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Santa Barbara Basin Study Extends Global Climate Record

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A fundamental goal of Earth science is to understand the remarkable instability of late Quaternary global climate prior to the beginning of the Holocene, about 11,000 years ago. This unusual climate behavior was characterized by millennial-scale climate oscillations on suborbital timescales, and a distinctive 'sawtooth' pattern of very abrupt glacial and stadial terminations (within decades) followed by more gradual global cooling [e.g., *Dansgaard et al.,* 1993; *Hendy and Kennett,* 1999]. The fact that both major (glacial) and minor (stadial) cooling periods in Earth's climate were terminated by similar abrupt warming episodes suggests a common mechanism driving such rapid changes in global climate.

Understanding the causes of this instability is crucial given developing concerns about global warming, yet knowledge about this climate behavior has been essentially confined to the last 150,000 years or so, owing to the absence of available sequences of sufficient age and chronological resolution. The high-resolution paleoclimate record from the Greenland ice cores is limited to about 110 thousand years ago (ka), and although Antarctic ice cores now extend back to more than 740 ka [*European Project for Ice Coring in Antarctica,* 2004], these latter cores primarily provide information about high-latitude conditions at much lower resolution than is required to address abrupt climate change.

Longer high-resolution paleoclimate records are thus essential to understanding the natural mechanisms of global climate change. Ideally, such records should represent changes in both the atmosphere and oceans, and at low, middle, and high latitude sites. For this reason, high-resolution paleoclimate records extracted from marine sediment cores are of critical importance.

Ocean Drilling Program (ODP) Site 893, located in Santa Barbara Basin (Figure 1), is one of the few high-fidelity, continuous climate records of the late Quaternary that exhibits this necessary high resolution at millennial, centennial, and decadal scales [*Kennett*, 1995]. Oxygen isotopic and microfossil analyses of these sediments reveal a remarkable correlation of climate change between Santa Barbara Basin and the high-resolution Greenland ice core (Greenland Ice Sheet Project) since 60 ka [*Behl and Kennett,* 1996], suggesting synchronous climate changes linked through the atmosphere. ODP 893 also provides, to date, the highest-resolution marine record in the world for the penultimate deglaciation (Termination II at ~130 ka) [*Cannariato and Kennett,* 2005].

Unfortunately, ODP 893 was only drilled to a depth of 200 meters below the seafloor, which takes this climate record back to about 160 ka. ODP decided not to extend this record by deeper drilling owing to various safety concerns. Another method was thus needed to extend this invaluable basin record back beyond 160 ka.

A Novel Approach: Sampling an Active Submarine Fold

Fortunately, Santa Barbara Basin is tectonically active. The basin is situated in the middle of a young, active fault-and-fold belt, and much of this deformation is less than one

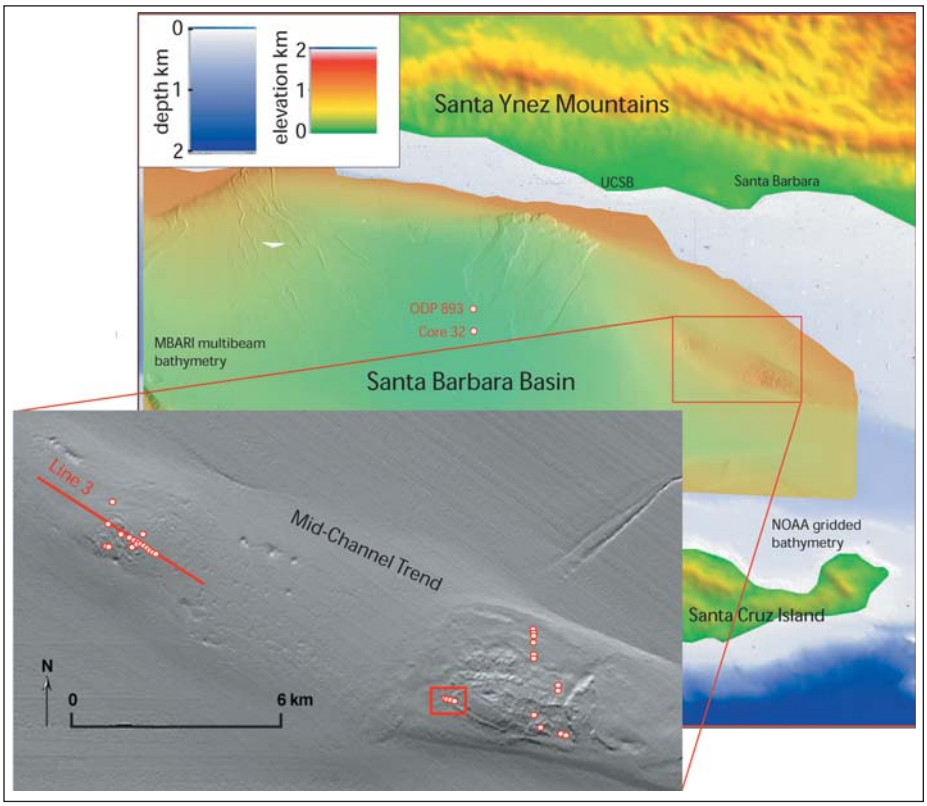

*Fig. 1. Map showing high-resolution multibeam bathymetry [*Monterey Bay Aquarium Research Institute (MBARI)*, 2000], ODP Site 893, and the principal coring area (large red box) along the Mid-Channel trend in Santa Barbara Basin. (inset) Closeup of the MBARI multibeam over the Mid-Channel trend showing outcrop of late Quaternary strata, locations of jumbo piston cores (white circles), and one of several high-resolution USGS chirp seismic lines (Melville line 3) acquired in August 2005 as part of a collaborative multidisciplinary effort to extend the high-resolution paleoclimate record in Santa Barbara Basin. Small red box in the inset shows the location of the Mona Lisa Suite of overlapping cores.*

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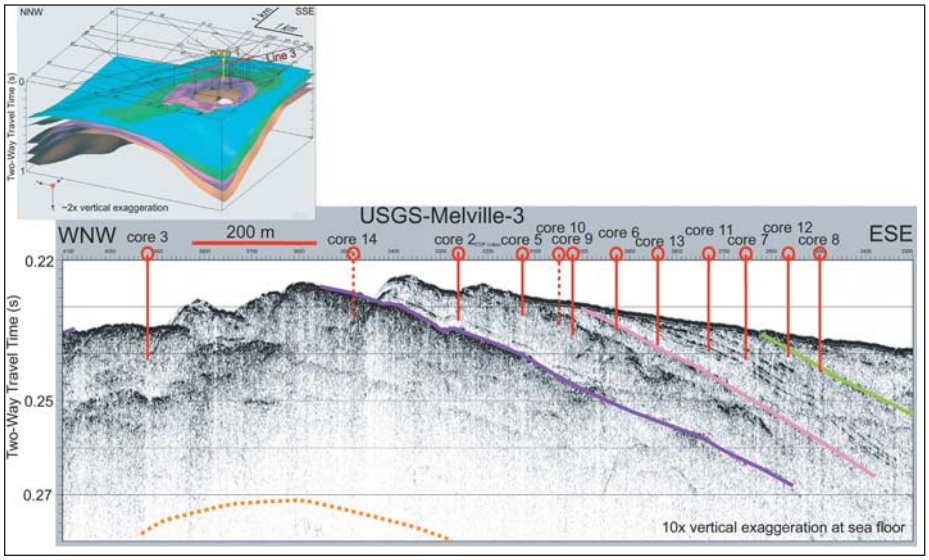

Fig. 2. High-resolution USGS-Melville chirp line 3 over the western culmination of the Mid-Channel trend showing dipping outcrop strata of late Quaternary age, mapped stratigraphic reference horizons (green, pink, violet, orange), and core locations along line with approximate core penetration depths converted to equivalent two-way travel time (seconds). (inset) Oblique cutaway view looking ENE across the western culmination of the Mid-Channel trend showing a grid of high-resolution seismic reflection lines (black) at the sea surface, five stratigraphic reference horizons used to define three-dimensional structure and outcrop stratigraphy, and locations of line 3 (red) and core 1 (yellow). Depth scale of volume is also in two-way travel time (seconds).

million years old. The global climate record produced and preserved in the basin is present in large part because of the basin's unique location within this tectonically active region. Detailed analysis of high-resolution multichannel seismic (MCS) reflection and single-channel data, and stratigraphic correlation with existing well data (including ODP Site 893) indicate that continuous, late Quaternary strata were deposited in the deep paleobathymetric basin beneath ODP Site 893.

These strata were subsequently uplifted, folded, and in places partially eroded across a young, active fault-related fold structure called the Mid-Channel trend (Figure 1) in the eastern Santa Barbara Channel. The result is a breached anticline that exposes at or near the seafloor a complete sequence of dipping upper bathyal sediments dating back to 500 ka or more (Figure 2), where they are now accessible to piston coring. By judicious sampling laterally in space across the anticline, much of these older, late Quaternary sequences can be systematically recovered.

Seismic Stratigraphy and Three-Dimensional Models

To determine specifically what stratigraphic sequences were present on the Mid-Channel anticline, a detailed seismic stratigraphy correlated to ODP Site 893 and other wells in Santa Barbara Basin was developed. This seismic stratigraphy included several distinctive sequence boundaries that seemed to correlate with major changes in late Quaternary global climate. By using different kinds of seismic reflection data, these sequence boundaries were consistently identified, correlated, and mapped across the basin to the Mid-Channel trend (Figure 2). Extensive grids of seismic reflection data were used. These included deep-penetration industry MCS data, high-resolution data recorded for seafloor hazard studies, and high-resolution seismic reflection and chirp data recorded by the U.S. Geological Survey (USGS) in 2002 specifically in anticipation of this coring project. Results of the mapping effort formed the basis for modeling the structure and stratigraphy of the Mid-Channel trend in three dimensions (Figure 2, inset), and for locating suitable sites for piston coring.

Towed Chirp and Coring Cruise

In August 2005, in collaboration with the USGS, 28 people, including 11 students, from nine institutions participated in a U.S. National Science Foundation (NSF)-funded towed chirp and coring cruise on the *R/V Melville*.

The primary purpose of this coring effort was to test a structural and stratigraphic model of the Mid-Channel trend and to answer the following questions:

- Are deep paleobasin sediments of late Quaternary age indeed present on the Mid-Channel trend, and are these sediments accessible at piston core depth?
- Do these sequences exhibit the undisturbed laminated character necessary to extract a high-resolution paleoclimate record, and can major climate transitions be identified and sampled?
- Can overlapping piston cores of dipping strata be acquired to produce longer, more continuous stratigraphic sections than normally available from just a single piston core?

With the first piston core, highly laminated deep basin sediments of late Quaternary age, alternating with more massive, bioturbated sequences, were recovered. These sequences are remarkably similar to the high-resolution stratigraphic sections from ODP Site 893. Many of the laminated sections retain the fine bimodal structure typically associated with annual (varved) deposits (Figure 3, photos), even though these older sediments are more compacted. In all, 32 piston cores were recovered over the Mid-Channel trend (Figure 1) ranging in length from about 3 to 5.5 meters. A 13-meter core in the deep basin near ODP 893 was also taken to resample the late Holocene.

A critical component of this coring program was the acquisition of high-resolution chirp data using the USGS deep-towed chirp system. As coring progressed, each new core location was selected interactively based on the newly acquired chirp data (Figure 2) integrated into a three-dimensional seismic interpretation system in near real time, and results from the previously recovered cores. This allowed researchers to take suites of overlapping piston cores across dipping outcrop strata to provide a more continuous, composite geologic record. Figure 3 shows the high-resolution chirp record used, and four overlapping cores of the 'Mona Lisa Suite,' so named because they provide a beautiful, textbook example of high-resolution piston core sampling near a major climate transition. Overlap was confirmed by correlating stratigraphic patterns of alternating laminated versus massive intervals, distinctive gray flood layers, and multisensor track density/porosity data.

Preliminary Core Results

The net result was that several suites of superb, high-resolution piston cores were thus acquired that provide critical 'windows' into the nature of past climate change during the late Quaternary. Based mostly on their relative seismic stratigraphic positions, the various core sections recovered from the Mid-Channel trend provide a range of ages (from ~130 ka to over 600 ka) previously unreachable by conventional methods. Nearly all of the cores exhibit the highly laminated (varved) sequences characteristic of the deep paleobathymetric Santa Barbara Basin, and, as many of the cores overlap stratigraphically, they likely provide a nearly continuous high-resolution record over much of this age range. More precise dating will result from a combination of biostratigraphy, tephrochronology, amino acid racemization, optically stimulated luminescence, and glacial-interglacial stratigraphy based on oxygen isotopes and planktonic foraminifera.

Preliminary microfossil studies indicate an abundance of well-preserved benthic and planktonic foraminifera throughout the sequence suitable for high-resolution climate and environmental investigations. Tentative age datums (one an ash layer, the other a biostratigraphic marker) have been found already in the oldest cores taken, suggesting

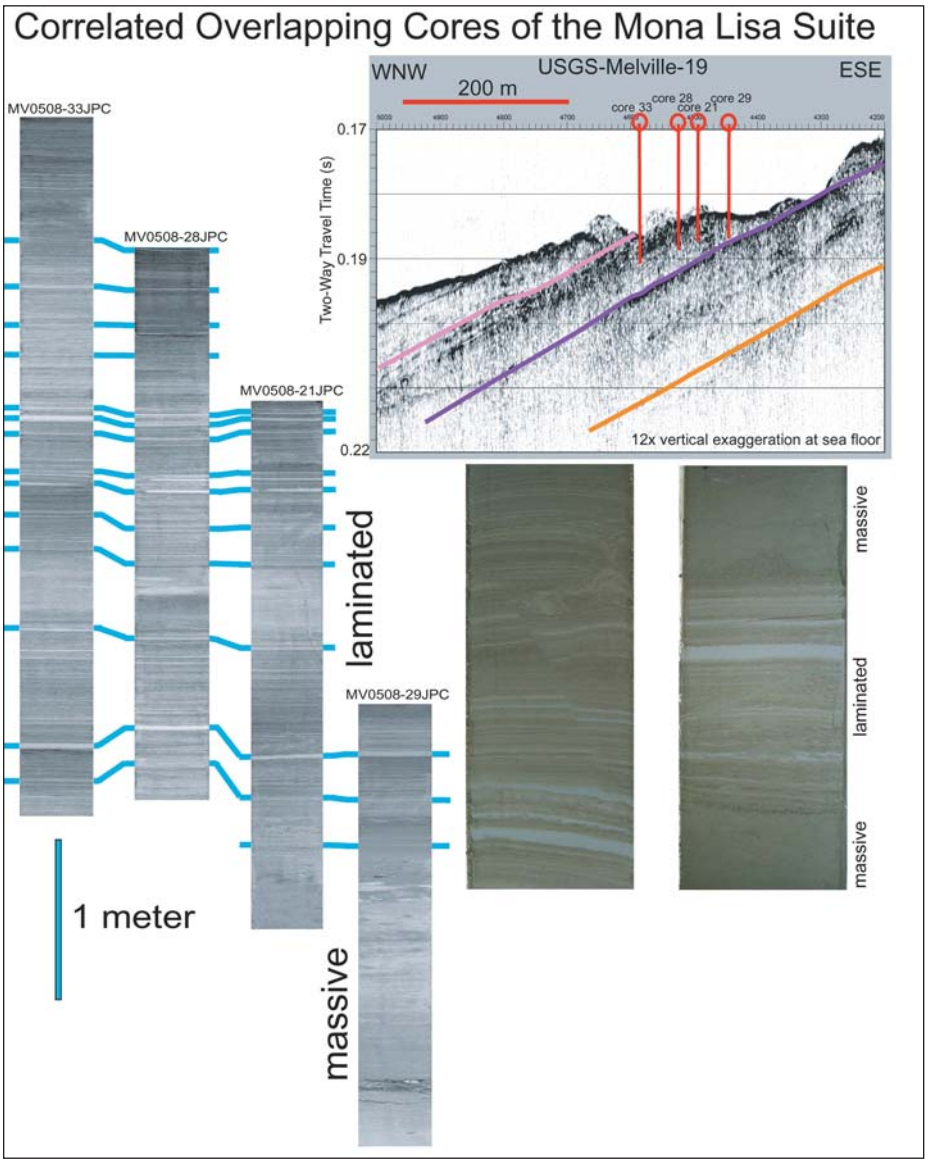

Fig. 3. (top) USGS-Melville chirp line 19 over the eastern culmination of the Mid-Channel trend and location of four overlapping piston cores of the Mona Lisa Suite. (left) Preliminary correlation of composite, overlapping Mona Lisa cores by distinctive 'gray-layer' flood event deposits, as well as patterns of alternating laminated and more massive deposits (inset photos). Core photos at left are horizontally exaggerated (4:1) to facilitate visual correlation. Correlation is being refined using multisensor track (MST) density, porosity, velocity, and magnetic susceptibility logs.

that core sampling may have extended back to about 700 ka. Sediments and microfossil sequences suggest a late Quaternary basin environment involving major changes in oxygenation state and inferred millennial-scale climatic oscillations that were evolving toward those documented at ODP Site 893.

Taken together, the cores will likely provide one of the highest-resolution paleoclimate records yet recovered from the world's oceans. The cores will be used to investigate critical aspects of mid-latitude climate behavior, including the nature and speed of abrupt climate change and the character of climate variability during this older time period. Moreover, the cores confirm that a continuous marine paleoclimate archive of unprecedented resolution extending back to the mid-Pleistocene is indeed present, preserved, and accessible by future drilling in Santa Barbara Basin.

Acknowledgments

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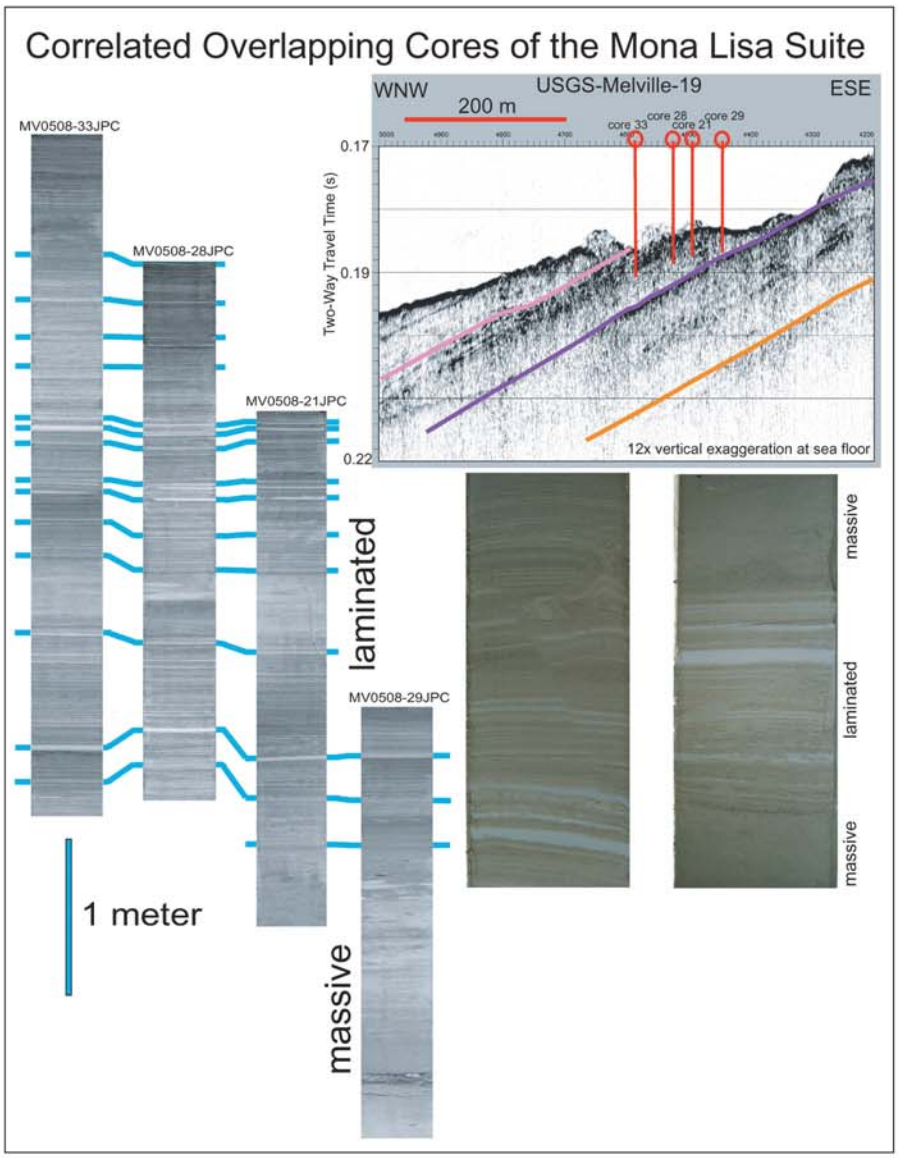
Correction

In the feature article, "Santa Barbara Basin Study Extends Global Climate Record," published in the 23 May 2006 issue (*Eos*, 87 (21), 2006), Figure 3 was inadvertently not printed in full. The correct Figure 3 is reproduced below in its entirety.



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