Lyle, M., Koizumi, I., Richter, C., et al., 1997
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1. LEG 167 INTRODUCTION[1]

Shipboard Scientific Party[2]

The California Current system is probably the best investigated eastern boundary current system in the world, with well-known physical dynamics, chemical structure, biological standing stocks, and biogeochemical fluxes. Nevertheless, the response of the California Current system and associated coastal upwelling systems to climate change is poorly documented. Climate models and available paleoceanographic data indicate that the California Current system changed dramatically with the growth and decay of the North American ice sheets. The paleoceanographic records, however, remain too sketchy to test the models (Kutzbach, 1987; Lyle et al., 1992).

Ocean Drilling Program (ODP) Leg 167 (Fig. 1) represents the first time since 1978 that the North American Pacific Margin was drilled to study ocean history. The leg shipboard scientific party collected both high-resolution records appropriate for studying events with durations of a few thousand years or less within the Pleistocene and Pliocene and lower resolution records to examine the record since the middle Miocene. Sites were drilled to collect sediments needed to study the links between the evolution of north Pacific climate and the development of the California Current system. The same material also will be used to study the climate links between the North Pacific Ocean and North America.

Only three other drilling legs, all part of the Deep Sea Drilling Project (DSDP), have sampled the sediment record along the California Margin (Table 1). The last major drilling effort of these three, DSDP Leg 63, occurred immediately before the first deployment of the advanced hydraulic piston core (APC). Recovered core from the DSDP drilling is discontinuous and very disturbed, so it is impossible to use this material for modern high-resolution paleoceanographic studies. Reconnaissance studies using DSDP cores and marine sedimentary sections exposed on land have shown, however, that the Leg 167 drilling region is highly sensitive to climate change (Fig. 2; Ingle, 1973) and that new ODP drilling would collect a detailed record of this variability.

ODP Site 893 in the Santa Barbara Basin collected the first continuous high-resolution sediment record from the California Margin (Table 1; Westbrook, Carson, Musgrave, et al., 1994; Kennett, Baldauf, and Lyle, 1995), with this APC representing all of ODP drilling along the California Margin prior to Leg 167. The 160 k.y. record shows that the region responds strongly to insolation changes. In addition, there are events in the Santa Barbara Basin record that may be related to Dansgaard-Oeschger events in the Greenland ice core records (Behl and Kennett, 1996).

Paleoceanographic studies along the California Margin using standard piston coring have suffered because sedimentation rates are so high that it is difficult to sample a full glacial cycle even with the longest standard piston cores. Nevertheless, the late Pleistocene paleoceanography of the region is now a subject of lively research (Gardner and Hemphill-Haley, 1986; Anderson et al., 1989; Lyle et al., 1992; Sancetta et al., 1992; Karlin et al., 1992; Prahl et al., 1995; Kennett and Ingram, 1995; Kennett, Baldauf, and Lyle, 1995; Ortiz

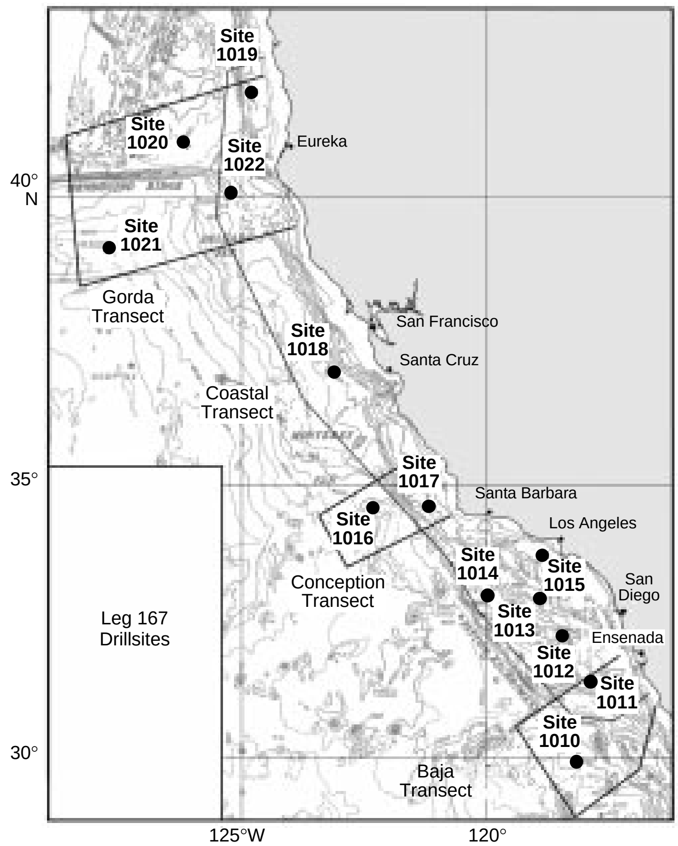

Figure 1. Location map for Leg 167 drill sites along the California Margin of North America. The coastal and onshore/offshore transects of Leg 167 have been outlined. Bathymetry is from Mammerickx (1989).

Table 1. Scientific drilling on the California Margin before Leg 167.

Site	Year drilled	Latitude	Recovery (%)
DSDP Site (Rotary drilled)			
36	1969	41°	99
35	1969	40.5°	24
173	1971	40°	58
34	1969	39.5°	28
33	1969	39.5°	38
32	1969	37°	40
467	1978	34°	41
468	1978	32.5°	35
469	1978	32.5°	39
470	1978	29°	54
ODP Site (APC drilled)			
893	1992	34°	100

[1] Lyle, M., Koizumi, I., Richter, C., et al., 1997. *Proc. ODP, Init. Repts.,* 167: College Station, TX (Ocean Drilling Program).

[2] Shipboard Scientific Party is given in the list preceding the Table of Contents.

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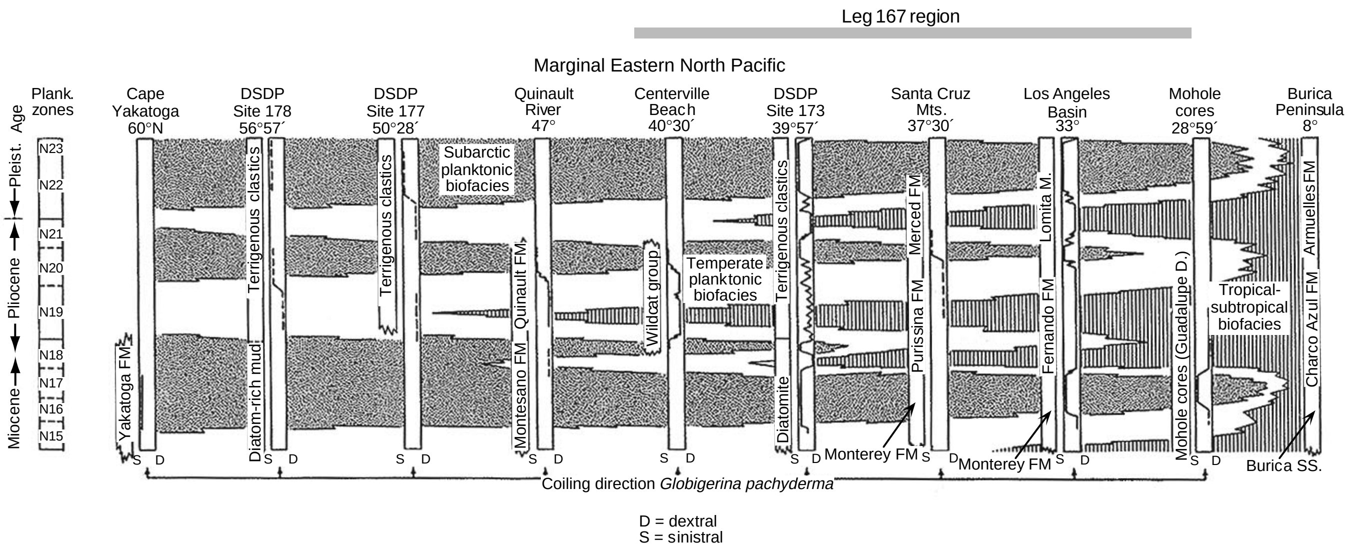

Figure 2. Schematic representation of major oscillations of temperature-sensitive planktonic foraminiferal biofacies within the California Current system and related Alaskan Current Gyre during the later Miocene through Pleistocene interval (from Ingle, 1973). FM = formation; SS = sandstone.

et al., in press). Much of the current research focuses upon the large temperature changes along the coast since the Last Glacial Maximum and the possible formation in glacial intervals of a strong source of cold, oxygenated, intermediate waters. These signals should be more apparent in the longer records that have been obtained during Leg 167.

BACKGROUND

Climatology and Oceanography of the California Margin

The modern California Current system is probably the best studied of the world's eastern boundary currents, and, because of these modern data sets, it is possible to reconstruct its past behavior with much greater confidence than for any other in the world. The California Cooperative Fisheries Program (CalCOFI) has taken seasonal measurements of hydrography and biology in transects across the current for more than 30 yr. Major physical oceanography experiments such as Coastal Upwelling Experiment and Analysis (CUEA), Coastal Dynamics Experiment (CODE), and the West Coast Satellite Time Series and Coastal Transition Zone program (Brink and Cowles, 1991, and references therein) are linking the dynamics of California Current flow and coastal upwelling to climate.

More long- and short-term studies of biogeochemical flux are available from this region than anywhere else in the world. They include the VERTEX study (Knauer et al., 1979; Knauer and Martin, 1981), MULTITRACERS (Ortiz et al., in press; Lyle et al., 1992; Dymond and Lyle, in press), Low Level Waste Disposal Project (Fischer et al., 1983; Dymond and Lyle, in press), long-term sediment trap deployments off Monterey (C. Pilskaln, unpubl. data), and short-term, sediment trap deployments in the California Borderland region (Dymond et al., 1981; Sautter and Thunell, 1991; J. Kennett, unpubl. data).

Dynamics of the California Current

The California Current combines diffuse southward flow extending hundreds of kilometers offshore with local high-velocity zones of southward flow. The southward jets separate nutrient-rich upwelled waters from the relatively barren offshore waters (e.g., Huyer et al., 1991). The core of the offshore California Current flow is located approximately 250−350 km from the coast at the border of Oregon and California and is about 300 km from the coast at Point Conception (~35°N; Hickey, 1979; Lynn and Simpson, 1987).

It is well known that the California Current is subject to both seasonal and interannual cycles. The pattern of winds along the coast controls seasonal variations (Fig. 3), whereas changes in the dynamic topography of the North Pacific Gyre produce interannual variability in the current (Fig. 4). California Current structure thus reflects both the local winds along the west coast of North America and basinwide events within the north and equatorial Pacific Ocean. The importance of both local and remote forcing in California Current flow has been emphasized by such modeling efforts as those of Pares-Sierra and O'Brien (1989), who found that the local wind field in the northeastern Pacific is adequate to drive the annual cycle of the current system and to create the general features of its structure. They could only model interannual variations of the California Current by coupling the local model with one driven by equatorial winds. Kelvin waves generated during El Niño−Southern Oscillation (ENSO) events in the equatorial Pacific propagate up the western coast of North America and strongly affect the California Current.

The modeling indicates that in the much longer climatic cycles that are observable by paleoceanographic studies, the location and strength both of trade winds and of westerlies should probably have a major impact on mean transport in the California Current. Shifts of the mean wind patterns (e.g., a shift in the position of the North Pacific high at the Last Glacial Maximum; Kutzbach, 1987; Kutzbach et al., 1993) should also strongly affect the structure of the California Current flow as well as the locations of maximum coastal upwelling. The available data support these interpretations.

Coastal California Upwelling

Upwelling along coastal California is driven by equatorward winds that roughly parallel the coast (Figs. 3, 5; Huyer, 1983). These winds cause Ekman transport of surface waters away from the coastline and upwelling of subthermocline nutrient-rich waters. The upwelling waters are restocked by shallow flow toward the shelf beneath the surface ocean layer. In northern California, the winds are seasonally to the south but, south of San Francisco, always blow toward the equator. The strongest, upwelling-favorable winds are in the north during the seasonal upwelling period. Today, this wind pattern causes the strongest July coastal upwelling to be located between Cape Blanco and San Francisco, but, in the winter months, it causes

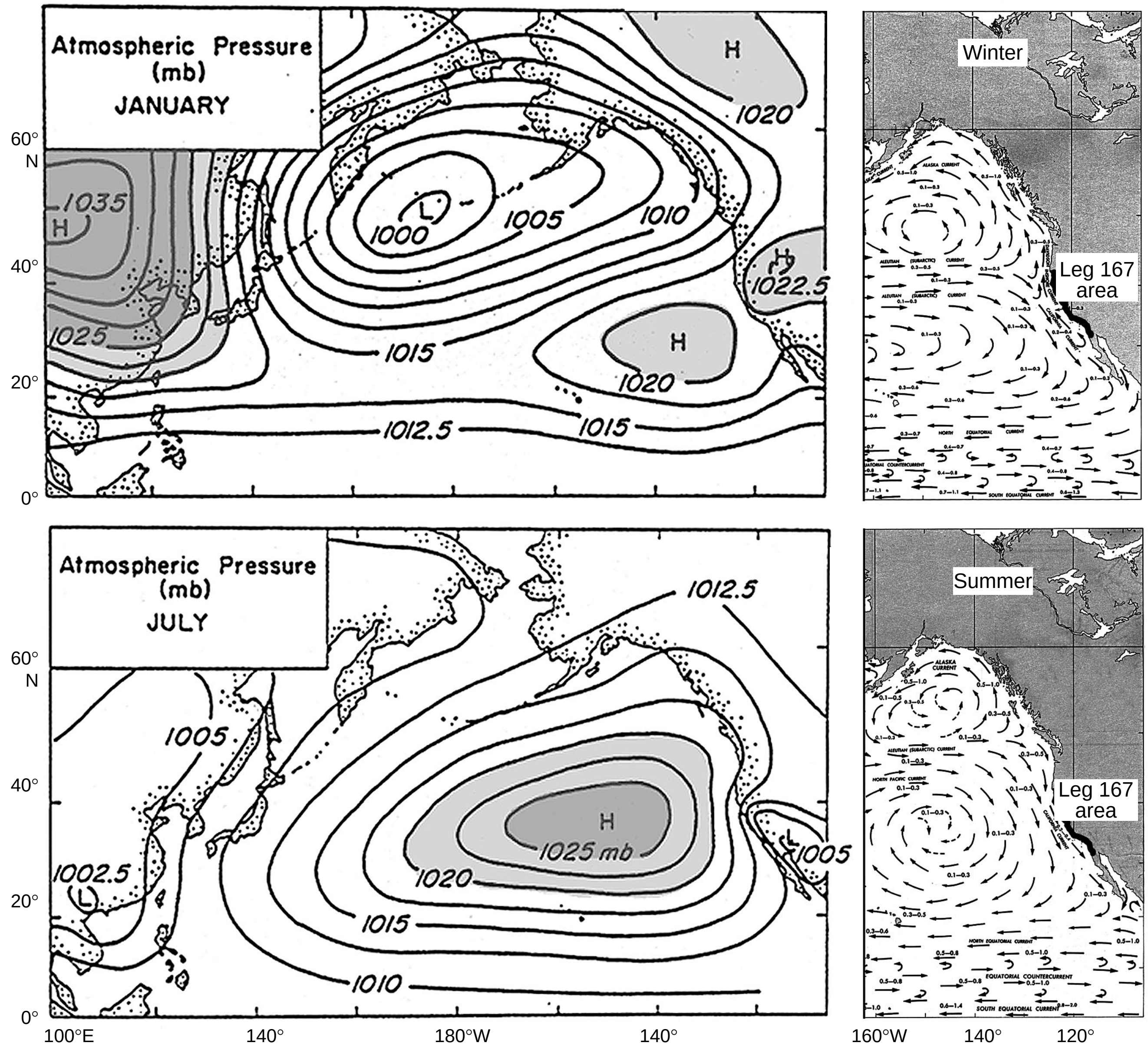

Figure 3. Surface atmospheric pressure, winter and summer (from Huyer, 1983), compared to seasonal changes in northeast Pacific surface currents (Defense Mapping Agency, 1989). Surface winds will approximately parallel atmospheric pressure gradients. Note that seasonal variation in current patterns is driven by northeastern Pacific winds. Note also how the high and low pressure associated with the Asian monsoon helps to strengthen northeastern Pacific wind patterns in both summer and winter.

the strongest upwelling to be located south of San Diego (Fig. 6; Huyer, 1983).

The seasonal cycle of winds and upwelling is a direct result of the annual migration of the North Pacific high-pressure regime. The North Pacific high migrates between its southerly limit at 28°N in February and its most northerly limit, 38°N, in July (Fig. 3; Huyer, 1983). By thus monitoring the strength and seasonality of coastal upwelling along coastal California with paleoceanographic data, we will be able to track the latitudinal position and strength of the North Pacific high as climate changes.

Deep-Water Circulation, North Pacific Ocean

The California Margin should be strongly affected by changes in formation of bottom water in the Antarctic, because it is directly upon a flow path for this bottom water into the North Pacific (Fig. 7; Gordon and Gerard, 1970; Mantyla, 1975). Newly formed bottom waters enter into the Pacific near New Zealand and move up along the western boundary of the Pacific Ocean. Bottom-water flow splits around the Hawaiian Islands and flows northeastward before the addition of buoyancy causes general upwelling in the Alaska Gyre region. One of the deep-water paths flows directly into the California Margin, creating a region favorable for monitoring changes in Pacific deep-water properties. For this reason, in the Leg 167 drilling program, we have emphasized sampling a range of depths from about 900 m to 4200 m (Fig. 8).

Intermediate Water Circulation, California Borderland

The basins of the California Borderland (Sites 1011 through 1015; Fig. 1) form a depth transect that samples upper intermediate water

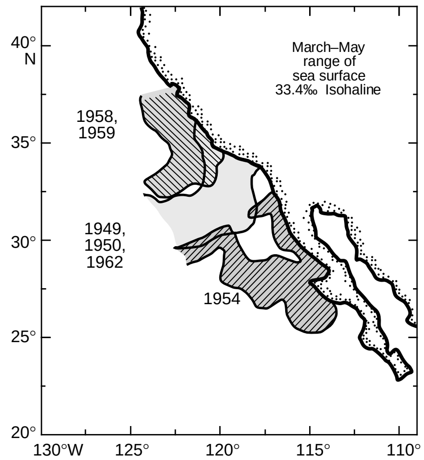

Figure 4. Illustration of strong interannual variation in California Current transport, from the CalCOFI data set (from Roessler and Chelton, 1987). Cold years (1949, 1950, 1954, and 1962) are typified by strong equatorward transport of subarctic (low salinity) water. Warm years (1958, 1959) are typified by weak equatorward transport. Most of the interannual variation is coupled to El Niño–Southern Oscillation (ENSO) events in the equatorial Pacific (Pares-Sierra and O'Brien, 1989).

structure in detail. Water flows into the California Borderland from the south, and each basin is filled with intermediate water at its sill depth (Table 2; Fig. 9). The sills block deeper water of higher density from entering the basin, so the benthic water mass in each basin is a sample of the intermediate waters at the sill depth (Fig. 10; Emery, 1960). Actual bottom-water temperatures measured during sediment heat flow runs on Leg 167 match expected bottom-water temperatures extrapolated from sill depths. The inclusion of a nearby slope site (Site 1017) adds additional detail in the upper part of the water column. The intermediate water profile produced by this strategy, including ODP Site 893, extends from about 500 mbsl to 1700 mbsl.

Nonconservative water mass properties like dissolved nutrients and oxygen will change in the deep waters of the California Borderland basins because the surface waters above are high in productivity and the basins' particulate flux is high in organic matter. Nevertheless, each basin inherits a signal from the open ocean (Fig. 11; Emery, 1960). The deep basins (e.g., San Clemente or East Cortes Basin) have significantly higher dissolved oxygen contents than shallower ones because of the oxygen minimum. All basin deep waters have less oxygen than the open ocean at an equivalent depth because of the local oxidation of organic matter. Nutrient profiles developed with these basins will also be a combination of local regeneration of nutrients superimposed upon regional gradients.

Tectonics of the California Margin

Tectonics not only defines the sedimentation history of many of the continental slope basins drilled on Leg 167 but also their positions. Leg 167 drilled sites hypothetically on three plates—the Pacific, Gorda, and North American Plates. Many of the sites, however, were drilled within the transition region between these three plates. The sites have been transported with motions that are intermediate between the motions of the major plates. Because of regional tectonics, many Leg 167 drill sites have moved relative to the others (see Lyle, this volume).

Much of the Pacific coast of North America is within a transition region between the Pacific and North American Plates (Bohannon and Parsons, 1995). The California Borderland sites, for example, have moved with neither Pacific Plate nor North American Plate motion. Sites 1011, 1012, 1013, 1014, 1015, 1017, 1019, and 1022 are in continental slope basins at the edge of North America (Fig. 12) and have all moved with respect to stable North America in the Neogene. The exact motion they have experienced is still being debated. Motion between the Pacific and North American Plates was concentrated in the early and middle Miocene along faults west of the San Andreas Fault. The San Andreas fault became the locus of Pacific/North American translational motion during the latest Miocene (Atwater, 1989). Apparently, because the Mendocino Triple Junction is unstable, the locus of translational motion periodically steps inward into continental North America. Slivers of continent are translated northwestward with time, and, periodically, new basins are formed in the south.

Other complexities affect the tectonics in the immediate vicinity of the Mendocino Triple Junction (Riddihough, 1980; Wilson, 1989; Magill, 1981). Because of deformation on the Gorda Plate as the southern part of the spreading center is being captured by the Pacific plate, actual plate motion with respect to North America is to the northeast (Fig. 13). Drag from the subducting slab may induce some unusual forces underneath the Eel River basin (Site 1019). In addition, rifting and extension of the Basin and Range Province expresses itself as another northwestward motion while the coastal ranges of Oregon and southern Washington are involved in a separate but probably related rotation toward the west north of 43°N.

SCIENTIFIC OBJECTIVES

The oceanographic and climate histories of the eastern and western equatorial Pacific (ODP Legs 138 and 130, respectively) and the high-latitude North Pacific (ODP Leg 145) have already been explored with scientific drilling, but sediments reflecting the history of the California Current and the temperate North Pacific, the oceanographic link between the two regions, had not previously been recovered using modern drilling techniques. Results from a single site in the Santa Barbara Basin (ODP Site 893) demonstrated decadal- to millennial-scale variations in intermediate and surface water properties linked to changes in North Atlantic climate. Climate model simulations indicate that the northeastern Pacific surface ocean and land surface are extremely responsive to Northern Hemisphere glaciation. During ODP Leg 167, 13 sites were drilled—Sites 1010 through 1022—along the climatically sensitive California Margin (Fig. 1; Table 3). These sites are arrayed in a series of depth and latitudinal transects to reconstruct the Neogene history of deep, intermediate, and surface ocean circulation and to understand the paleoclimatic and geochemical history of this region.

Leg 167 sites provide an opportunity to address paleoceanographic questions about the evolution of the California Current and the links between high and low latitudes from millennial and orbital to tectonic time scales. Shipboard results document the suitability of these sediments for addressing these questions. Sites have continuous sedimentation records with high deposition rates. Calcium carbonate is present throughout the records, and foraminifers for oxygen and carbon isotopic studies are generally common to abundant. Pioneering biostratigraphy will refine the chronostratigraphic control for this otherwise poorly constrained oceanic regime. Magnetostratigraphy constrains the age models at many sites, and advances in understanding magnetic reversals and the effects of sediment diagenesis on magnetic signals will be possible from these sediments. Significant variations occur in sediment properties on all time scales as seen in high-resolution nondestructive shipboard measurements (e.g., bulk density, magnetic susceptibility, natural gamma-ray activity, all from the multisensor track, and color reflectance and color video imaging), high- to intermediate-resolution downhole log measurements (e.g., bulk density, resistivity, and magnetic susceptibility), and lower-resolution discrete shipboard measurements (e.g., physical properties and carbon geochemistry). Key topics for investigation include variations in productivity, upwelling, sea surface temperature, hydrography, sedimentation fluxes, and carbon and nutrient budgets.

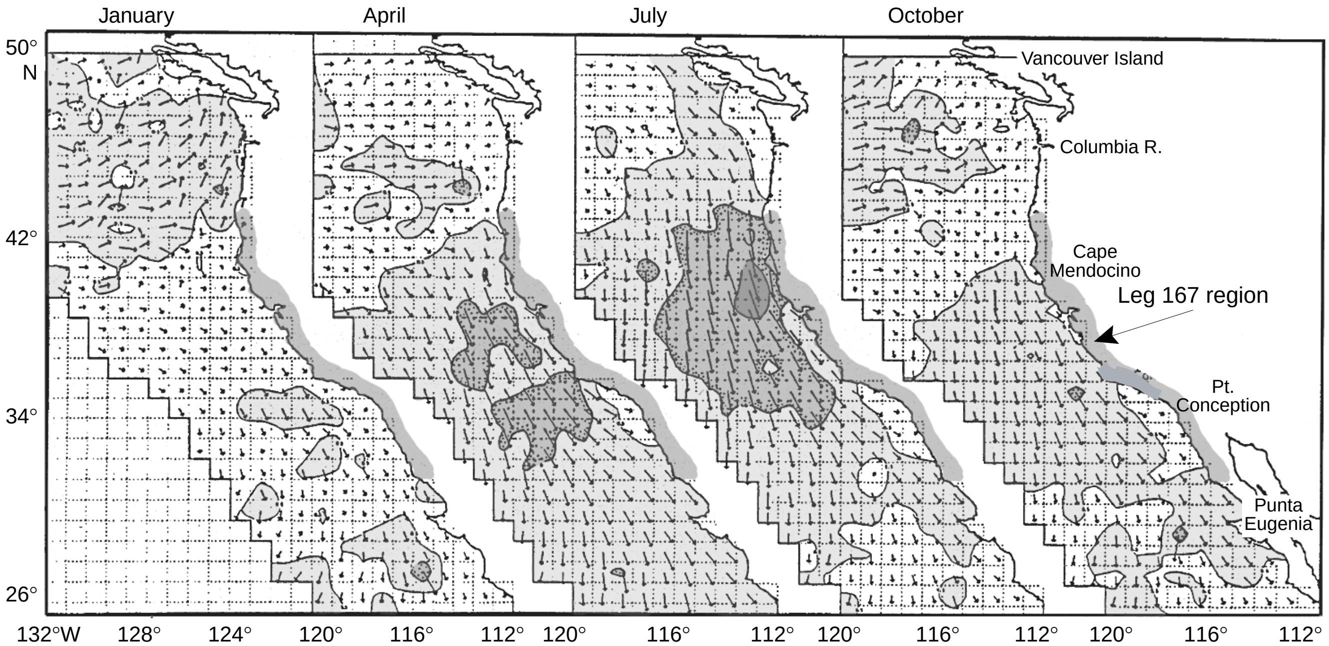

Figure 5. Seasonal wind stress along the California Margin from ship reports in the period 1854 through 1972 (from Huyer, 1983). Darkest shading marks wind stress >1.5 dynes/cm^2, whereas intermediate and light shading represents 1.0–1.5 and 0.5–1.0 dynes/cm^2, respectively. Upwelling wind stress (southward vectors parallel to the California Margin) varies tremendously by season. Just north of the Leg 167 region at about 45°N, there is little seasonal upwelling; instead, there are short upwelling events. The northern end of the Leg 167 region exhibits the highest seasonality because of movements of the northeast Pacific high.

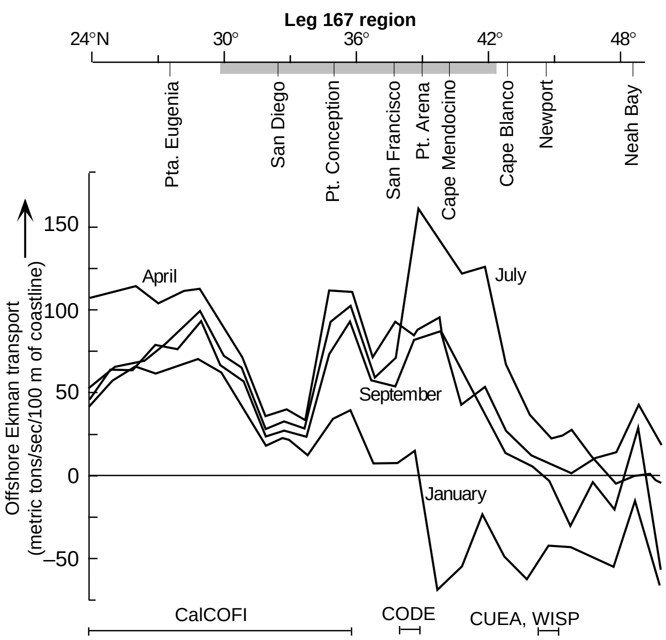

Figure 6. Offshore Ekman transport, computed from long-term mean wind stress data for one-degree squares adjacent to the coast, for January, April, July, and September (from Huyer, 1983). Bars indicate the alongshore extent of major upwelling studies. See text for abbreviations.

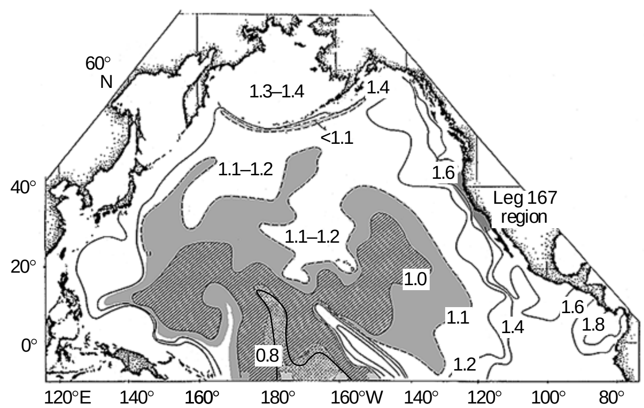

Figure 7. Modern deep-water flow paths in the Pacific Ocean, based upon bottom potential temperature (Gordon and Gerard, 1970). Young bottom waters are directed toward the Leg 167 region.

Research Themes

Priority ocean history research objectives for the California Margin sites focus on a few major threads. These are (1) documenting the record of surface ocean processes in the northeastern Pacific, (2) documenting intermediate and deep water variability in the northeastern Pacific, (3) establishing accumulation rate records for major and minor sedimentary components as records of carbon and nutrient budgets and of terrestrial inputs, and (4) investigating the links between the oceanographic evolution of the northeastern Pacific and continental records of marine and terrestrial processes.

Several other research threads are necessary and significant prerequisites for achieving these ocean history goals and for relating results from individual drill sites to regional scale syntheses and global records. These are (5) defining accurate depth and age frameworks for all sites, (6) defining geophysical and tectonic frameworks for all sites (including site backtracks and the ties between sediment properties and seismic reflectors), (7) defining the accuracy and resolution of geochemical, sedimentological, and oceanic signals in California Margin sediments, and (8) defining the role of diagenesis in the loss

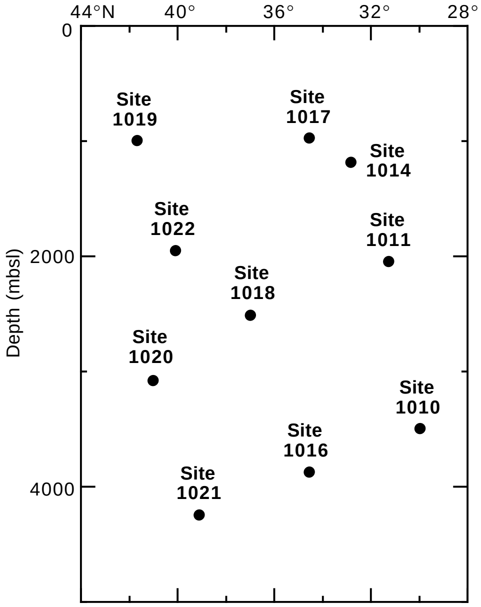

Figure 8. Depths of Leg 167 open ocean drill sites, to illustrate the depth profiles that will be studied post-cruise.

Table 2. Sill depths for Leg 167 drill sites in the California Borderland basins.

Basin name	Proposed site	Site	Sill depth
Santa Monica Basin	BA-4	1015	737 m*
Santa Lucia Slope	CA-9	1017	974 m
San Nicolas Basin	BA-2	1013	1106 m*
Tanner Basin	CA-15	1014	1164 m*
East Cortes Basin	BA-1	1012	1415 m*
Animal Basin	CAM-2	1011	~1600 m

* From Emery (1960).

of geochemical, sedimentological, and oceanic signal fidelity through time.

Unique Scientific Opportunities Along the California Margin

Besides more general themes, the California Margin provided an opportunity to sample gas hydrates in the Eel River Basin (Site 1019). We assumed that the gas hydrate interval should be located above a bottom-simulating reflector that was observed in the site survey at about 200 mbsf. The study of the structure, composition, and environment of a potential gas hydrate section should provide important information on the potential to store methane, a greenhouse gas, in continental margin sediments. APC coring of the east flank of the Gorda Ridge (Site 1020) with core orientation should help to constrain deformation processes on the Gorda Plate and better understand the tectonics in this tectonically complex region. At Sites 1010, 1011, and 1020, basement was also sampled for later petrologic studies.

Site Characteristics

Significant contrasts in sedimentary environments occur along the California Margin, including the unique tectonic and sedimentary environments of the basins in the California Borderland. Site selection exploited these opportunities, constructing latitudinal, longitudinal,

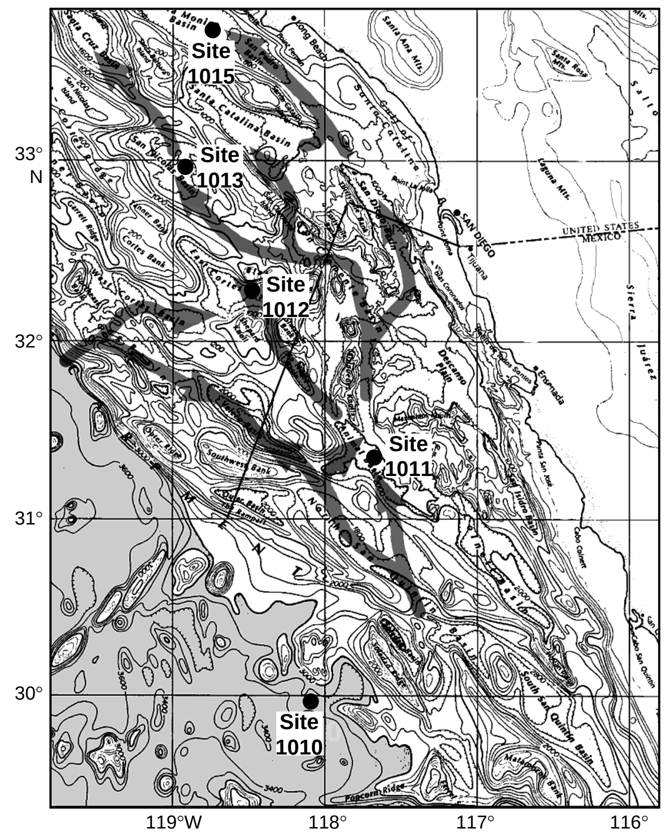

Figure 9. Water flow paths for the California Borderland, based on water temperatures below sill depths in each basin (from Emery, 1960).

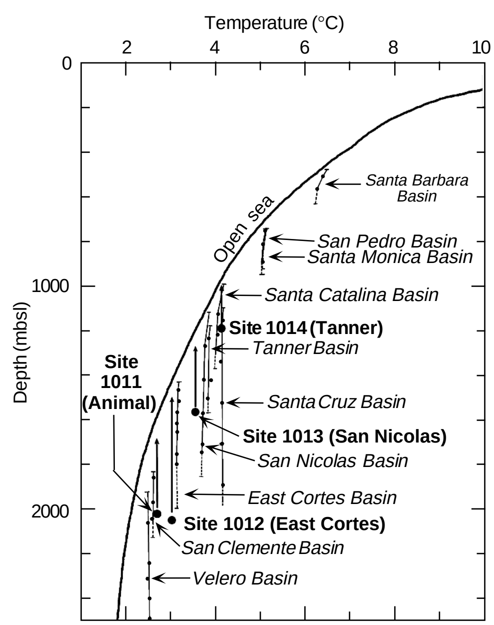

Figure 10. Temperature profiles below the sill depth (marked by curved line) in the California Borderland basins (from Emery, 1960). In bold are Leg 167 drill sites, each located at its bathymetric depth and by the bottom water temperature measured for sediment heat flow. Sill depths based upon the ocean temperature profile match the bathymetrically defined sill depths of the basins.

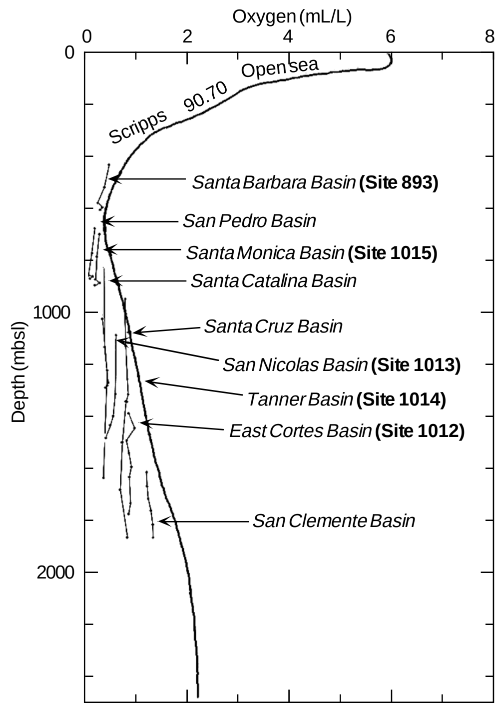

Figure 11. Oxygen profiles within each California Borderland basin (from Emery, 1960). As a rule, the oxygen content in benthic waters from each basin is inherited from the open ocean—basins near the oxygen minimum have significantly less dissolved oxygen than deeper basins. Nevertheless, local organic matter degradation consumes additional oxygen.

and depth transects. There are three east-west transects, with at least two sites in each transect, one located in the coastal upwelling zone (from 50–90 km offshore, 1000–2000 m water depth) and one in the core of the California Current proper (from 150–360 km offshore, 3500–4200 m water depth). The **Gorda Transect** (~40°N—Sites 1019, 1022, 1020, and 1021) is in a region of strong summer upwelling. The **Conception Transect** (~35°N—Sites 1017 and 1016) is influenced by year-round upwelling with relatively cool surface waters. The **Baja Transect** (~30°N—Sites 1011 and 1010) is influenced by year-round upwelling with warmer surface waters. The oldest sediments from the inshore sites are Pleistocene and from the offshore sites, middle or upper Miocene. Coastal upwelling processes at the margin will be reflected in the nearshore sites, while nutrient supply by California Current processes will be reflected in the deeper sites.

The north-south **Coastal Transect** covers the latitude range of 31° to 42°N (in order from north to south, Sites 1019, 1022, 1018, 1017, 1014, 1013, 1012, and 1011). All sites are <160 km offshore, in water depths of 1000–2500 m. Oldest sediments from all sites are at least Pleistocene, with some that range to the upper Miocene. The coastal transect will detail the history of coastal upwelling and of continent-ocean interaction.

Sites also constitute two depth transects. The **Northern Depth Transect** (~37° to 42°N, from 60–360 km offshore—Sites 1019, 1022, 1018, 1020, and 1021) covers 1000–4200 m water depth. Oldest sediments from Site 1019 are Pleistocene, while the sediments from the deepest water site (Site 1021) range from uppermost middle Miocene to Quaternary. The **Southern Depth Transect** (~30° to 35°N, from 30 to 210 km offshore—Sites 893 [Leg 146], 1015, 1017, 1013, 1014, 1012, 1011, 1010, and 1016) covers 475–3850 m water depth. This transect takes advantage of the different sill depths within the California Borderland for detailed study of the shallow intermediate water column. The oldest sediments from sites with the shallower water depths are at least upper Pleistocene, while basal sediments from the sites with deeper water depths are typically upper Miocene. These depth transects will provide sediments to investigate hypotheses about water depth control of sedimentation processes and water column structure and its evolution through time.

Drilling and Logging Strategy

Because of the need to collect continuous sedimentary sections, sites were triple-piston cored at a minimum; typically, two APCs were taken to refusal, whereas the third was taken to 100 mbsf or more. Extended core barrel (XCB) drilling deepened the drill holes to their total depths. Deep-water sites on each of the transects and one site on the continental slope were drilled to basement (or massive chert in the case of Site 1016). Basement was sampled when possible with the motor-driven core barrel (MDCB), if appropriate. Many sites in the coastal transect were planned to be shallow because at this stage of our understanding of the California Current system, a higher priority was placed upon obtaining the geographic coverage needed to better understand the Pleistocene and late Pliocene climatic interval than to sample the entire sediment column at any given drill site. Older Neogene sediments were collected at the deep-water drill sites but with only moderate success. Because massive chert was encountered at Site 1016, only an upper Miocene to Holocene section was recovered, while surprisingly high sedimentation rates at Site 1021 meant that we recovered approximately one-third of the total possible age interval after sampling more than three-quarters of the projected depth interval. Only Site 1010 completely achieved its Neogene objective.

The logging program on Leg 167 was designed to detect physical properties that result from variations in biogenic calcium carbonate, biogenic opal, and terrigenous deposition associated with regional paleoclimate and paleoceanographic changes. Coring was not always continuous over deeper intervals because of gas expansion or coring disturbance, so downhole log data presented excellent resources for developing continuous, quantitative paleoclimatic and paleoceanographic time series. Logging at most sites comprised the density-porosity combination (natural gamma-ray activity, resistivity, density/porosity) and combined sonic-Formation MicroScanner, with inclusion of the geological high-sensitivity magnetic tool (GHMT) for most holes.

Expected Scientific Results From Leg 167

The response of California Current structure and hydrography to insolation forcing and Northern Hemisphere glaciation will be defined by Leg 167 studies, as will the longer term oceanographic evolution of the northeastern Pacific. The sediments collected on Leg 167 will provide one of the first direct opportunities to quantify the linkages between tropical and polar climates over a broad spectrum of age scales. The Neogene histories of biogenic calcium carbonate and biogenic opal accumulation at these drill sites will constrain their basinal and global distributions. Results from the depth transect sites will shed light on questions about deep-water hydrography, such as the existence and significance of Pacific intermediate- or deep-water formation and the linkages between deep Atlantic and Pacific circulation and calcium carbonate burial. Significant advances in the understanding of regional biostratigraphy, of the origin of physical property variations, of rock magnetic properties, and of lithologic cyclicity will result as well. Modeling, ranging from simple box models to coupled ocean/atmosphere models, will complement data interpretation. Diagenesis of organic matter and inorganic components in sediments will be much better understood from the study of interstitial water and solid phase composition from the variety of different environments drilled during Leg 167.

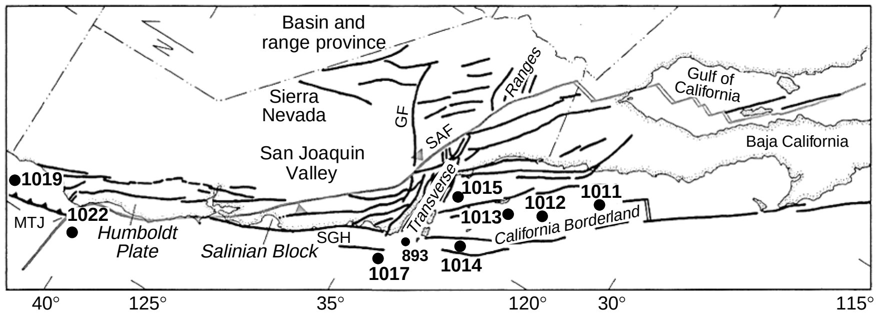

Figure 12. Leg 167 drill sites on continental crust, displayed on a tectonic map from Atwater (1989). All these coastal drill sites may have moved with respect to both the North American and Pacific Plates. MTJ = Mendocino Triple Junction; SGH = San Gregorio-Hosgri Fault; GF = Garlock Fault; SAF = San Andreas Fault.

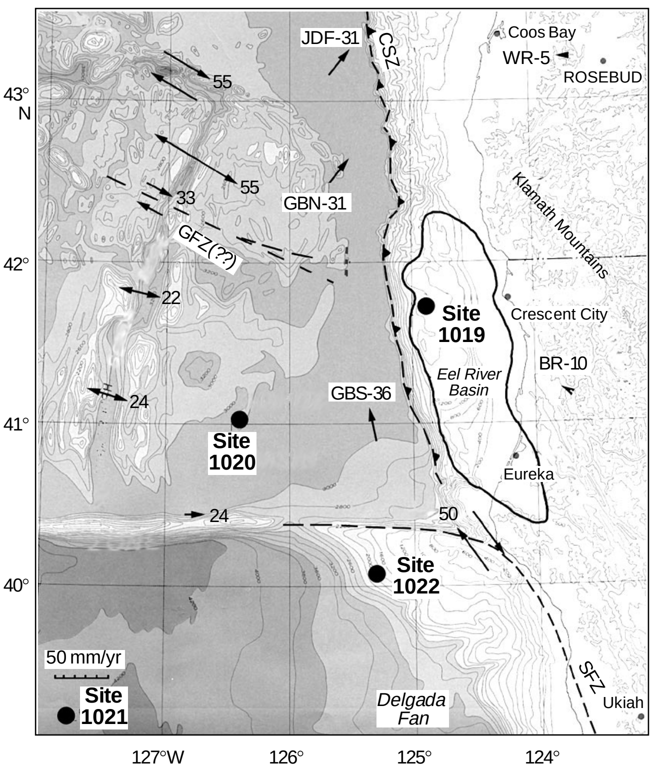

Figure 13. Location map for Gorda Transect drill sites, from Gallaway (in press). Also shown are full spreading rates along the Gorda Ridge in millimeters per year, and plate motions in millimeters per year with respect to the stable interior of North America (GBS = Gorda Basin South; GBN = Gorda Basin North; JDF = Juan de Fuca Plate; BR = Basin and Range rifting; WR = Willamette Block Rotation); SFZ = San Andreas Fault Zone, where most of the motion between the Pacific Plate and North America is concentrated; GFZ = possible Gorda Fracture Zone; CSZ = Cascadia Subduction Zone.

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Table 3. Leg 167 drill sites.

Site	Location	Distance from shore (km)	Water depth [Basin sill depth][a] (m)	Sediment thickness drilled (mbsf)	Age of oldest sediment recovered[b] (Ma)	Linear sedimentation rate range (mcd/m.y.)[c]
1010	Ocean crust near Guadalupe Island	209	3465	209	middle Miocene (14.0)	5–24
1011	Animal Basin	85	2033 [1600]	276	late Miocene (9.0)	24–45
1012	East Cortes Basin	105	1783 [1415]	274	late Miocene (5.0)	37–80
1013	San Nicolas Basin	115	1575 [1106]	146	late Pliocene (2.8)	34–73
1014	Tanner Basin	155	1177 [1165]	449	late Miocene (5.0)	27–214
1015	Santa Monica Basin	31	912 [737]	150	late Pleistocene[d]	
1016	Pelagic site, off Point Conception	148	3846	317	late Miocene (6.3)	10–72
1017	Santa Lucia Slope	52	967	204	Pleistocene (1.5)	118–204
1018	Sediment drift, south of Guide Seamount	76	2476	426	late Pliocene (3.5)	56–193
1019	Eel River Basin	59	989	248	Pleistocene (1.0)	122–498
1020	Eastern flank, Gorda Ridge	167	3050	278	early Pliocene	40–120
1021	Outer Delgada Fan	364	4215	310	middle Miocene	10–40
1022	Delgada Slope	87	1927	388	Miocene?	~110
893	Santa Barbara Basin (Leg 146)	15	577 [475]	200	late Pleistocene	1200

[a] The sill depths for ventilation of the California Borderland Basins are given in [ ] for each site after the site water depth. These can be considered the effective water depth for these sites in investigating water column structure, although each basin is also affected by nutrient remineralization within the basin.
[b] Absolute ages for the oldest sediments given are from shipboard age models for sedimentation rate calculations and are within 0.5 m.y. of the oldest recovered sediment.
[c] Sedimentation rates are given in meters composite depth (mcd) per m.y.
[d] The dominance of turbidite sedimentation at this site, as well as the disruption of recovered material by gas expansion, prevented the development of satisfactory working age models for estimating sedimentation rates.