.2	16.8	674.9	61.4	1.6	0.05	0.1	0.6	24.0
0.4	15.8	1139.5	394.6	360.9	45.1	1296.7	184.4	3.5	0.10	0.1	0.6	23.4
0.5	18.4	1265.3	460.5	414.3	47.7	1405.1	204.5	3.9	0.11	0.1	0.6	23.0
0.5	20.4	1288.5	461.3	424.6	56.8	1404.2	207.0	3.9	0.10	0.1	0.6	23.4
0.6	22.3	1121.3	461.7	422.1	29.6	1227.0	150.0	3.5	0.08	0.1	0.6	21.7
0.6	24.3	1474.1	480.4	542.0	64.4	1577.1	264.6	4.5	0.09	0.1	0.6	25.6
0.7	26.3	1018.0	342.5	322.3	31.9	1160.5	142.6	3.1	0.09	0.1	0.6	23.0
0.7	28.3	924.6	310.7	264.6	25.3	1079.6	112.8	2.8	0.08	0.1	0.6	21.6
0.8	30.2	1005.6	290.0	314.2	26.9	1129.8	129.6	3.0	0.07	0.1	0.6	24.3
0.8	32.2	540.7	162.2	161.9	15.4	658.5	53.9	1.6	0.03	0.0	0.6	22.8
0.9	34.2	455.1	134.6	122.5	12.2	529.8	47.7	1.3	0.04	0.1	0.6	22.2
0.9	36.1	496.1	143.7	134.1	10.8	606.7	57.9	1.5	0.04	0.1	0.6	22.7
1.0	38.1	385.6	103.3	86.9	10.0	474.3	38.5	1.1	0.04	0.1	0.6	21.7
1.0	39.9	397.9	112.6	115.3	11.6	473.5	48.6	1.2	0.04	0.1	0.6	23.9
1.1	41.7	850.4	270.0	242.2	23.4	1025.1	110.1	2.6	0.08	0.1	0.6	22.5
1.1	43.5	1022.6	376.8	339.3	34.7	1186.5	157.0	3.2	0.09	0.1	0.6	22.7
1.2	45.3	532.6	136.9	126.4	13.0	643.4	57.3	1.6	0.04	0.1	0.6	22.9
1.2	47.0	759.2	256.8	251.4	24.4	904.4	115.4	2.4	0.07	0.1	0.6	23.6
1.3	48.9	551.0	167.8	152.9	14.8	719.7	62.5	1.7	0.05	0.1	0.6	22.3
1.3	52.2	682.4	186.8	169.4	17.3	831.7	70.1	2.0	0.05	0.1	0.6	22.4
1.4	55.5	818.2	234.3	206.5	20.0	998.7	82.0	2.4	0.07	0.1	0.6	21.8
1.4	58.8	538.9	125.7	113.6	13.2	719.1	48.7	1.6	0.05	0.1	0.6	22.5
1.5	62.2	427.5	88.1	85.1	10.9	577.4	41.1	1.3	0.04	0.1	0.6	23.9
1.6	72.4	474.4	118.3	104.1	10.8	623.8	48.4	1.4	0.04	0.1	0.6	22.4
1.6	77.4	491.8	105.9	110.9	12.2	649.8	50.2	1.5	0.06	0.1	0.6	24.4
1.7	82.3	541.4	141.5	122.3	14.0	725.9	52.9	1.6	0.04	0.1	0.6	22.0
1.7	83.1	454.3	100.2	93.4	11.4	592.8	43.0	1.3	0.05	0.1	0.6	23.2
1.8	83.9	339.0	77.2	81.4	9.7	519.1	41.3	1.1	0.04	0.1	0.6	25.0
1.8	84.7	82.7	18.7	20.8	3.6	141.3	11.8	0.3	0.01	0.1	0.7	26.2
1.9	85.6	248.1	53.5	58.8	7.6	368.8	28.6	0.8	0.05	0.1	0.6	25.3
1.9	86.4	732.6	192.6	176.9	18.5	879.0	72.8	2.1	0.07	0.1	0.6	22.5
2.0	87.2	751.6	227.3	206.9	21.6	909.7	88.4	2.3	0.06	0.1	0.6	22.5
2.0	90.2	743.9	245.5	215.2	20.7	964.9	103.1	2.4	0.08	0.1	0.6	22.4
2.1	93.4	393.1	104.4	93.3	11.7	566.2	45.4	1.3	0.06	0.1	0.6	22.9
2.1	96.5	474.6	100.5	105.2	12.4	623.3	45.8	1.4	0.04	0.1	0.6	24.4
2.2	98.8	363.1	92.6	91.4	10.1	477.4	38.0	1.1	0.05	0.1	0.6	23.5

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Depth (mcd)	Age (ka)	GDGT-0 (ng/g)	GDGT-1 (ng/g)	GDGT-2 (ng/g)	GDGT-3 (ng/g)	Cren (ng/g)	Cren* (ng/g)	isoGDGTs (ug/g)	brGDGTs (ug/g)	BIT	TEX86	Temp. (°C)
2.2	101.0	258.5	56.0	53.3	7.1	386.0	28.6	0.8	0.05	0.1	0.6	24.1
2.3	103.3	401.8	82.0	90.2	10.2	583.0	45.9	1.3	0.06	0.1	0.6	25.4
2.3	107.1	772.5	238.0	255.9	26.0	966.1	113.6	2.5	0.09	0.1	0.6	24.6
2.4	112.0	518.5	131.0	121.4	12.3	700.9	57.7	1.6	0.08	0.1	0.6	23.1
2.4	115.7	335.3	77.8	77.2	10.1	527.1	41.9	1.1	0.07	0.1	0.6	24.6
2.5	119.0	522.8	149.6	151.7	15.7	770.1	74.0	1.7	0.06	0.1	0.6	24.3
2.5	122.3	351.3	104.7	128.0	13.7	554.2	64.1	1.3	0.06	0.1	0.7	26.4
2.6	125.6	384.2	109.5	151.3	15.3	691.4	68.8	1.5	0.05	0.1	0.7	27.3
2.6	128.8	785.5	260.7	302.0	39.9	1267.6	168.5	2.9	0.12	0.1	0.7	26.3
2.7	130.6	640.5	186.9	231.0	30.0	1009.7	124.4	2.3	0.08	0.1	0.7	26.9
2.7	131.9	1128.8	440.4	442.2	61.3	1532.6	223.6	3.9	0.10	0.1	0.6	24.5
2.8	133.0	800.2	252.5	236.0	25.7	993.9	108.1	2.5	0.07	0.1	0.6	23.1
2.8	135.1	962.4	305.8	283.2	36.6	1190.5	164.0	3.0	0.06	0.0	0.6	24.1
2.9	138.7	976.9	309.6	277.4	31.5	1249.7	139.9	3.1	0.08	0.1	0.6	23.0
2.9	142.2	1084.2	196.9	187.9	20.6	1498.0	58.4	3.1	0.02	0.0	0.6	22.2
3.0	143.3	891.0	168.8	142.0	14.0	1113.5	44.6	2.4	0.02	0.0	0.5	20.5
3.1	145.6	552.2	90.1	79.6	10.6	766.2	28.8	1.5	0.02	0.0	0.6	21.9
3.1	146.8	898.5	141.9	125.4	15.5	1229.0	43.8	2.5	0.02	0.0	0.6	21.7
3.2	147.9	959.7	175.4	149.1	16.4	1308.9	49.1	2.7	0.03	0.0	0.6	20.9

Table 1-2. Alkenones and U^K_{37'}-derived temperature at ODP Site 1241 (EPWP)

Depth (mcd)	Age (ka)	37:3 MK (ug/g)	37:2 MK (ug/g)	Alkenones (ug/g)	UK37'	Temp. (°C)
0.05	1.78	0.0	0.2	0.5	0.9	25.8
0.1	3.31	0.1	0.5	0.8	0.9	25.3
0.15	4.83	0.0	0.3	0.6	0.9	24.6
0.2	6.36	0.0	0.3	0.6	0.9	26.1
0.25	7.88	0.0	0.4	0.9	0.9	25.7
0.3	10.46	0.1	0.5	1.1	0.9	24.4
0.35	13.11	0.1	1.0	2.2	0.9	25.6
0.4	15.77	0.3	2.7	5.9	0.9	25.6
0.45	18.39	0.3	2.4	5.3	0.9	25.4
0.5	20.36	0.3	2.5	5.6	0.9	24.9
0.55	22.34	0.2	2.6	5.4	0.9	26.0
0.6	24.31	0.2	1.6	3.5	0.9	25.0
0.65	26.28	0.2	1.5	3.4	0.9	25.6
0.7	28.25	0.1	1.0	2.1	0.9	25.4
0.75	30.22	0.1	1.3	2.9	0.9	25.3
0.8	32.20	0.1	1.1	2.4	0.9	25.6
0.85	34.17	0.1	1.0	2.1	0.9	25.8
0.9	36.14	0.1	1.8	3.8	0.9	26.1
0.95	38.10	0.2	1.0	2.1	0.9	24.1
1	39.89	0.1	1.1	2.4	0.9	25.5
1.05	41.68	0.1	1.3	2.7	0.9	25.8
1.1	43.46	0.1	1.5	3.2	0.9	25.9
1.15	45.25	0.1	0.8	1.7	0.9	25.9
1.2	47.04	0.1	1.3	2.9	0.9	25.8
1.25	48.88	0.1	1.2	2.4	0.9	26.2
1.3	52.20	0.1	1.3	2.7	0.9	25.8
1.35	55.52	0.0	1.8	3.6	1.0	27.5
1.4	58.84	0.1	1.8	3.5	1.0	27.2
1.45	62.23	0.1	1.9	3.6	1.0	27.1
1.55	72.36	0.1	1.3	2.7	1.0	27.1
1.6	77.42	0.1	1.3	2.7	0.9	26.7
1.65	82.34	0.1	1.8	3.7	0.9	26.5
1.7	83.14	0.1	1.0	2.1	0.9	26.3
1.75	83.94	0.0	0.4	0.7	1.0	27.3
1.85	85.55	0.0	1.0	2.0	1.0	27.3
1.9	86.36	0.1	1.8	3.5	0.9	26.7
1.95	87.16	0.1	2.1	4.2	1.0	27.2
2	90.23	0.1	1.7	3.3	1.0	27.2
2.05	93.36	0.0	1.3	2.5	1.0	27.9
2.1	96.49	0.0	1.0	1.8	1.0	27.8

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Depth (mcd)	Age (ka)	37:3 MK (ug/g)	37:2 MK (ug/g)	Alkenones (ug/g)	UK37'	Temp. (°C)
2.15	98.75	0.0	1.2	1.2	1.0	27.1
2.2	101.02	0.0	0.5	1.0	1.0	27.7
2.25	103.29	0.1	0.9	0.9	0.9	26.6
2.3	107.09	0.0	1.1	2.7	1.0	27.8
2.35	112.00	0.0	0.9	1.7	1.0	27.2
2.45	119.00	0.0	0.8	0.8	1.0	27.4
2.5	122.27	0.0	0.4	0.8	1.0	27.5
2.55	125.55	0.0	0.4	0.9	1.0	27.5
2.6	128.83	0.0	1.6	3.2	1.0	27.8
2.65	130.60	0.0	1.2	2.3	1.0	27.8
2.7	131.92	0.1	2.1	4.3	1.0	27.5
2.75	133.01	0.1	1.8	3.8	1.0	27.4
2.8	135.10	0.1	2.2	4.7	0.9	26.7
2.85	138.69	0.1	2.4	4.9	1.0	27.4
2.9	142.19	0.1	2.6	5.2	1.0	27.5
2.95	143.34	0.1	2.5	5.1	1.0	27.4
3.05	145.63	0.1	2.4	4.9	1.0	27.3
3.1	146.78	0.1	2.0	4.2	1.0	27.2
3.15	147.92	0.1	3.1	6.5	1.0	27.3

Table 1-3. GDGTs and TEX₈₆^H-derived temperature at ODP Site 1239 (EEP)

Depth (mcd)	Age (ka)	GDGT-0 (ng/g)	GDGT-1 (ng/g)	GDGT-2 (ng/g)	GDGT-3 (ng/g)	Cren (ng/g)	Cren* (ng/g)	isoGDGTs (ug/g)	brGDGTs (ug/g)	BIT	TEX86	Temp. (°C)
0.0	0.4	953.7	259.8	254.6	40.7	1314.0	154.8	3.0	0.03	0.02	0.6	25.1
0.0	0.9	1185.0	336.6	322.8	48.4	1701.8	186.0	3.8	0.03	0.02	0.6	24.6
0.1	1.7	735.8	200.3	207.6	35.9	1097.4	118.6	2.4	0.02	0.02	0.6	25.5
0.1	2.2	565.9	141.1	165.6	30.0	864.0	83.5	1.9	0.02	0.02	0.7	26.4
0.1	2.5	622.2	166.0	174.4	30.6	911.7	102.9	2.0	0.02	0.02	0.6	25.8
0.1	3.0	1168.9	454.0	493.1	65.8	1609.4	251.3	4.0	0.02	0.01	0.6	25.4
0.2	3.5	958.9	294.9	313.6	43.7	1348.5	174.1	3.1	0.02	0.02	0.6	25.5
0.2	3.9	1202.2	438.5	485.0	63.2	1522.5	268.5	4.0	0.02	0.02	0.7	25.8
0.2	4.5	1164.2	349.4	389.5	58.5	1649.8	195.7	3.8	0.02	0.01	0.6	25.7
0.2	4.8	1065.9	361.4	413.4	54.0	1425.6	228.1	3.5	0.02	0.01	0.7	26.2
0.2	5.2	856.6	281.9	312.7	43.2	1152.2	154.7	2.8	0.02	0.02	0.6	25.5
0.3	5.6	1180.1	442.2	471.9	62.4	1536.9	254.1	3.9	0.03	0.02	0.6	25.4
0.3	6.1	1097.4	307.2	325.2	56.0	1691.7	181.8	3.7	0.03	0.02	0.6	25.7
0.3	6.7	1324.8	367.5	423.2	61.0	1833.9	219.6	4.2	0.03	0.02	0.7	26.1
0.3	6.9	1155.2	360.1	358.8	54.9	1598.1	225.7	3.8	0.03	0.02	0.6	25.3
0.3	7.4	1072.1	375.3	401.6	57.0	1416.3	213.0	3.5	0.03	0.02	0.6	25.4
0.4	7.8	883.9	259.3	277.8	57.5	1573.3	170.7	3.2	0.03	0.02	0.7	26.3
0.4	8.2	1255.8	399.2	437.6	62.6	1689.5	222.2	4.1	0.03	0.02	0.6	25.5
0.4	8.7	2067.1	717.9	760.8	96.0	2738.7	423.7	6.8	0.04	0.01	0.6	25.4
0.4	9.1	899.8	244.9	263.4	45.8	1417.9	162.6	3.0	0.02	0.01	0.7	26.2
0.4	9.5	1627.5	615.3	659.2	95.1	2140.8	333.0	5.5	0.03	0.02	0.6	25.3
0.5	10.0	2085.4	738.2	761.7	105.8	2820.1	410.9	6.9	0.04	0.01	0.6	25.1
0.5	10.4	2035.8	611.7	634.1	100.2	3134.2	365.1	6.9	0.05	0.01	0.6	25.5
0.5	10.8	2225.2	623.1	745.7	111.5	3402.4	461.9	7.6	0.05	0.01	0.7	27.1
0.6	12.5	2211.0	881.8	875.9	155.9	2530.3	471.4	7.1	0.04	0.01	0.6	24.9
0.6	13.2	1693.4	517.7	581.5	92.3	2287.0	291.3	5.5	0.04	0.02	0.7	25.8
0.7	14.7	1812.7	729.7	782.2	127.0	2292.8	427.8	6.2	0.03	0.01	0.6	25.7
0.7	15.1	1853.4	577.9	578.6	97.1	2326.5	471.7	5.9	0.04	0.02	0.7	26.5
0.8	17.3	3906.0	1363.7	1225.7	217.6	4260.3	786.8	11.8	0.05	0.01	0.6	24.4
0.8	17.5	2561.4	854.9	769.1	124.5	2727.9	420.7	7.5	0.04	0.01	0.6	23.7
0.8	18.2	1845.1	599.7	502.9	79.7	1991.8	223.8	5.2	0.03	0.02	0.6	22.1
0.9	18.8	2363.3	826.4	731.3	123.5	2606.3	368.4	7.0	0.04	0.01	0.6	23.3
0.9	20.6	2207.1	732.9	615.4	103.9	2361.2	272.0	6.3	0.04	0.01	0.6	22.2
0.9	21.7	2698.7	867.3	731.2	118.8	2803.2	351.2	7.6	0.04	0.01	0.6	22.5
1.0	23.2	3490.3	1244.3	1067.3	188.2	3526.9	503.5	10.0	0.05	0.01	0.6	22.7
1.0	23.9	2910.7	936.4	754.0	113.5	3086.4	369.6	8.2	0.04	0.01	0.6	21.9
1.0	24.3	3527.3	1234.7	1052.1	170.0	3717.7	520.7	10.2	0.05	0.01	0.6	22.7
1.1	26.1	3514.5	1273.2	1038.9	170.3	3481.9	472.4	10.0	0.04	0.01	0.6	21.9
1.1	28.3	2752.8	939.2	769.8	126.0	2847.6	354.6	7.8	0.04	0.01	0.6	22.0
1.1	29.1	2661.7	768.3	598.4	131.5	3026.2	377.1	7.6	0.04	0.01	0.6	22.9
1.2	29.8	1978.0	631.5	529.3	91.6	2052.9	221.9	5.5	0.03	0.02	0.6	22.0
1.2	30.2	1532.7	440.4	332.0	58.5	1690.6	162.9	4.2	0.03	0.02	0.6	21.2

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Depth (mcd)	Age (ka)	GDGT-0 (ng/g)	GDGT-1 (ng/g)	GDGT-2 (ng/g)	GDGT-3 (ng/g)	Cren (ng/g)	Cren* (ng/g)	isoGDGTs (ug/g)	brGDGTs (ug/g)	BIT	TEX86	Temp. (°C)
1.2	30.5	2450.0	798.8	629.5	102.5	2577.2	280.8	6.8	0.04	0.01	0.6	21.3
1.2	31.6	2216.8	565.2	435.0	80.0	2599.3	198.3	6.1	0.04	0.02	0.6	21.3
1.2	30.9	1352.7	311.6	241.4	46.7	1624.9	118.6	3.7	0.02	0.01	0.6	21.7
1.2	31.6	2166.7	624.5	503.6	82.3	2613.1	220.8	6.2	0.04	0.02	0.6	21.6
1.2	32.4	1893.6	583.7	467.6	71.5	2102.9	194.1	5.3	0.03	0.02	0.6	21.2
1.3	33.5	3099.7	1005.4	756.3	118.0	3201.9	341.2	8.5	0.05	0.02	0.5	20.7
1.3	33.8	2290.0	730.1	572.8	87.0	2642.0	280.2	6.6	0.04	0.01	0.6	21.5
1.3	35.3	1808.2	581.0	480.0	72.0	1992.8	223.7	5.2	0.03	0.02	0.6	22.0
1.4	36.8	1841.8	516.9	412.5	60.5	2071.0	196.7	5.1	0.03	0.01	0.6	21.6
1.4	37.2	1847.1	583.7	490.0	75.2	2081.9	254.6	5.3	0.03	0.02	0.6	22.6
1.4	38.3	4446.4	1315.5	1063.2	155.3	4874.9	544.9	12.4	0.06	0.01	0.6	22.0
1.4	39.7	3265.4	1000.0	847.2	124.3	4503.1	374.8	10.1	0.06	0.01	0.6	22.1
1.5	40.5	3234.4	821.8	637.8	111.1	3907.4	330.5	9.0	0.06	0.02	0.6	21.8
1.5	40.8	2094.9	626.9	499.8	86.3	2525.0	277.0	6.1	0.04	0.02	0.6	22.4
1.5	41.2	3404.2	1132.0	917.8	127.8	3676.3	496.3	9.8	0.05	0.01	0.6	22.2
1.5	42.7	3410.7	1165.4	927.8	134.7	3533.9	461.5	9.6	0.05	0.01	0.6	21.7
1.6	44.1	4504.5	1258.6	1001.4	149.3	5065.2	506.2	12.5	0.06	0.01	0.6	21.8
1.6	44.9	1925.9	643.1	534.3	81.6	2129.3	260.1	5.6	0.03	0.01	0.6	22.2
1.6	45.6	2522.4	784.5	663.7	98.2	2805.9	329.1	7.2	0.04	0.01	0.6	22.5
1.7	47.8	1788.8	605.7	519.8	75.0	2022.4	229.7	5.2	0.03	0.02	0.6	22.2
1.7	48.6	714.6	172.0	135.4	26.4	884.0	62.4	2.0	0.01	0.02	0.6	21.7
1.7	49.3	728.7	172.0	145.0	30.8	954.5	75.6	2.1	0.02	0.02	0.6	23.1
1.7	50.0	589.9	129.8	108.2	23.4	759.3	61.2	1.7	0.01	0.02	0.6	23.3
1.8	51.9	2012.8	756.8	646.5	104.3	2112.3	329.6	6.0	0.04	0.02	0.6	22.8
1.8	52.2	777.1	192.2	152.0	27.4	939.2	82.2	2.2	0.02	0.02	0.6	22.2
1.8	53.7	317.1	69.5	56.1	12.8	420.7	38.1	0.9	0.01	0.02	0.6	23.7
1.8	54.4	286.7	71.4	55.1	12.4	389.6	34.6	0.8	0.01	0.02	0.6	22.8
1.9	55.5	1951.1	570.4	455.8	77.4	2260.2	254.4	5.6	0.04	0.02	0.6	22.4
1.9	56.1	2088.9	655.7	525.4	85.4	2254.6	254.1	5.9	0.04	0.02	0.6	21.8
1.9	57.8	1832.6	586.2	477.1	83.2	2056.8	236.7	5.3	0.03	0.02	0.6	22.2
2.0	59.2	2083.6	636.9	556.1	88.7	2538.0	251.4	6.2	0.04	0.02	0.6	22.7
2.0	59.6	1586.7	537.9	443.1	70.2	1786.1	223.3	4.6	0.04	0.02	0.6	22.3
2.0	60.7	2110.6	766.2	654.7	101.6	2456.3	350.2	6.4	0.04	0.02	0.6	23.0
2.0	62.2	1605.1	549.9	466.9	72.1	1897.5	265.8	4.9	0.03	0.02	0.6	23.1
2.1	63.3	1938.4	724.0	639.6	98.7	2066.9	319.2	5.8	0.04	0.02	0.6	23.1
2.1	63.6	1568.2	555.8	487.6	70.1	1834.2	246.3	4.8	0.02	0.01	0.6	23.0
2.1	65.1	2134.1	683.1	587.2	94.7	2294.2	269.8	6.1	0.04	0.02	0.6	22.5
2.2	66.6	1624.9	543.4	446.6	69.0	1878.1	230.9	4.8	0.03	0.02	0.6	22.4
2.2	67.0	1682.0	454.7	338.5	56.6	1964.8	191.7	4.7	0.04	0.02	0.6	21.6
2.2	67.3	2020.6	726.6	607.4	92.6	2292.3	358.2	6.1	0.04	0.02	0.6	23.1
2.2	68.1	2901.1	896.4	728.0	100.2	3344.2	284.4	8.3	0.05	0.01	0.6	21.0
2.2	69.6	1819.2	629.6	506.9	73.7	2038.8	252.4	5.3	0.03	0.01	0.6	21.9
2.3	70.9	2246.4	756.3	622.9	100.2	2317.9	291.5	6.3	0.04	0.02	0.6	22.1
2.3	71.3	1826.6	687.2	567.5	89.5	1887.3	259.9	5.3	0.03	0.01	0.6	22.0

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Depth (mcd)	Age (ka)	GDGT-0 (ng/g)	GDGT-1 (ng/g)	GDGT-2 (ng/g)	GDGT-3 (ng/g)	Cren (ng/g)	Cren* (ng/g)	isoGDGTs (ug/g)	brGDGTs (ug/g)	BIT	TEX86	Temp. (°C)
2.3	73.1	1608.0	494.9	411.4	57.3	1828.1	226.0	4.6	0.03	0.02	0.6	22.6
2.3	73.9	2069.7	735.6	630.6	96.0	2291.1	363.3	6.2	0.04	0.02	0.6	23.3
2.4	74.8	1409.8	539.4	439.1	60.5	1674.6	255.1	4.4	0.02	0.01	0.6	22.6
2.4	75.2	1902.2	625.8	551.8	79.7	2151.7	255.0	5.6	0.04	0.02	0.6	22.7
2.4	76.5	1725.1	607.0	532.3	71.1	2096.4	406.2	5.4	0.04	0.02	0.6	24.6
2.4	78.3	1869.2	780.0	738.9	100.7	2260.4	307.2	6.1	0.04	0.02	0.6	23.2
2.5	79.6	1365.2	447.7	416.5	55.7	1660.7	192.1	4.1	0.03	0.02	0.6	23.3
2.5	80.0	1266.0	379.0	348.3	44.1	1579.4	184.9	3.8	0.03	0.02	0.6	23.6
2.5	81.7	1939.2	660.6	574.8	83.5	2385.5	476.6	6.1	0.03	0.01	0.6	25.0
2.6	83.5	1605.8	533.2	470.0	67.2	1741.8	255.4	4.7	0.03	0.02	0.6	23.3
2.6	83.9	2116.7	677.5	558.2	85.5	2363.5	270.8	6.1	0.05	0.02	0.6	22.1
2.6	85.2	1728.9	639.0	563.3	85.4	1931.4	320.1	5.3	0.04	0.02	0.6	23.6
2.6	86.9	2194.2	750.6	603.0	87.1	2213.6	248.6	6.1	0.03	0.01	0.6	21.1
2.7	88.3	2191.8	718.6	575.8	83.0	2371.1	285.6	6.2	0.04	0.02	0.6	21.8
2.7	88.7	1458.9	557.8	479.3	77.5	1620.8	237.5	4.4	0.03	0.02	0.6	22.8
2.7	90.4	2377.3	879.9	758.2	121.3	2732.3	427.7	7.3	0.04	0.02	0.6	23.3
2.8	92.1	1578.5	605.9	558.8	73.3	1985.0	299.9	5.1	0.03	0.01	0.6	23.7
2.8	92.6	1761.6	639.2	573.3	84.6	1934.3	306.0	5.3	0.04	0.02	0.6	23.5
2.8	93.9	2022.2	726.4	670.6	98.8	2420.9	367.4	6.3	0.03	0.01	0.6	23.9
2.8	95.6	2743.6	820.4	751.1	102.5	3801.4	409.1	8.6	0.05	0.01	0.6	23.7
2.9	96.9	1796.5	658.7	607.3	90.4	2056.0	336.2	5.5	0.05	0.02	0.6	24.0
2.9	97.3	2270.9	898.0	833.0	114.1	2768.7	449.3	7.3	0.04	0.02	0.6	23.8
2.9	99.1	1360.0	510.4	445.9	68.1	1598.7	254.1	4.2	0.03	0.02	0.6	23.5
3.0	100.8	1483.4	535.7	470.8	74.2	1761.7	286.0	4.6	0.03	0.02	0.6	23.8
3.0	101.3	2364.1	898.4	817.3	135.2	2566.0	426.9	7.2	0.06	0.02	0.6	23.7
3.0	102.6	1662.4	572.5	475.1	78.3	1967.3	250.4	5.0	0.04	0.02	0.6	22.6
3.0	104.3	2381.3	902.6	805.5	132.8	2667.5	432.8	7.3	0.05	0.02	0.6	23.6
3.1	105.6	1941.4	732.1	633.7	111.2	2058.5	347.9	5.8	0.05	0.02	0.6	23.4
3.1	106.0	1768.3	662.2	586.4	93.0	2028.3	323.6	5.5	0.04	0.02	0.6	23.5
3.1	107.8	2188.2	817.8	718.0	114.6	2573.0	385.1	6.8	0.05	0.02	0.6	23.3
3.2	109.5	1917.9	691.0	599.1	95.7	2233.9	345.5	5.9	0.03	0.02	0.6	23.5
3.2	109.9	1772.1	601.0	518.5	83.8	2038.8	308.9	5.3	0.05	0.02	0.6	23.6
3.2	111.2	1463.2	524.9	475.7	77.7	1806.8	276.7	4.6	0.04	0.02	0.6	24.0
3.2	112.1	1293.9	423.4	381.6	59.2	1617.6	237.4	4.0	0.03	0.02	0.6	24.2
3.2	112.7	1723.5	646.7	570.6	86.0	2039.8	288.0	5.4	0.04	0.02	0.6	23.1
3.3	113.4	2177.9	814.1	782.5	124.4	2797.4	478.3	7.2	0.05	0.02	0.6	24.9
3.3	113.7	1989.5	747.2	707.6	121.5	2254.9	433.1	6.3	0.04	0.02	0.6	24.8
3.3	114.0	1387.8	532.9	501.2	75.7	1788.5	288.8	4.6	0.03	0.02	0.6	24.4
3.3	114.7	1822.5	707.6	681.1	110.7	2223.5	449.6	6.0	0.03	0.01	0.6	25.2
3.3	115.3	2029.9	786.9	726.5	122.3	2849.5	495.5	7.0	0.05	0.02	0.6	24.9
3.3	116.0	1409.5	507.5	526.2	68.3	2062.8	292.9	4.9	0.03	0.01	0.6	25.2
3.4	117.3	1704.6	632.5	696.0	108.3	2171.5	434.1	5.7	0.04	0.02	0.7	26.3
3.5	120.5	891.6	294.0	341.9	48.4	1391.1	206.6	3.2	0.02	0.02	0.7	26.7
3.6	123.8	1596.2	644.4	731.3	111.0	2241.2	462.9	5.8	0.05	0.02	0.7	26.7

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Depth (mcd)	Age (ka)	GDGT-0 (ng/g)	GDGT-1 (ng/g)	GDGT-2 (ng/g)	GDGT-3 (ng/g)	Cren (ng/g)	Cren* (ng/g)	isoGDGTs (ug/g)	brGDGTs (ug/g)	BIT	TEX86	Temp. (°C)
3.7	127.1	1682.5	641.9	749.5	117.2	2479.7	502.9	6.2	0.05	0.02	0.7	27.2
3.8	130.3	2327.4	986.1	1132.3	216.2	3181.5	747.2	8.6	0.05	0.02	0.7	27.1
3.9	133.6	2843.2	1241.0	1271.4	326.0	3304.1	802.9	9.8	0.07	0.02	0.7	26.2
4.0	137.3	2536.2	1026.4	930.1	202.3	2763.2	488.2	7.9	0.05	0.02	0.6	24.0
4.1	141.9	2240.2	488.3	443.7	72.9	3655.4	177.2	7.1	0.06	0.02	0.6	22.8
4.2	147.3	1125.0	194.8	159.3	21.6	1612.8	56.0	3.2	0.02	0.01	0.5	20.8
4.3	150.9	793.5	162.1	122.6	19.4	1023.6	47.0	2.2	0.03	0.03	0.5	20.2
4.4	155.5	1511.2	274.5	206.4	29.2	2151.6	77.1	4.2	0.03	0.02	0.5	19.9
4.5	160.0	1018.7	206.5	154.6	21.5	1399.2	60.5	2.9	0.02	0.02	0.5	20.0
4.6	164.5	1014.2	187.3	154.6	19.7	1308.1	66.5	2.8	0.03	0.02	0.6	21.5
4.7	169.1	1385.5	307.6	246.7	35.5	2241.6	92.3	4.3	0.04	0.02	0.5	20.8
4.8	173.6	1249.2	271.0	204.7	24.6	1873.1	76.3	3.7	0.03	0.02	0.5	19.7
4.9	178.6	772.0	159.8	131.4	17.7	1110.6	47.3	2.2	0.03	0.03	0.6	20.9
4.9	179.5	1886.3	394.4	307.1	41.4	2904.1	117.4	5.7	0.05	0.02	0.5	20.4
5.1	187.6	1897.7	398.1	320.7	36.5	3292.6	117.5	6.1	0.05	0.02	0.5	20.5
5.2	190.0	375.5	89.1	73.1	8.7	607.2	29.0	1.2	0.01	0.02	0.6	21.1
5.3	193.4	762.3	190.4	174.3	19.3	1483.8	74.1	2.7	0.03	0.02	0.6	22.6
5.4	196.2	792.6	206.4	208.6	27.4	1462.0	101.5	2.8	0.06	0.04	0.6	24.4
5.5	199.0	1405.1	340.2	324.7	35.8	2915.7	141.9	5.2	0.05	0.02	0.6	23.2
5.6	201.2	697.3	161.8	150.3	16.5	1327.9	70.7	2.4	0.02	0.01	0.6	23.2
5.6	201.8	687.6	160.6	162.8	17.2	1404.8	74.6	2.5	0.02	0.02	0.6	24.1
5.7	204.6	2138.2	492.5	467.0	51.1	4189.7	222.7	7.6	0.05	0.01	0.6	23.5
5.8	207.4	1147.0	280.6	276.8	28.7	2360.9	125.9	4.2	0.04	0.01	0.6	23.7
5.9	210.2	2360.2	594.2	531.6	54.7	4773.6	249.1	8.6	0.04	0.01	0.6	22.6
6.0	213.0	950.5	235.6	258.6	23.9	2045.3	120.1	3.6	0.02	0.01	0.6	24.9
6.1	215.6	1110.2	271.1	289.6	29.4	2300.6	143.2	4.1	0.03	0.01	0.6	24.9
6.2	218.6	1901.8	526.1	513.1	46.8	3960.7	221.2	7.2	0.04	0.01	0.6	23.3
6.3	221.4	2058.9	483.9	500.6	52.2	4405.1	223.8	7.7	0.06	0.01	0.6	24.2
6.4	224.2	3070.5	681.6	587.8	61.5	5866.8	203.0	10.5	0.08	0.01	0.6	21.1
6.5	226.5	3308.6	738.5	688.6	82.5	6972.7	268.1	12.1	0.08	0.01	0.6	22.7
6.6	228.7	2423.2	577.2	475.1	65.2	4845.0	198.0	8.6	0.06	0.01	0.6	21.4
6.7	231.0	1116.2	276.1	229.7	34.4	2222.1	101.8	4.0	0.03	0.01	0.6	21.9
6.8	232.2	44.3	12.1	9.9	1.2	68.7	4.3	0.1	0.00	0.04	0.6	21.5
6.8	233.3	243.2	59.3	55.2	8.1	394.3	19.9	0.8	0.01	0.02	0.6	22.6
6.9	235.6	1288.8	273.2	211.1	27.7	1921.5	73.9	3.8	0.04	0.02	0.5	19.9
7.0	237.6	373.9	84.7	66.3	9.6	583.2	26.2	1.1	0.01	0.02	0.5	20.7
7.0	237.9	2196.4	484.5	388.8	47.6	3956.2	141.9	7.2	0.06	0.02	0.5	20.5
7.1	240.2	2316.5	512.2	413.3	52.9	4275.8	173.8	7.7	0.06	0.01	0.6	21.1
7.2	242.4	2406.1	641.0	671.4	84.7	5875.7	287.4	10.0	0.07	0.01	0.6	24.4
7.3	243.6	2782.5	619.7	616.0	71.8	5564.6	269.7	9.9	0.06	0.01	0.6	23.8
7.3	245.4	2001.1	389.7	348.3	39.5	3878.7	167.3	6.8	0.04	0.01	0.6	22.8
7.5	248.6	1156.0	212.0	173.0	20.9	1778.0	77.7	3.4	0.03	0.02	0.6	21.5
7.5	251.0	2883.7	532.0	420.9	47.2	4173.2	168.8	8.2	0.05	0.01	0.5	20.6
7.7	254.6	1429.9	252.8	208.6	23.4	2028.4	84.0	4.0	0.03	0.01	0.6	21.1

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Depth (mcd)	Age (ka)	GDGT-0 (ng/g)	GDGT-1 (ng/g)	GDGT-2 (ng/g)	GDGT-3 (ng/g)	Cren (ng/g)	Cren* (ng/g)	isoGDGTs (ug/g)	brGDGTs (ug/g)	BIT	TEX86	Temp. (°C)
7.7	257.0	1790.2	303.0	230.4	30.3	2504.7	106.8	5.0	0.03	0.01	0.5	20.7
7.9	260.6	1957.5	414.2	322.7	40.9	3050.4	146.4	5.9	0.04	0.01	0.6	20.9
7.9	262.1	1430.9	268.4	207.1	26.1	2163.5	96.7	4.2	0.03	0.01	0.6	20.9
8.0	266.3	1370.8	268.8	218.1	26.1	2031.2	102.9	4.0	0.04	0.02	0.6	21.6
8.2	270.6	1804.2	379.7	288.4	30.2	2543.7	114.2	5.2	0.05	0.02	0.5	19.9
8.3	274.8	1382.4	290.9	236.7	24.6	2075.3	99.5	4.1	0.03	0.02	0.6	21.0
8.5	279.0	1344.1	288.4	226.9	25.5	2006.7	104.9	4.0	0.04	0.02	0.6	21.0
8.6	283.2	914.4	254.0	204.7	29.3	1303.3	88.0	2.8	0.03	0.02	0.6	21.3
8.6	283.5	2973.9	761.0	640.0	76.8	5954.1	257.0	10.7	0.07	0.01	0.6	21.4
8.7	286.5	3746.1	821.8	741.2	86.4	7215.2	266.9	12.9	0.07	0.01	0.6	22.0
8.7	286.8	197.7	54.0	50.9	6.8	389.9	25.3	0.7	0.01	0.02	0.6	23.7
8.8	288.8	1689.8	373.6	293.5	38.7	2993.8	118.6	5.5	0.05	0.02	0.5	20.7
8.9	290.8	1800.3	391.6	306.7	46.0	3185.3	121.9	5.9	0.06	0.02	0.5	20.7
9.0	292.9	2288.2	462.4	368.5	51.0	3760.2	157.1	7.1	0.06	0.02	0.6	21.1
9.1	294.9	2936.0	604.4	496.4	70.6	5218.0	201.7	9.5	0.08	0.01	0.6	21.4
9.2	297.0	2497.9	549.0	388.6	58.4	4138.3	168.1	7.8	0.06	0.01	0.5	19.6
9.3	299.2	2130.1	445.3	361.1	50.2	3859.8	150.3	7.0	0.07	0.02	0.6	21.3
9.4	301.3	2106.5	477.6	414.8	47.7	4432.8	173.4	7.7	0.06	0.01	0.6	22.0
9.5	303.3	2184.2	449.0	326.9	43.8	3794.7	141.1	6.9	0.05	0.01	0.5	19.9
9.6	305.4	1412.0	320.3	254.1	35.3	2456.3	110.0	4.6	0.06	0.02	0.6	21.1
9.7	307.4	1205.1	319.2	276.5	38.0	1907.3	121.5	3.9	0.12	0.06	0.6	22.3
9.8	309.5	1497.2	417.3	408.2	57.9	3032.3	224.4	5.6	0.10	0.03	0.6	24.6
9.9	311.5	2961.8	681.3	582.0	71.5	6645.5	243.7	11.2	0.09	0.01	0.6	21.8
10.1	315.6	1159.4	291.7	261.7	36.2	2667.8	142.6	4.6	0.05	0.02	0.6	23.5
10.2	317.7	1428.4	391.4	382.0	44.1	3595.1	180.2	6.0	0.05	0.01	0.6	23.8
10.3	319.8	1543.7	426.7	390.4	48.2	3790.6	203.8	6.4	0.06	0.02	0.6	23.5
10.4	321.8	1310.5	353.3	384.2	43.4	3407.7	190.0	5.7	0.06	0.02	0.6	25.2
10.5	323.9	1031.3	271.5	293.3	35.1	2620.1	159.4	4.4	0.04	0.02	0.6	25.5
10.6	325.9	1618.7	523.6	564.1	87.4	4721.8	331.0	7.8	0.08	0.02	0.7	25.9
10.7	328.0	1770.4	530.6	579.9	89.0	5512.9	290.3	8.8	0.08	0.01	0.6	25.5
10.8	330.2	2393.3	689.2	675.5	95.1	6678.8	313.4	10.8	0.08	0.01	0.6	24.0
10.9	332.3	2788.7	679.6	629.7	76.9	6589.0	256.9	11.0	0.09	0.01	0.6	22.7
11.0	334.3	1716.9	399.0	333.6	43.8	3448.6	120.3	6.1	0.06	0.02	0.6	21.1
11.1	336.4	1562.8	350.8	295.6	36.5	2947.8	110.2	5.3	0.06	0.02	0.6	21.3
11.2	338.4	2616.5	631.0	587.9	69.2	5765.1	232.6	9.9	0.07	0.01	0.6	22.7
11.3	340.5	2676.4	649.5	671.0	79.7	6763.1	272.0	11.1	0.07	0.01	0.6	24.0
11.4	344.2	1780.5	407.3	340.9	38.1	3540.0	135.1	6.2	0.05	0.01	0.6	21.3
11.4	345.3	2147.4	516.1	382.1	43.9	4206.7	131.3	7.4	0.06	0.01	0.5	19.1
11.5	350.9	1917.0	464.9	355.1	43.0	3543.2	138.5	6.5	0.06	0.02	0.5	20.1
11.6	356.6	2364.0	538.2	428.6	47.0	4370.0	150.9	7.9	0.06	0.01	0.5	20.2
11.7	362.3	1423.1	346.1	278.6	38.4	2416.7	110.0	4.6	0.07	0.03	0.6	21.0
11.8	368.0	1614.4	364.8	256.4	33.4	2647.8	98.3	5.0	0.06	0.02	0.5	18.9
11.9	373.7	1554.8	347.2	241.3	26.6	2682.1	88.8	4.9	0.05	0.02	0.5	18.4
12.0	376.8	1213.1	244.6	179.0	23.0	1932.8	72.3	3.7	0.05	0.02	0.5	19.7

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Depth (mcd)	Age (ka)	GDGT-0 (ng/g)	GDGT-1 (ng/g)	GDGT-2 (ng/g)	GDGT-3 (ng/g)	Cren (ng/g)	Cren* (ng/g)	isoGDGTs (ug/g)	brGDGTs (ug/g)	BIT	TEX86	Temp. (°C)
12.1	378.8	1609.7	323.3	234.5	28.7	2689.3	85.8	5.0	0.05	0.02	0.5	19.1
12.2	380.8	1641.0	332.0	234.5	31.2	2776.6	100.5	5.1	0.05	0.02	0.5	19.4
12.4	384.7	1939.5	391.9	274.7	34.4	3309.9	104.9	6.1	0.05	0.02	0.5	18.8
12.5	386.7	1660.2	355.5	260.0	37.3	2850.7	115.5	5.3	0.06	0.02	0.5	20.1
12.6	388.5	1314.9	299.1	232.7	35.3	2519.8	117.2	4.5	0.06	0.02	0.6	21.5
12.7	390.3	2061.8	431.6	326.4	45.4	3735.4	145.9	6.7	0.06	0.02	0.5	20.6
12.8	392.7	1869.7	407.1	326.7	45.1	3946.0	140.7	6.7	0.08	0.02	0.6	21.2
12.9	397.3	1238.4	273.3	217.7	30.1	2399.0	103.1	4.3	0.05	0.02	0.6	21.5
13.0	398.4	2184.0	524.9	420.1	51.7	4360.6	167.6	7.7	0.07	0.01	0.5	20.8
13.1	398.7	1607.8	396.9	327.2	40.4	3605.3	159.7	6.1	0.06	0.02	0.6	21.9
13.2	400.7	1614.2	452.8	444.2	53.2	3664.3	221.5	6.5	0.06	0.02	0.6	24.1
13.3	402.7	720.8	175.4	170.0	20.3	1522.2	91.5	2.7	0.03	0.02	0.6	24.2
13.4	404.7	842.8	256.8	241.0	31.4	1878.2	139.1	3.4	0.05	0.02	0.6	24.2
13.5	406.7	939.6	299.5	266.3	35.3	1956.2	151.2	3.6	0.04	0.02	0.6	23.5
13.6	408.7	957.2	310.5	293.6	38.6	1991.1	152.3	3.7	0.05	0.03	0.6	23.9
13.7	410.7	36.6	13.5	14.7	2.0	55.0	8.6	low conc.	0.00	0.02	0.7	25.9
13.7	411.1	759.7	229.1	264.3	25.6	1400.4	144.3	2.8	0.04	0.03	0.7	26.0
13.8	412.5	495.5	162.3	174.1	21.3	1087.7	95.8	2.0	0.04	0.03	0.6	25.4
13.8	412.9	905.3	277.2	309.7	35.4	1833.2	164.9	3.5	0.05	0.03	0.6	25.7
13.9	414.9	486.3	137.6	174.2	18.4	989.0	94.3	1.9	0.03	0.03	0.7	27.0
14.0	416.9	752.8	245.9	269.9	33.5	1759.3	153.7	3.2	0.04	0.02	0.7	25.8
14.1	418.9	1160.3	377.0	423.9	42.3	2510.0	235.0	4.7	0.06	0.02	0.7	25.8
14.2	420.9	822.4	240.3	281.4	32.2	2007.0	161.5	3.5	0.05	0.02	0.7	26.4
14.3	422.9	986.6	314.3	347.7	40.7	2127.9	182.4	4.0	0.04	0.02	0.6	25.6
14.4	424.9	1183.2	375.4	442.1	51.6	2665.2	219.6	4.9	0.06	0.02	0.7	26.0
14.5	427.0	1923.9	571.0	632.5	84.0	4571.5	309.5	8.1	0.07	0.02	0.6	25.5
14.6	429.0	91.7	34.8	31.0	4.8	110.0	15.4	low conc.	0.00	0.04	0.6	23.2
14.7	431.0	1271.4	355.0	258.9	32.0	2259.5	104.3	4.3	0.04	0.02	0.5	19.6

Table 1-4. Alkenones and U^K_{37'}-derived temperature at ODP Site 1239 (EEP)

Depth (mcd)	Age (ka)	37:3 MK (ug/g)	37:2 MK (ug/g)	Alkenones (ug/g)	UK37'	Temp. (°C)
0.0	0.4	0.2	1.5	3.3	0.9	24.7
0.0	0.9	0.2	1.5	3.2	0.9	24.8
0.1	1.7	0.2	1.5	3.2	0.9	24.5
0.1	2.2	0.2	1.2	2.6	0.9	24.8
0.1	2.5	0.1	0.7	1.5	0.9	24.8
0.1	3.0	0.2	1.1	2.4	0.9	24.3
0.2	3.5	0.1	1.0	2.2	0.9	24.6
0.2	3.9	0.1	0.9	2.1	0.9	25.3
0.2	4.5	0.1	0.7	1.4	0.9	24.7
0.2	4.8	0.2	1.1	2.4	0.9	24.1
0.2	5.2	0.2	1.1	2.5	0.9	23.9
0.3	5.6	0.2	1.1	2.4	0.9	24.0
0.3	6.1	0.2	1.2	2.5	0.9	24.6
0.3	6.5	0.1	1.0	2.1	0.9	24.8
0.3	6.7	0.1	0.6	1.4	0.9	24.7
0.3	6.9	0.2	1.0	2.3	0.9	24.4
0.3	7.4	0.2	1.1	2.3	0.9	24.4
0.4	7.8	n.t	n.t	n.t	n.t	n.t
0.4	8.2	0.1	0.9	2.0	0.9	24.3
0.4	8.7	0.2	1.1	2.5	0.9	24.1
0.4	9.1	0.1	0.4	1.0	0.9	24.5
0.4	9.5	0.2	1.1	2.4	0.9	23.9
0.5	10.0	0.2	1.0	2.2	0.9	24.0
0.5	10.4	0.1	0.9	2.1	0.9	24.2
0.5	10.8	0.2	0.9	2.0	0.8	23.6
0.6	12.5	0.3	1.4	3.1	0.8	22.4
0.6	13.2	0.2	0.8	1.9	0.8	22.6
0.7	14.7	0.3	1.2	2.7	0.8	22.6
0.7	15.1	0.2	0.9	2.1	0.8	22.5
0.8	17.3	0.6	2.1	5.1	0.8	21.7
0.8	17.5	0.1	0.7	1.7	0.8	23.5
0.8	18.2	0.5	2.0	4.9	0.8	22.1
0.9	18.8	0.4	1.5	3.6	0.8	21.5
0.9	20.6	0.3	1.2	3.0	0.8	22.3
0.9	21.7	0.8	2.5	6.1	0.8	21.6
1.0	23.2	0.9	3.2	7.6	0.8	21.9
1.0	23.9	0.7	2.5	5.8	0.8	22.1
1.0	24.3	0.5	1.8	4.4	0.8	22.3
1.1	26.1	0.7	2.7	6.4	0.8	22.1
1.1	28.3	0.6	2.3	5.4	0.8	22.4
1.1	29.1	0.6	2.2	5.2	0.8	22.4
1.2	29.8	0.6	2.2	5.3	0.8	22.0

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Depth (mcd)	Age (ka)	37:3 MK (ug/g)	37:2 MK (ug/g)	Alkenones (ug/g)	UK37'	Temp. (°C)
1.2	30.2	0.3	1.4	3.1	0.8	23.0
1.2	30.5	0.5	2.0	4.9	0.8	22.2
1.2	30.9	0.5	2.1	4.7	0.8	22.5
1.2	31.6	0.3	1.1	2.8	0.8	23.0
1.2	32.4	0.6	2.4	5.5	0.8	22.7
1.3	33.5	0.4	2.2	5.3	0.8	23.4
1.3	33.8	0.5	2.1	4.8	0.8	22.8
1.3	35.3	0.2	1.2	2.6	0.8	23.8
1.4	36.8	0.4	1.8	4.1	0.8	23.1
1.4	37.2	0.3	1.5	3.3	0.8	23.6
1.4	38.3	0.4	2.5	5.6	0.8	23.4
1.4	39.7	0.3	2.6	5.7	0.9	24.7
1.5	40.5	0.6	2.6	6.0	0.8	22.7
1.5	40.8	0.4	2.0	4.6	0.8	23.1
1.5	41.2	0.6	2.9	6.5	0.8	22.7
1.5	42.7	0.7	2.8	6.6	0.8	22.4
1.6	44.1	0.7	2.9	6.7	0.8	22.7
1.6	44.9	0.3	1.3	3.0	0.8	23.2
1.6	45.6	0.5	2.1	4.9	0.8	22.3
1.7	47.8	0.2	1.1	2.7	0.8	23.0
1.7	48.6	0.1	0.7	1.5	0.8	22.9
1.7	49.3	0.1	0.5	1.2	0.8	22.5
1.7	50.0	0.1	0.6	1.3	0.8	22.5
1.8	51.9	0.4	1.8	4.3	0.8	22.8
1.8	52.2	0.1	0.5	1.1	0.8	22.8
1.8	53.7	0.1	0.2	0.5	0.8	22.5
1.8	54.4	0.1	0.3	0.8	0.8	23.6
1.9	55.5	0.7	2.2	5.3	0.8	22.8
1.9	56.1	0.3	1.3	3.0	0.8	23.4
1.9	57.8	0.5	2.1	4.8	0.8	22.9
2.0	59.2	0.4	2.2	4.9	0.8	23.3
2.0	59.6	0.3	1.7	3.9	0.8	23.5
2.0	60.7	0.5	2.6	5.7	0.8	23.4
2.0	62.2	0.3	2.0	4.3	0.8	23.6
2.1	63.3	0.3	1.6	3.7	0.8	23.5
2.1	63.6	0.5	2.4	5.4	0.8	23.6
2.1	65.1	0.7	3.0	6.9	0.8	22.8
2.2	66.6	0.7	2.8	6.5	0.8	22.7
2.2	67.0	0.4	1.8	4.2	0.8	23.0
2.2	67.3	0.6	3.2	7.1	0.8	23.2
2.2	68.1	0.6	3.7	8.2	0.8	23.3
2.2	69.6	0.6	3.1	6.9	0.8	23.4
2.3	70.9	0.5	2.3	5.3	0.8	23.2
2.3	71.3	0.2	3.2	6.9	0.8	23.7

Continue to the next pages

Depth (mcd)	Age (ka)	37:3 MK (ug/g)	37:2 MK (ug/g)	Alkenones (ug/g)	UK37'	Temp. (°C)
2.3	73.1	0.5	3.2	7.1	0.9	24.3
2.3	73.9	0.5	3.8	8.1	0.9	24.8
2.4	74.8	0.5	2.9	6.2	0.9	24.1
2.4	75.2	0.3	2.0	4.4	0.9	24.1
2.4	76.5	0.5	4.0	8.4	0.9	25.3
2.4	78.3	0.5	3.9	8.1	0.9	25.2
2.5	79.6	0.2	2.0	4.2	0.9	25.8
2.5	80.0	0.1	3.4	6.7	0.9	25.6
2.5	81.7	0.2	4.5	9.2	0.9	25.2
2.6	83.5	0.2	5.3	11.0	0.9	25.3
2.6	83.9	0.5	5.4	11.5	0.9	25.6
2.6	85.2	0.3	6.0	12.4	0.9	24.9
2.6	86.9	0.3	5.3	11.4	0.9	25.1
2.7	88.3	0.6	5.3	11.3	0.9	25.2
2.7	88.7	0.2	5.5	11.7	0.9	25.4
2.7	90.4	0.2	5.8	12.4	0.9	25.3
2.8	92.1	0.3	5.1	10.6	0.9	25.1
2.8	92.6	0.4	4.1	9.2	0.9	25.4
2.8	93.9	0.2	4.4	9.5	0.9	25.1
2.8	95.6	0.2	4.5	9.5	0.9	25.3
2.9	96.9	0.6	4.5	9.8	0.9	25.0
2.9	97.3	0.3	5.1	10.7	0.9	24.7
2.9	99.1	0.3	4.5	9.4	0.9	24.7
3.0	100.8	0.3	4.2	8.8	0.9	24.7
3.0	101.3	0.5	4.5	9.5	0.9	25.1
3.0	102.6	0.2	4.1	8.6	0.9	24.7
3.0	104.3	0.3	4.3	9.0	0.9	24.9
3.1	105.6	0.5	3.7	8.1	0.9	24.6
3.1	106.0	0.3	5.2	10.8	0.9	24.8
3.1	107.8	0.2	5.3	10.7	0.9	25.4
3.2	109.5	0.2	4.8	9.5	0.9	25.2
3.2	109.9	0.4	2.9	6.1	0.9	25.0
3.2	111.2	0.3	4.1	8.3	0.9	24.8
3.2	112.1	0.2	3.6	7.3	0.9	24.8
3.2	112.7	0.3	3.8	8.0	0.9	24.6
3.3	113.4	0.2	4.7	9.5	0.9	25.5
3.3	113.7	0.4	3.8	8.0	0.9	25.8
3.3	114.0	0.2	3.3	6.8	0.9	25.7
3.3	114.7	0.2	4.9	10.0	0.9	25.6
3.3	115.3	0.2	3.3	6.8	0.9	25.6
3.3	116.0	0.1	2.6	5.3	0.9	25.7
3.4	117.3	0.2	2.5	5.5	0.9	26.0
3.5	120.5	0.1	1.0	2.2	0.9	26.6
3.6	123.8	0.1	1.8	3.8	0.9	26.1

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Depth (mcd)	Age (ka)	37:3 MK (ug/g)	37:2 MK (ug/g)	Alkenones (ug/g)	UK37'	Temp. (°C)
3.7	127.1	0.2	2.4	4.9	0.9	26.1
3.8	130.3	0.2	3.0	6.3	0.9	26.1
3.9	133.6	0.5	5.2	10.8	0.9	25.7
4.0	137.3	0.5	3.8	8.7	0.9	24.9
4.1	141.9	0.5	4.6	10.2	0.9	25.3
4.2	147.3	0.2	1.4	3.4	0.9	24.6
4.3	150.9	0.2	1.3	3.3	0.9	24.9
4.4	155.5	0.2	2.1	4.9	0.9	25.4
4.5	160.0	0.2	1.8	4.0	0.9	25.5
4.6	164.5	0.4	3.2	7.5	0.9	25.0
4.7	169.1	0.2	1.6	3.9	0.9	25.3
4.8	173.6	0.3	2.1	5.3	0.9	25.2
4.9	178.6	0.3	2.8	6.7	0.9	25.6
4.9	179.5	0.6	6.5	14.9	0.9	26.0
5.1	187.6	0.5	5.4	12.3	0.9	25.6
5.2	190.0	0.1	0.8	1.7	0.9	25.8
5.3	193.4	0.1	1.2	3.0	0.9	25.4
5.4	196.2	0.2	3.1	6.7	0.9	26.4
5.5	199.0	0.2	2.6	6.2	0.9	25.9
5.6	201.2	0.1	1.5	3.4	0.9	26.3
5.6	201.8	0.1	1.4	3.2	0.9	26.1
5.7	204.6	0.6	4.4	10.3	0.9	24.9
5.8	207.4	0.2	1.9	4.5	0.9	25.2
5.9	210.2	0.4	3.2	7.3	0.9	25.0
6.0	213.0	0.2	1.7	3.6	0.9	25.6
6.1	215.6	0.3	2.1	5.0	0.9	24.9
6.2	218.6	0.4	2.6	6.1	0.9	24.4
6.3	221.4	0.4	2.4	5.8	0.9	24.2
6.4	224.2	0.6	3.4	8.3	0.9	23.9
6.5	226.5	0.6	3.4	8.1	0.8	23.6
6.6	228.7	0.3	2.2	5.0	0.9	24.5
6.7	231.0	0.3	1.8	4.2	0.9	24.7
6.8	232.2	n.t	n.t	n.t	n.t	n.t
6.8	233.3	0.1	0.8	1.8	0.9	24.8
6.9	235.6	0.6	4.2	9.9	0.9	24.8
7.0	237.6	0.2	1.5	3.4	0.9	24.4
7.0	237.9	1.0	8.0	17.9	0.9	25.0
7.1	240.2	0.8	7.2	15.9	0.9	25.3
7.2	242.4	0.3	4.1	9.4	0.9	26.1
7.3	243.6	0.9	7.4	15.5	0.9	24.9
7.3	245.4	1.2	7.0	15.3	0.9	24.1
7.5	248.6	1.4	7.2	16.7	0.8	23.4
7.5	251.0	1.4	6.8	15.5	0.8	23.3
7.7	254.6	1.6	6.2	15.2	0.8	22.3

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Depth (mcd)	Age (ka)	37:3 MK (ug/g)	37:2 MK (ug/g)	Alkenones (ug/g)	UK37'	Temp. (°C)
7.7	257.0	1.5	6.0	14.8	0.8	22.4
7.9	260.6	1.8	7.8	18.6	0.8	22.8
7.9	262.1	1.9	7.5	18.3	0.8	22.4
8.0	266.3	1.7	6.8	16.3	0.8	22.5
8.2	270.6	1.5	6.7	15.7	0.8	23.0
8.3	274.8	1.2	5.5	12.5	0.8	23.2
8.5	279.0	1.0	5.4	12.0	0.8	23.7
8.6	283.2	0.5	3.6	7.7	0.9	24.6
8.6	283.5	0.6	4.4	10.1	0.9	24.7
8.7	286.5	0.6	4.2	9.9	0.9	24.5
8.7	286.8	0.1	0.8	1.7	0.9	24.7
8.8	288.8	0.8	5.7	13.8	0.9	24.7
8.9	290.8	0.8	5.2	12.7	0.9	24.5
9.0	292.9	0.9	6.8	16.5	0.9	25.0
9.1	294.9	1.1	7.4	17.1	0.9	24.5
9.2	297.0	0.8	5.1	12.5	0.9	24.2
9.3	299.2	0.6	4.0	10.1	0.9	24.5
9.4	301.3	0.9	6.5	14.8	0.9	24.7
9.5	303.3	0.9	5.7	13.1	0.9	24.3
9.6	305.4	0.6	5.3	11.6	0.9	25.2
9.7	307.4	0.6	5.6	12.2	0.9	25.3
9.8	309.5	0.7	6.9	14.8	0.9	25.4
9.9	311.5	0.7	6.9	16.8	0.9	25.6
10.1	315.6	0.4	4.7	10.7	0.9	26.1
10.2	317.7	0.2	3.3	7.7	0.9	26.2
10.3	319.8	0.2	3.2	7.5	0.9	26.3
10.4	321.8	0.2	2.5	5.6	0.9	26.2
10.5	323.9	0.2	2.6	5.8	0.9	26.2
10.6	325.9	0.3	4.3	8.9	0.9	26.2
10.7	328.0	0.6	6.1	12.8	0.9	25.8
10.8	330.2	0.8	9.1	19.0	0.9	25.9
10.9	332.3	1.1	6.8	15.8	0.9	24.0
11.0	334.3	1.0	5.9	14.1	0.9	24.1
11.1	336.4	1.4	6.6	16.6	0.8	23.0
11.2	338.4	1.5	7.4	18.7	0.8	23.2
11.4	344.2	1.3	6.0	15.0	0.8	23.2
11.4	345.3	2.1	8.5	21.9	0.8	22.5
11.5	350.9	2.2	8.4	21.5	0.8	22.3
11.6	356.6	1.5	6.9	16.7	0.8	22.9
11.7	362.3	n.t	n.t	n.t	n.t	n.t
11.8	368.0	1.5	7.2	17.5	0.8	23.3
11.9	373.7	1.2	5.8	14.0	0.8	23.3
12.0	376.8	1.1	6.5	15.0	0.9	24.0
12.1	378.8	1.1	6.7	15.2	0.9	24.0

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Depth (mcd)	Age (ka)	37:3 MK (ug/g)	37:2 MK (ug/g)	Alkenones (ug/g)	UK37'	Temp. (°C)
12.2	380.8	1.3	7.1	16.2	0.8	23.6
12.4	384.7	1.5	9.0	20.1	0.9	24.0
12.5	386.7	1.3	9.6	20.8	0.9	24.8
12.6	388.5	1.1	9.6	20.0	0.9	25.2
12.7	390.3	1.3	10.7	22.3	0.9	25.2
12.8	392.7	1.5	13.2	27.8	0.9	25.3
12.9	397.3	1.5	10.4	22.2	0.9	24.7
13.0	398.4	2.1	12.2	26.7	0.9	24.0
13.1	398.7	1.2	6.8	15.0	0.8	23.7
13.2	400.7	0.5	2.7	5.9	0.9	23.9
13.3	402.7	0.5	3.8	8.1	0.9	24.5
13.4	404.7	0.5	3.8	8.7	0.9	25.0
13.5	406.7	0.5	3.8	8.6	0.9	25.1
13.6	408.7	0.7	4.9	10.9	0.9	24.4
13.7	410.7	0.4	2.4	5.4	0.9	24.4
13.7	411.1	0.6	3.4	7.8	0.9	24.1
13.8	412.5	0.4	2.6	6.0	0.9	24.7
13.8	412.9	0.4	2.9	6.6	0.9	24.3
13.9	414.9	0.4	2.5	5.8	0.9	24.1
14.0	416.9	0.4	3.2	7.0	0.9	24.7
14.1	418.9	0.4	2.8	6.2	0.9	24.5
14.2	420.9	0.4	2.6	5.9	0.9	24.1
14.3	422.9	0.4	2.4	5.3	0.9	24.1
14.4	424.9	0.6	3.1	7.1	0.8	23.8
14.5	427.0	0.7	3.0	7.0	0.8	22.7
14.6	429.0	0.9	3.7	9.0	0.8	22.5
14.7	431.0	1.0	3.6	8.9	0.8	21.6

Table 1-5. GDGTs and TEX₈₆^H-derived temperature at ODP Site 1237 (Peru margin)

Depth (mcd)	Age (ka)	GDGT-0 (ng/g)	GDGT-1 (ng/g)	GDGT-2 (ng/g)	GDGT-3 (ng/g)	Cren (ng/g)	Cren* (ng/g)	isoGDGTs (ug/g)	brGDGTs (ug/g)	BIT	TEX86	Temp. (°C)
0.0	1.1	1108.0	148.6	107.2	15.4	1123.2	64.0	2.6	0.04	0.04	0.6	21.2
0.1	1.4	696.3	124.7	95.1	12.7	1005.5	56.2	2.0	0.05	0.04	0.6	21.8
0.1	1.7	419.7	91.7	60.4	8.0	605.7	27.4	1.2	0.03	0.04	0.5	18.7
0.1	2.0	537.0	101.3	79.1	8.7	885.7	43.6	1.7	0.03	0.03	0.6	21.6
0.2	3.0	3714.6	747.3	516.6	48.3	5634.7	252.2	10.9	0.00	0.00	0.5	19.3
0.2	4.0	1952.3	408.2	291.3	31.8	2930.6	125.1	5.8	0.04	0.02	0.5	19.4
0.2	5.1	1868.5	288.2	248.4	26.0	2366.0	146.7	5.0	0.05	0.02	0.6	23.1
0.3	6.1	1972.7	304.8	301.6	34.5	3104.0	152.6	5.9	0.04	0.01	0.6	24.2
0.3	7.1	1657.0	305.8	255.4	28.1	2634.8	142.1	5.1	0.04	0.01	0.6	22.5
0.3	8.1	2887.8	516.4	379.0	33.1	3383.3	165.9	7.4	0.05	0.01	0.5	19.6
0.3	8.8	2054.6	368.2	311.8	34.3	2915.1	135.4	5.9	0.06	0.02	0.6	21.7
0.4	9.5	1627.6	307.3	276.4	35.3	2366.4	93.5	4.7	0.03	0.01	0.6	21.8
0.4	10.2	1791.2	424.8	327.7	38.7	2866.6	188.7	5.7	0.08	0.03	0.6	21.7
0.4	10.9	1608.2	331.9	258.2	28.0	2377.8	149.7	4.8	0.04	0.02	0.6	21.8
0.5	11.6	2577.4	434.3	340.0	35.3	3260.1	175.9	6.9	0.08	0.03	0.6	21.3
0.5	12.3	4958.6	681.7	463.7	58.1	5177.5	241.2	11.7	0.08	0.02	0.5	19.6
0.5	13.0	2833.0	504.2	380.2	39.7	4126.8	211.5	8.2	0.08	0.02	0.6	21.2
0.6	13.7	2742.1	526.3	414.8	43.7	4022.7	166.8	8.0	0.07	0.02	0.5	20.5
0.6	14.4	4070.3	713.5	520.6	55.3	5524.2	256.0	11.2	0.09	0.02	0.5	20.2
0.6	15.1	3790.9	685.5	533.7	54.9	5184.2	199.6	10.6	0.13	0.02	0.5	20.0
0.6	15.8	5243.2	806.0	521.1	57.3	7456.0	233.4	14.4	0.08	0.01	0.5	18.1
0.7	16.5	4630.5	700.9	416.1	53.9	6398.1	209.6	12.5	0.05	0.01	0.5	17.5
0.7	17.2	4713.3	708.9	457.3	58.9	7327.2	208.5	13.5	0.05	0.01	0.5	18.3
0.7	17.9	5523.7	1008.4	633.5	79.7	6863.2	266.0	14.4	0.00	0.00	0.5	17.6
0.8	18.9	5323.8	778.1	557.2	64.7	6237.5	238.9	13.3	0.07	0.01	0.5	19.5
0.8	20.1	2460.7	326.2	244.8	29.1	3205.7	116.7	6.5	0.09	0.03	0.5	20.6
0.8	21.3	2752.8	457.5	299.3	34.8	3795.1	116.3	7.5	0.07	0.02	0.5	17.8
0.9	22.4	2914.8	455.9	276.7	38.6	3772.2	117.0	7.7	0.13	0.03	0.5	17.2
0.9	23.6	4443.4	686.2	432.4	57.8	5630.1	182.7	11.5	0.07	0.01	0.5	17.7
0.9	24.7	3710.2	583.2	401.3	54.8	4770.2	161.0	9.8	0.08	0.02	0.5	18.8
0.9	25.9	2611.0	414.8	279.8	43.9	3427.7	129.8	7.0	0.06	0.02	0.5	19.3
1.0	27.7	4532.1	710.8	421.0	49.8	5518.5	189.7	11.5	0.06	0.01	0.5	16.9
1.0	29.5	4400.9	737.7	411.3	47.6	5389.7	160.1	11.2	0.05	0.01	0.5	15.3
1.0	31.2	2535.6	438.3	343.5	36.8	3266.8	114.5	6.8	0.08	0.02	0.5	19.8
1.1	33.0	3832.7	524.8	349.1	48.0	4945.2	164.2	9.9	0.08	0.02	0.5	19.0
1.1	34.8	4670.8	1406.4	1023.6	145.1	4751.1	497.7	12.7	0.16	0.03	0.5	20.4
1.1	36.5	5641.4	799.6	542.3	63.8	6913.8	212.6	14.2	0.06	0.01	0.5	18.4
1.2	38.3	3974.6	563.6	398.0	53.5	5073.2	147.2	10.3	0.07	0.01	0.5	18.9
1.2	40.3	4310.6	661.3	464.5	54.6	5782.0	185.4	11.5	0.06	0.01	0.5	18.9
1.2	42.2	2232.9	325.3	212.1	33.3	2922.5	78.3	5.9	0.06	0.02	0.5	17.9
1.3	46.0	2373.5	403.1	230.2	27.7	3374.5	95.7	6.5	0.03	0.01	0.5	16.0
1.4	51.8	1788.7	295.4	171.5	20.2	2212.1	70.3	4.6	0.03	0.01	0.5	16.2

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Depth (mcd)	Age (ka)	GDGT-0 (ng/g)	GDGT-1 (ng/g)	GDGT-2 (ng/g)	GDGT-3 (ng/g)	Cren (ng/g)	Cren* (ng/g)	isoGDGTs (ug/g)	brGDGTs (ug/g)	BIT	TEX86	Temp. (°C)
1.4	53.6	3510.3	597.2	346.6	36.3	4713.2	127.9	9.4	0.04	0.01	0.5	15.6
1.5	56.2	1699.6	272.8	172.8	18.7	2160.4	78.7	4.4	0.03	0.01	0.5	17.9
1.6	58.8	2443.4	360.3	228.3	29.4	3039.1	106.3	6.2	0.03	0.01	0.5	18.2
1.7	60.6	2185.6	334.3	208.6	24.4	2705.6	80.5	5.6	0.03	0.01	0.5	17.0
1.7	62.3	3112.1	490.7	292.9	33.9	3741.0	116.3	7.8	0.04	0.01	0.5	16.5
1.8	63.2	2622.1	407.1	256.2	32.0	2791.5	92.6	6.2	0.03	0.01	0.5	17.0
1.8	65.1	2647.8	468.5	303.2	42.7	3199.0	97.1	6.8	0.03	0.01	0.5	17.2
1.9	67.0	2309.0	394.1	250.7	23.8	3090.6	99.6	6.2	0.04	0.01	0.5	17.2
1.9	68.8	2076.6	464.5	266.5	26.7	2198.0	247.5	5.3	0.04	0.02	0.5	17.8
2.0	71.6	1941.8	282.0	173.6	23.9	2375.3	83.0	4.9	0.02	0.01	0.5	17.9
2.1	74.4	896.9	134.4	87.9	10.3	1095.3	47.8	2.3	0.03	0.02	0.5	19.2
2.1	75.3	1185.4	187.5	106.9	12.3	1393.5	37.8	3.0	0.03	0.02	0.5	15.3
2.3	78.2	1987.1	296.1	192.2	27.1	2738.3	108.7	5.4	0.06	0.02	0.5	19.5
2.3	79.6	2159.5	322.2	199.3	22.8	2556.0	64.0	5.4	0.03	0.01	0.5	16.2
2.4	81.1	1125.8	191.7	113.8	12.9	1268.0	45.9	2.8	0.03	0.02	0.5	16.4
2.4	82.5	1324.2	222.9	137.0	16.9	1494.6	59.0	3.3	0.03	0.02	0.5	17.3
2.5	84.0	2718.8	473.5	262.5	27.4	3282.9	102.1	6.9	0.03	0.01	0.5	15.1
2.6	87.0	1617.8	290.1	186.2	19.7	2261.7	82.2	4.5	0.02	0.01	0.5	17.9
2.7	88.0	2262.3	356.1	226.4	26.4	2574.6	85.4	5.6	0.04	0.02	0.5	17.2
2.7	89.0	1527.6	255.7	134.9	18.1	1835.3	56.6	3.9	0.02	0.01	0.5	14.9
2.8	89.9	2724.2	482.9	236.0	28.6	3309.6	104.0	6.9	0.03	0.01	0.4	13.7
2.9	90.9	2459.7	403.6	273.7	25.9	3185.1	97.9	6.5	0.03	0.01	0.5	17.8
2.9	92.4	3018.2	531.2	320.3	32.9	3432.4	125.5	7.5	0.03	0.01	0.5	16.4
3.1	94.5	2395.3	417.7	247.0	24.4	2887.6	86.0	6.1	0.03	0.01	0.5	15.6
3.1	94.9	1601.6	255.4	139.5	17.8	2113.6	66.1	4.2	0.03	0.01	0.5	16.0
3.1	95.4	3782.8	614.9	415.6	43.1	4295.6	141.0	9.3	0.05	0.01	0.5	17.6
3.2	95.9	2753.0	460.9	281.8	30.3	3491.5	116.6	7.2	0.04	0.01	0.5	16.9
3.3	101.6	1514.3	243.3	141.7	16.8	1925.9	51.3	3.9	0.03	0.01	0.5	15.7
3.3	104.5	667.3	98.3	64.9	8.6	865.6	30.4	1.8	0.02	0.02	0.5	18.8
3.3	107.7	2096.8	352.2	196.3	20.3	2707.1	73.5	5.5	0.03	0.01	0.5	15.0
3.4	109.2	2504.1	414.3	282.9	27.8	3185.9	103.2	6.6	0.03	0.01	0.5	18.0
3.4	115.5	1264.4	205.4	147.2	17.3	1497.2	60.7	3.2	0.05	0.04	0.5	19.3
3.4	116.1	1072.7	179.0	132.4	13.1	1451.8	58.8	3.0	0.06	0.04	0.5	19.9
3.5	117.7	1958.5	274.3	193.3	15.3	2477.8	73.9	5.0	0.04	0.02	0.5	18.4
3.6	118.0	2467.2	405.9	238.0	21.5	3154.0	78.4	6.4	0.04	0.01	0.5	15.2
3.7	118.6	1599.6	239.6	152.8	14.2	2004.1	57.0	4.1	0.04	0.02	0.5	17.0
3.7	119.5	1847.9	263.9	170.9	18.0	2380.3	62.1	4.8	0.04	0.02	0.5	17.3
3.8	120.6	1339.8	196.3	149.5	12.8	1721.8	54.6	3.5	0.03	0.02	0.5	19.5
3.9	121.5	1600.0	255.7	182.0	15.0	2305.9	64.1	4.5	0.03	0.01	0.5	18.3
4.0	122.4	1938.2	286.4	186.7	16.7	2478.0	66.0	5.0	0.04	0.01	0.5	17.1
4.1	123.3	1932.4	286.4	177.7	18.9	2405.9	64.2	4.9	0.03	0.01	0.5	16.6
4.2	124.0	2015.4	257.4	166.6	16.4	2464.2	58.2	5.0	0.03	0.01	0.5	17.0
4.3	126.8	688.8	95.7	62.0	8.3	960.1	30.4	1.9	0.03	0.04	0.5	18.8
4.3	128.8	888.0	161.6	120.7	12.4	1267.5	56.6	2.5	0.03	0.03	0.5	20.3

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Depth (mcd)	Age (ka)	GDGT-0 (ng/g)	GDGT-1 (ng/g)	GDGT-2 (ng/g)	GDGT-3 (ng/g)	Cren (ng/g)	Cren* (ng/g)	isoGDGTs (ug/g)	brGDGTs (ug/g)	BIT	TEX86	Temp. (°C)
4.4	130.7	1008.0	224.7	158.0	18.2	1556.5	75.0	3.1	0.02	0.01	0.5	19.6
4.5	133.8	1357.4	224.6	155.0	22.0	1954.8	72.2	3.8	0.03	0.02	0.5	19.5
4.5	135.0	1140.2	186.1	145.0	15.7	1550.9	62.4	3.1	0.03	0.02	0.5	20.6
4.6	139.9	1825.9	335.4	222.1	20.2	2352.5	79.0	4.9	0.03	0.01	0.5	17.4
4.7	141.8	1539.2	284.0	191.8	19.2	2156.0	78.3	4.3	0.02	0.01	0.5	18.3
4.8	142.8	1150.4	188.4	110.7	13.0	1478.6	47.1	3.0	0.03	0.02	0.5	16.5
4.9	143.7	982.8	160.4	111.8	11.8	1166.7	41.1	2.5	0.02	0.02	0.5	18.4
4.9	144.6	1392.2	228.6	154.6	16.4	1520.1	53.7	3.4	0.03	0.02	0.5	17.8
5.0	145.1	1212.3	208.4	126.6	13.7	1558.2	52.1	3.2	0.02	0.01	0.5	16.8
5.0	145.6	1153.7	191.1	136.6	12.8	1361.3	50.5	2.9	0.03	0.02	0.5	18.7
5.0	146.6	1526.0	253.3	174.9	15.9	1804.0	60.4	3.9	0.02	0.01	0.5	17.9
5.1	148.0	1815.1	367.4	241.6	24.1	2240.6	88.9	4.8	0.04	0.02	0.5	17.5
5.2	149.0	1479.9	268.2	182.9	19.3	1637.7	69.2	3.7	0.02	0.01	0.5	18.2
5.3	150.0	1164.9	253.4	177.6	17.8	1474.4	71.5	3.2	0.02	0.02	0.5	18.8

Table 1-6. Alkenones and U^K_{37'}-derived temperature ODP Site 1237 (Peru margin)

Depth (mcd)	Age (ka)	37:3 MK (ug/g)	37:2 MK (ug/g)	Alkenones (ug/g)	UK37'	Temp. (°C)
0.0	1.1	0.5	1.3	3.4	0.7	19.9
0.1	1.4	0.5	1.3	4.0	0.7	19.7
0.1	1.7	0.6	1.4	3.7	0.7	19.6
0.1	2.0	0.6	1.4	3.9	0.7	19.3
0.2	3.0	0.8	1.8	4.8	0.7	19.6
0.2	4.0	0.7	1.8	4.6	0.7	19.7
0.2	5.1	0.7	1.7	4.5	0.7	19.8
0.3	6.1	0.7	1.7	4.4	0.7	20.0
0.3	7.1	0.6	1.5	3.9	0.7	20.1
0.3	8.1	0.6	1.5	3.8	0.7	20.1
0.3	8.8	0.8	2.0	5.5	0.7	19.8
0.4	9.5	0.7	1.6	4.3	0.7	19.6
0.4	10.2	0.7	1.8	4.7	0.7	19.6
0.4	10.9	0.6	1.5	3.9	0.7	20.2
0.5	11.6	1.1	3.0	7.9	0.7	20.6
0.5	12.3	1.2	3.2	8.8	0.7	20.1
0.5	13.0	1.3	3.2	8.5	0.7	19.9
0.6	13.7	1.5	3.6	9.7	0.7	19.7
0.6	14.4	1.7	3.6	10.3	0.7	18.8
0.6	15.1	1.6	3.7	10.3	0.7	19.5
0.6	15.8	1.6	3.3	9.7	0.7	18.8
0.7	16.5	1.1	2.2	6.8	0.7	18.4
0.7	17.2	1.2	2.2	6.6	0.7	18.0
0.7	17.9	1.0	2.1	6.6	0.7	18.5
0.8	18.9	0.8	1.7	5.5	0.7	18.9
0.8	20.1	1.1	2.1	6.5	0.6	17.9
0.8	21.3	1.0	2.0	6.4	0.7	18.4
0.9	22.4	1.4	2.5	7.6	0.6	17.6
0.9	23.6	1.2	2.2	3.4	0.6	17.9
0.9	24.7	1.3	2.5	8.2	0.7	18.1
0.9	25.9	1.2	2.2	7.3	0.7	18.0
1.0	27.7	1.3	2.2	7.3	0.6	17.2
1.0	29.5	1.4	2.5	7.8	0.6	17.8
1.0	31.2	1.1	2.1	6.4	0.6	17.8
1.1	33.0	1.4	2.3	7.8	0.6	17.2
1.1	34.8	0.6	0.9	3.8	0.6	16.4
1.1	36.5	1.2	1.9	6.5	0.6	17.0
1.2	38.3	1.3	2.0	6.2	0.6	16.7
1.2	40.3	1.4	2.2	7.1	0.6	17.1
1.2	42.2	1.2	1.9	6.0	0.6	16.8
1.3	46.0	1.5	2.3	7.2	0.6	16.8
1.4	51.8	1.4	2.5	7.7	0.6	17.7

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Depth (mcd)	Age (ka)	37:3 MK (ug/g)	37:2 MK (ug/g)	Alkenones (ug/g)	UK37'	Temp. (°C)
1.4	53.6	1.6	2.6	7.9	0.6	17.2
1.5	56.2	1.3	2.1	6.6	0.6	17.1
1.6	58.8	1.5	2.4	7.4	0.6	16.9
1.7	60.6	1.5	2.4	7.2	0.6	17.1
1.7	62.3	1.7	2.8	8.4	0.6	17.1
1.8	63.2	1.3	2.6	7.6	0.7	18.2
1.8	65.1	1.8	2.7	8.9	0.6	16.8
1.9	67.0	1.5	2.7	7.9	0.6	17.7
1.9	68.8	1.6	2.9	8.6	0.6	17.8
2.0	71.6	1.7	2.6	8.3	0.6	16.7
2.1	74.4	1.2	1.9	6.0	0.6	17.1
2.1	75.3	1.1	2.0	5.9	0.6	17.7
2.3	78.2	1.8	3.1	9.4	0.6	17.7
2.3	79.6	1.3	2.3	6.8	0.6	17.5
2.4	81.1	1.3	2.7	8.1	0.7	18.7
2.4	82.5	1.2	2.4	6.6	0.7	18.7
2.5	84.0	1.6	3.1	9.0	0.7	18.3
2.6	87.0	1.3	3.0	8.3	0.7	19.5
2.7	88.0	1.5	2.8	8.4	0.7	18.2
2.7	89.0	1.3	3.1	8.9	0.7	19.5
2.8	89.9	2.1	4.0	11.9	0.7	18.1
2.9	90.9	2.1	3.9	11.4	0.7	18.0
3.0	92.4	1.6	3.1	10.0	0.7	18.5
3.1	94.5	1.6	3.5	9.4	0.7	19.1
3.1	94.9	1.7	3.6	9.9	0.7	18.7
3.1	95.4	1.8	3.7	9.9	0.7	18.6
3.2	95.9	1.3	2.9	7.8	0.7	18.9
3.3	101.6	1.7	3.3	9.1	0.7	18.4
3.3	104.5	1.6	3.4	9.1	0.7	19.0
3.3	107.7	1.4	3.6	9.6	0.7	19.9
3.4	109.2	1.3	2.8	7.8	0.7	19.1
3.4	115.5	2.3	6.3	16.2	0.7	20.4
3.4	116.1	2.0	5.5	14.1	0.7	20.3
3.6	117.7	2.0	5.1	13.1	0.7	20.0
3.6	118.0	2.0	5.5	14.6	0.7	20.4
3.7	118.6	1.7	4.3	11.4	0.7	19.9
3.7	119.5	1.5	3.5	9.1	0.7	19.5
3.8	120.6	1.3	3.1	8.3	0.7	19.5
3.9	121.5	2.0	4.6	12.5	0.7	19.3
4.0	122.4	2.5	6.3	16.7	0.7	20.0
4.1	123.3	1.7	4.3	11.4	0.7	20.0
4.2	124.0	1.3	3.6	9.3	0.7	20.7
4.3	126.8	0.6	1.9	4.8	0.8	21.6
4.3	128.8	1.0	3.1	7.8	0.7	20.8

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Depth (mcd)	Age (ka)	37:3 MK (ug/g)	37:2 MK (ug/g)	Alkenones (ug/g)	UK37'	Temp. (°C)
4.4	130.7	0.7	1.7	4.6	0.7	20.0
4.5	133.8	1.3	4.0	10.5	0.7	20.8
4.5	135.0	1.2	3.5	9.3	0.7	20.6
4.6	139.9	1.4	3.4	9.2	0.7	19.4
4.7	141.8	1.3	2.8	8.0	0.7	18.7
4.8	142.8	1.3	2.6	7.4	0.7	18.6
4.9	143.7	1.0	2.2	6.2	0.7	18.8
4.9	144.6	1.2	2.7	7.4	0.7	19.1
5.0	145.1	1.3	2.7	7.5	0.7	18.4
5.0	145.6	1.2	2.4	6.8	0.7	18.5
5.0	146.6	1.0	2.1	5.9	0.7	18.7
5.1	148.0	2.0	4.0	11.5	0.7	18.4
5.2	149.0	1.8	3.5	10.3	0.7	18.3
5.3	150.0	2.0	3.9	11.2	0.7	18.2