4. BACKGROUND AND SUMMARY OF DRILLING RESULTS—OMAN MARGIN[1]

Shipboard Scientific Party[2]

INTRODUCTION

A major portion of Leg 117 was dedicated to the study of the Arabian continental margin between 17°30′N and 18°30′N offshore of Oman. Eight sites were drilled here in water depths ranging from 310 to 1430 m (Table 1, Fig. 1). The primary goal of drilling in this sector of the Arabian Sea was to understand the origin and variability of organic-carbon-rich sediments that result from the combined effects of monsoon-induced upwelling and the related oxygen-minimum zone (OMZ), which lies between 200 and 1200 m of water depth. The sites were selected to recover continuous and expanded sedimentary sections from zones of high biological productivity in order to establish the history of the depositional system. A secondary goal was to clarify the Neogene tectonic evolution of the Oman margin.

The majority of the margin sites have common objectives. Here, we summarize the geologic and oceanographic background for the margin sites, state the general objectives of drilling on the margin, and outline the principal results. Site-specific information is presented in the individual site chapters.

AGE, STRUCTURE, AND SEDIMENTS OF THE SOUTHEAST OMAN MARGIN

Most plate-tectonic reconstructions of the Indian Ocean infer that the Arabian margin and the adjacent Owen Basin are Jurassic in age, and that the margin is passive in character (Whitmarsh, 1979). Some aspects of the modern margin appear to be inconsistent with this interpretation (Mountain and Prell, in press). Much of the Oman margin is characterized by a narrow continental shelf bordered by an extremely steep continental slope, which is thought to be a megashear associated with the formation of the margin (Whitmarsh, 1979; Stein and Cochran, 1985). However, the embayment between Ras al Madrakah and Ras Sharbithat has a relatively wide continental shelf (about 75 km), which abuts the Sharbithat Ridge to the south and converges on the Ras al Madrakah headland to the north. The continental slope in this area is characterized by a series of linear, north-northeast-trending sediment terraces underlain by sedimentary basins. These terraces lie at water depths ranging from 500 to 1000 m in the upper basin and from 1400 to 1500 m in the lower basin, and thus accumulate sediments in the interval influenced by the intermediate-water OMZ (see below).

Seismic-reflection profiles of the margin reveal that the upper basin is bounded landward (west) by the steeply dipping Siquirah Fault (Mountain and Prell, in press) and seaward by a buried ridge of acoustic basement (Figs. 1 and 2). The upper basin shoals and narrows to the north. The southern part of the basin lies at about 1000 m and is about 15 km wide, whereas the northern part lies at about 600 m and is about 5 km wide. Seismic profiles show that the sediments in these basins are thick, acoustically highly layered, and structurally isolated from the sediments of adjacent basins by bounding faults, with the exception of the shallowest few hundred meters. The sediments are thickest in the center of the basin (more than 2000 m; Mountain and Prell, in press), forming a syncline-shaped deposit. Along the strike of the basin, the surface and subsurface layers dip gently to the southwest and are relatively conformable, although some deformational and slump-related structures are observed.

The deeper slope basin lies at about 1500 m and is about 8 km wide, but it only extends approximately 15 km along the strike of the margin. The basin is bounded on the south by the Sharbithat Ridge and on the north by an erosional scarp. The eastern and western boundaries are basement highs. The sediments of the basin onlap onto and have been deformed by movement relative to the adjacent basement structures. The shallow sediments dip seaward from the upper slope basin toward the lower constraining basement peak. Sediments are thickest near the center of the lower basin, forming a synclinal-shaped deposit that thins by pinch-out and onlap to the east and west.

The age and composition of acoustic basement along this portion of the margin is not directly known. The basement structure is complex, characterized as it is by several major faults, such as the Siquirah Fault, and by long, narrow ridges formed from basement peaks. Several lines of evidence support an interpretation, however, of the basement as landward-thrust oceanic crust (ophiolitic rocks). First, the seismic, gravity, and magnetic data collected during RC2704 (Mountain and Prell, this volume) did not identify anomalies that are characteristic of either salt or igneous intrusions. Second, the coastal geology of Oman includes ophiolites unconformably overlain by Eocene limestones, such as those on both Ras al Madrakah and Masirah Island, which are directly upstrike from our study area (Moseley and Abbotts, 1979). Third, industrial multichannel seismic data indicate that another major fault, the Masirah Fault, lies immediately landward of these exposed ophiolites, suggesting that the basement material seen in the study area is of similar origin and has been obducted onto the continental margin. Given these data, we infer that ophiolites underlie the outer shelf and slope basins. Testing this hypothesis was one of the objectives of drilling on the Oman margin.

Studies of box and piston cores from the upper slope basin indicate that Holocene accumulation rates range from 80 to 150 m/m.y., while carbonate and organic carbon contents range from 20 to 60 wt% and 4% to 8%, respectively (Shimmield et al., in press; Prell, unpubl. data). Accumulation rates in the lower basin are about 50–60 m/m.y. (about one-third of the rates in the upper basin). Carbonate and organic carbon contents range from 45 to 70 wt% and 2% to 4%, respectively. Most of the sediment on the margin is bioturbated, even though oxygen values in the bottom water on the margin are as low as 0.2 mL/L. Shimmield et al. (in press) report the occurrence of laminated sediments in small shelf basins within the OMZ; these laminated sediments also contain excess SiO_2 interpreted as diatomaceous opal. Diatom frustules contribute considerably to

[1] Prell, W. L., Niitsuma, N., et al., 1989. *Proc. ODP, Init. Repts.*, 117: College Station, TX (Ocean Drilling Program).

[2] Shipboard Scientific Party is as given in the list of Participants preceding the contents.

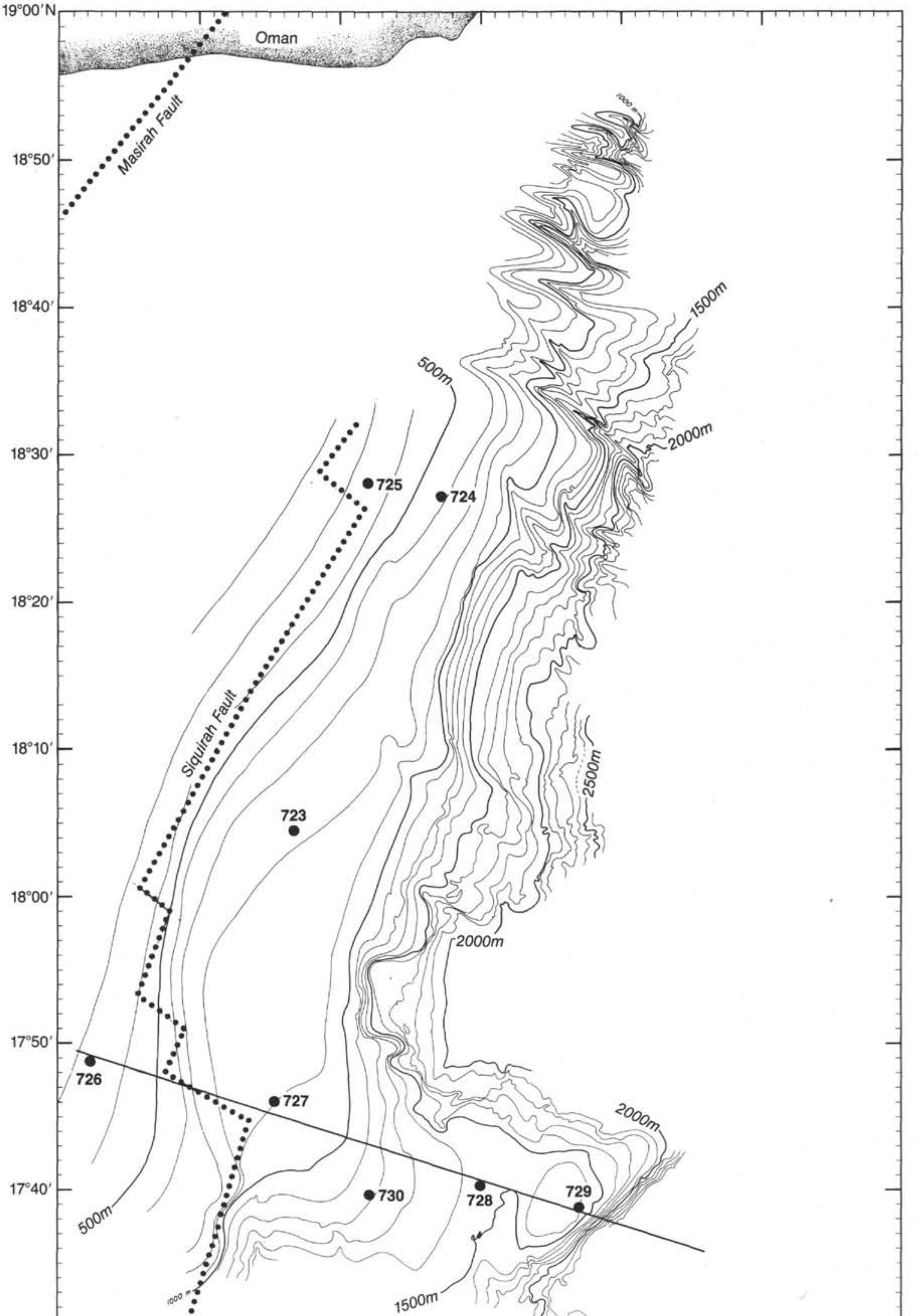

Figure 1. Location of ODP Leg 117 drill sites on the Oman margin. The line shows the approximate location of the idealized depth transect depicted in Figure 2. Water depths in Table 1 and Figure 1 may disagree in some cases. Bathymetry is from Mountain and Press (this volume; in press).

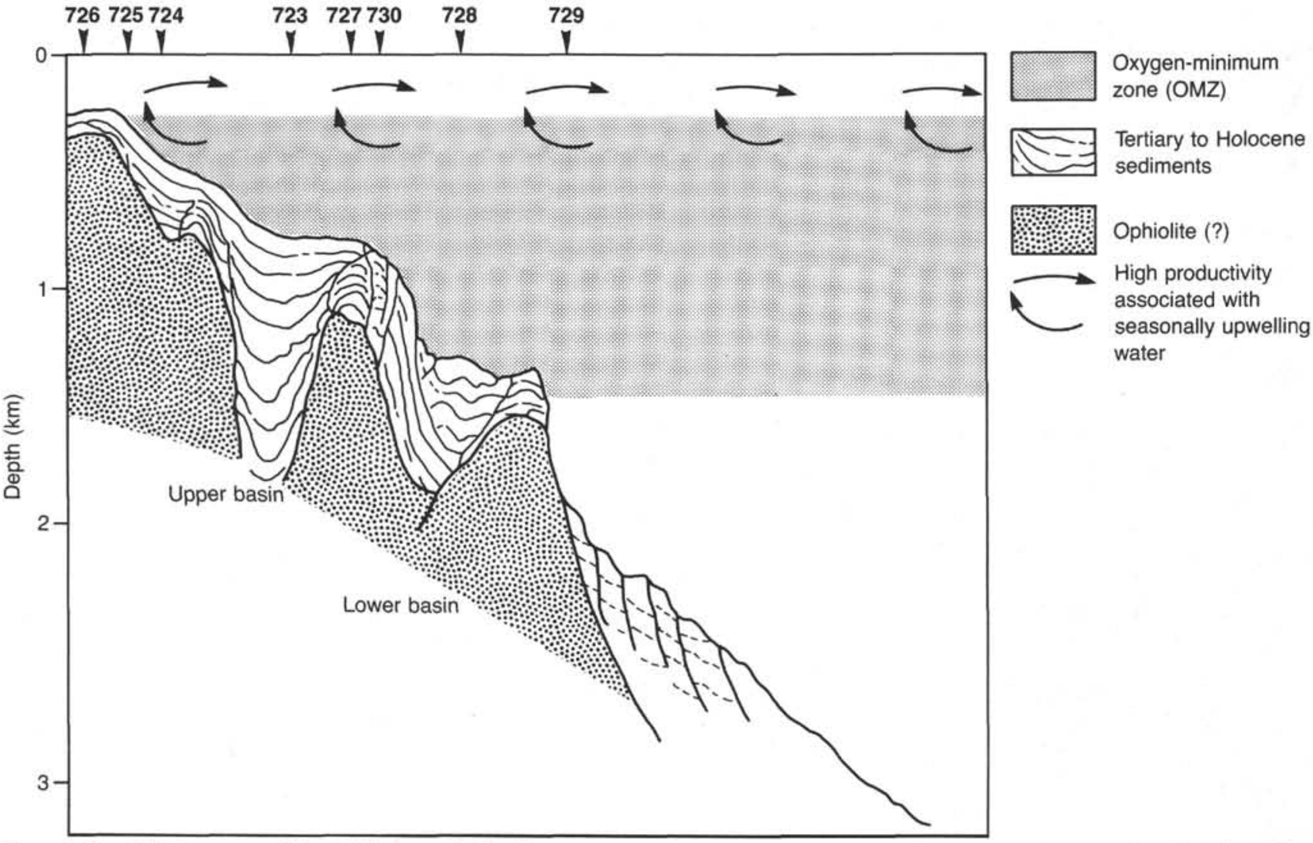

Figure 2. Simplified transect of the Arabian margin showing oceanographic and structural relationships offshore Oman, and the location of Leg 117 drill sites on this margin.

the total annual particulate flux in the upwelling areas of the northwest Indian Ocean (Krey, 1973), but they are not preserved in most surface sediments.

MODERN AND ANCIENT OCEANOGRAPHY OF THE SOUTHEAST OMAN MARGIN

The modern oceanography of the Arabian margin is characterized by seasonal monsoonal upwelling and a strong midwater OMZ. As outlined in the "Introduction" (this volume), strong, southwesterly, near-surface winds during the summer drive an offshore Ekman transport of surface waters, which are replaced by colder, nutrient-rich waters from several hundred meters deep. Sea-surface temperatures of less than 20°C occur over the shelf during the southwest monsoonal season (Currie et al., 1973). Nutrient concentrations at the surface during the southwest monsoon average >2 μmol/L for phosphate, >10 mmol/L for nitrate, and >10 μmol/L for silicate (Wyrtki, 1973; Krey and Babenerd, 1976). In contrast, surface-water concentrations are 0.4 μmol/L, <0.5 mmol/L, and >5 μmol/L, respectively, during the nonupwelling period from November to April.

In response to the richer nutrient supply, primary production in surface waters averages >500 mg C/m^2/day in May to October and drops to values as low as 150 mg C/m^2/day during November to April (Krey and Babenerd, 1976). Thus, wind speed and the duration of the monsoon control the strength and duration of upwelling, which in turn causes enhanced production of biogenic sedimentary components. By identifying the processes that control the production and preservation of various sedimentary components, the clastic and biogenic components deposited beneath the centers of upwelling can be used to interpret the history of monsoonal upwelling, including upwelling intensity, monsoon strength, and the oceanographic history of surface waters in the northwest Arabian Sea.

At present, the intermediate waters of the northwest Arabian Sea (200–1000 m of water depth) are characterized by high salinity, oxygen depletion between 200 and 1200 m water depth (<1 mL/L in all areas north of 3°N), and spatial and temporal stability. The sources of the intermediate waters are the Red Sea overflow, which spreads at about 800 m, and the Persian Gulf overflow, which spreads at about 300 m. Other sources of intermediate waters are the low-latitude regions of the Arabian Sea and the Gulf of Aden. These four sources combine to form North Indian Intermediate Water (NIIW), which has a uniform salinity of about 34.8 ‰ (Wyrtki, 1971, 1973) and occupies a depth of approximately 200–1200 m throughout the Arabian Sea. Limited horizontal advection of central Indian Ocean water, stable salinity and temperature stratification, and high chemical oxygen demand due to upwelling-related high productivity (>500 mg C/m^2/day) combine to form a stable zone of oxygen depletion, the OMZ. The OMZ presently occurs at depths from 200 to 1200 m, where values <0.2 mL/L O_2 are commonly found (Wyrtki, 1971; Spencer et al., 1982; Shimmield et al., in press). This oxygen-deficient layer is intercalated between the oxygen-rich and highly productive shallow mixed layer and the deeper layers originating from circumpolar and North Atlantic deep waters. The saline (34.84 ‰) and cold (2.2°C) deep waters reach the northern Indian Ocean with a moderate O_2 content (approximately 4 mL/L), and lie below the OMZ.

The OMZ of the Arabian Sea today thus reflects a combination of biochemical processes (productivity and bacterial oxygen consumption), stable stratification of the water masses, and sluggish subsurface circulation. Many of these influences may have changed in the past, either in response to climatic or oceanographic variability on time scales of glacial-interglacial cycles, or during Neogene sea-level fluctuations and tectonic events. We can expect such changes to be reflected in the sediments of the margin, which we can consider as high-quality records of the regional paleoceanographic history.

Prior to Leg 117, knowledge of the paleoceanography of the Arabian Sea and the history of monsoonal circulation was limited to numeric climate models and sedimentary records of the last 500 k.y. In order to improve our understanding of long-term climatic and ocean-circulation variability, longer high-resolution sedimentary records were needed to examine changes in climatic forcing and the sedimentary response over geologic time.

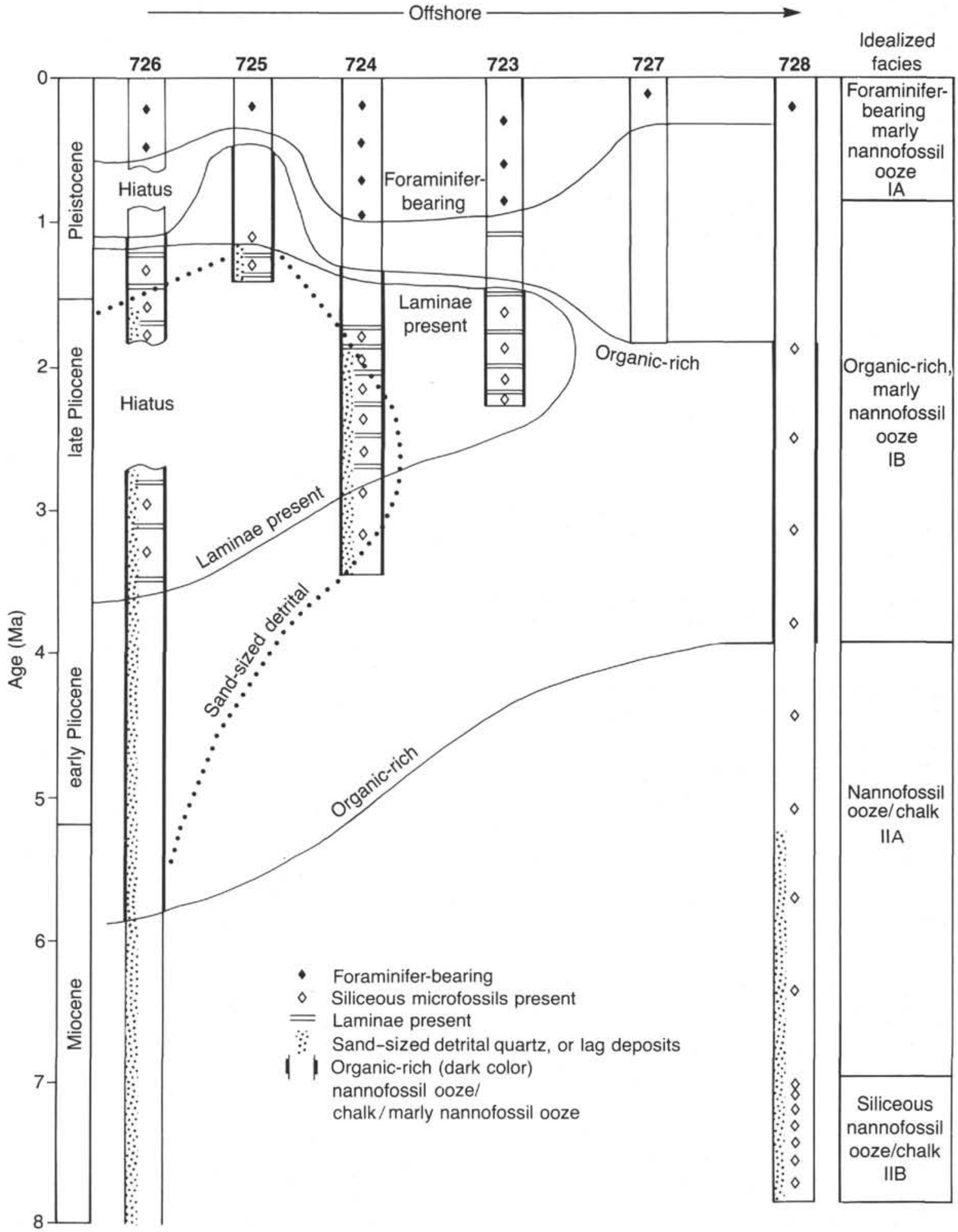

Figure 3. Schematic representation of sedimentary facies at margin sites through time. See text for discussion.

OBJECTIVES

The above summary of geologic and oceanographic information about the Oman margin raises a number of questions that can be addressed by drilling. The main objectives of drilling on the continental margin of Oman during Leg 117 can be summarized as follows:

1. To identify and characterize the proximal (coastal) upwelling facies on the margin in order to compare it with the distal upwelling records recovered from the Owen Ridge. Do these two areas show the same trends during the Neogene in response to climatic and tectonic events?
2. To define the depositional history of organic-carbon-rich sediments underlying a productive upwelling area and to relate variations in the constituents of sediments to differing climatic and oceanographic regimes.
3. To trace the influence of suboxic deposition and diagenesis in organic-carbon-rich sediments over a range of water depths and oxygen contents. Can variations of the OMZ be inferred from such data?
4. To determine whether margin sediments record changes in the water-mass structure of the northwest Indian Ocean and changes in the supply of water from the Red Sea and the Persian Gulf throughout the depositional history.
5. To investigate the age and nature of the acoustic basement and the tectonic history of shelf and slope basins, and to examine the relationship between uplift on the Owen Ridge and the tectonic history of the Oman margin.

SUMMARY OF DRILLING RESULTS ON THE OMAN MARGIN

More than 2600 m of core were recovered (at a mean recovery rate of 80%) at the eight sites (16 holes) drilled on the Oman margin (Table 1, Figs. 1 and 2). The water depths sampled at this transect across the margin ranged from 311 to 1428 m and bracketed the depth interval where the OMZ impinges on the modern margin. The oldest sediments recovered were Eocene (?) shallow-water foraminifer limestones. Unfortunately, we did not penetrate the acoustic basement at Sites 726 and 729, so we were unable to confirm our speculation that it is formed of ophiolitic rocks. The Eocene (?) limestones were overlain by upwelling-influenced sediments of Miocene to Holocene age. The upwelling-influenced sediments are dominated by green to olive calcareous oozes to clayey silts, are rich in organic carbon (2%–8%), and

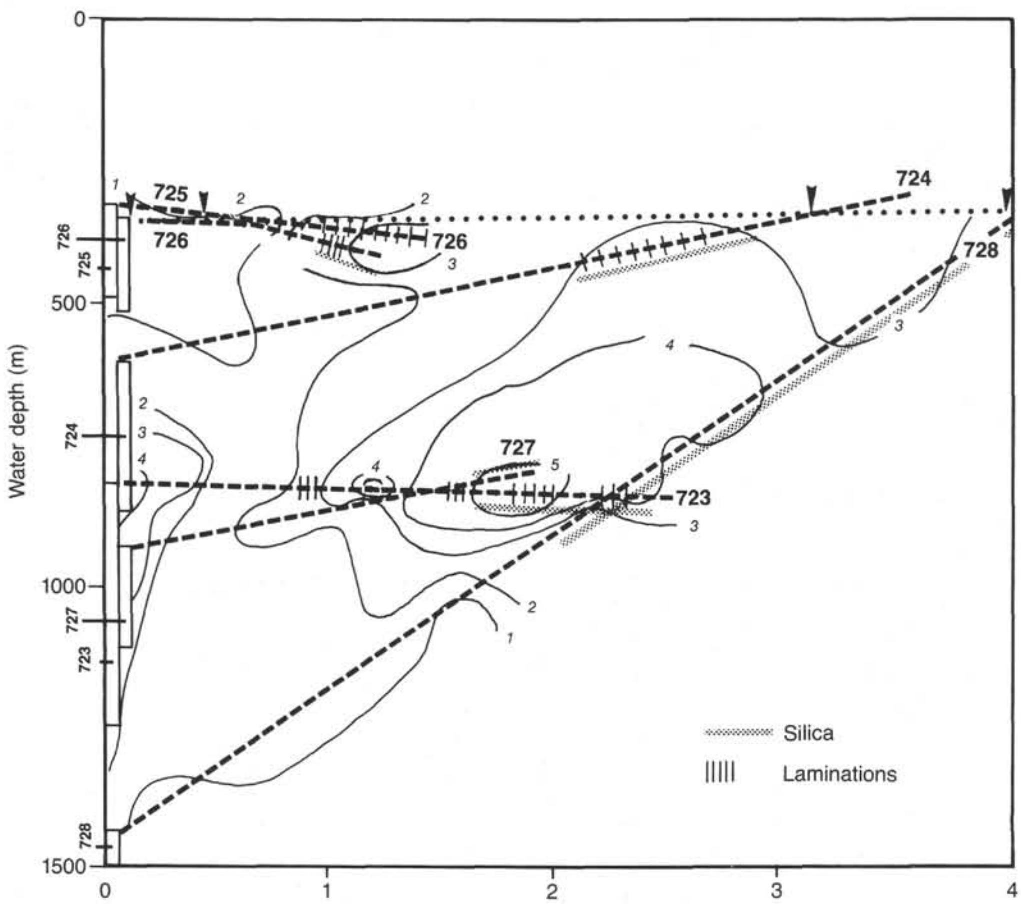

Figure 4. Age (in m.y.) vs. depth (m) of Oman margin Sites 723 through 728. Sediment sections recovered at individual sites are plotted to the left of the diagram according to their present water depth and the total depth drilled. The estimated depth of the sediment/water interface through time is indicated by the dashed line for each site and was reconstructed using the presence or absence of the benthic foraminifer *Ammonia beccarii*. The occurrence of this species is considered an indication of water depth shallower than 350 m. Arrows on the backtracking lines (dotted lines) for each site denote the transitions from <350 m to >350 m water depth based on this indicator. Isopleths of organic carbon concentrations of the paleosurface sediments are shown for the correct water depths and ages. Vertical lines in the backtracking curves denote laminated intervals, and occurrences of biogenic opal are indicated by dark shading.

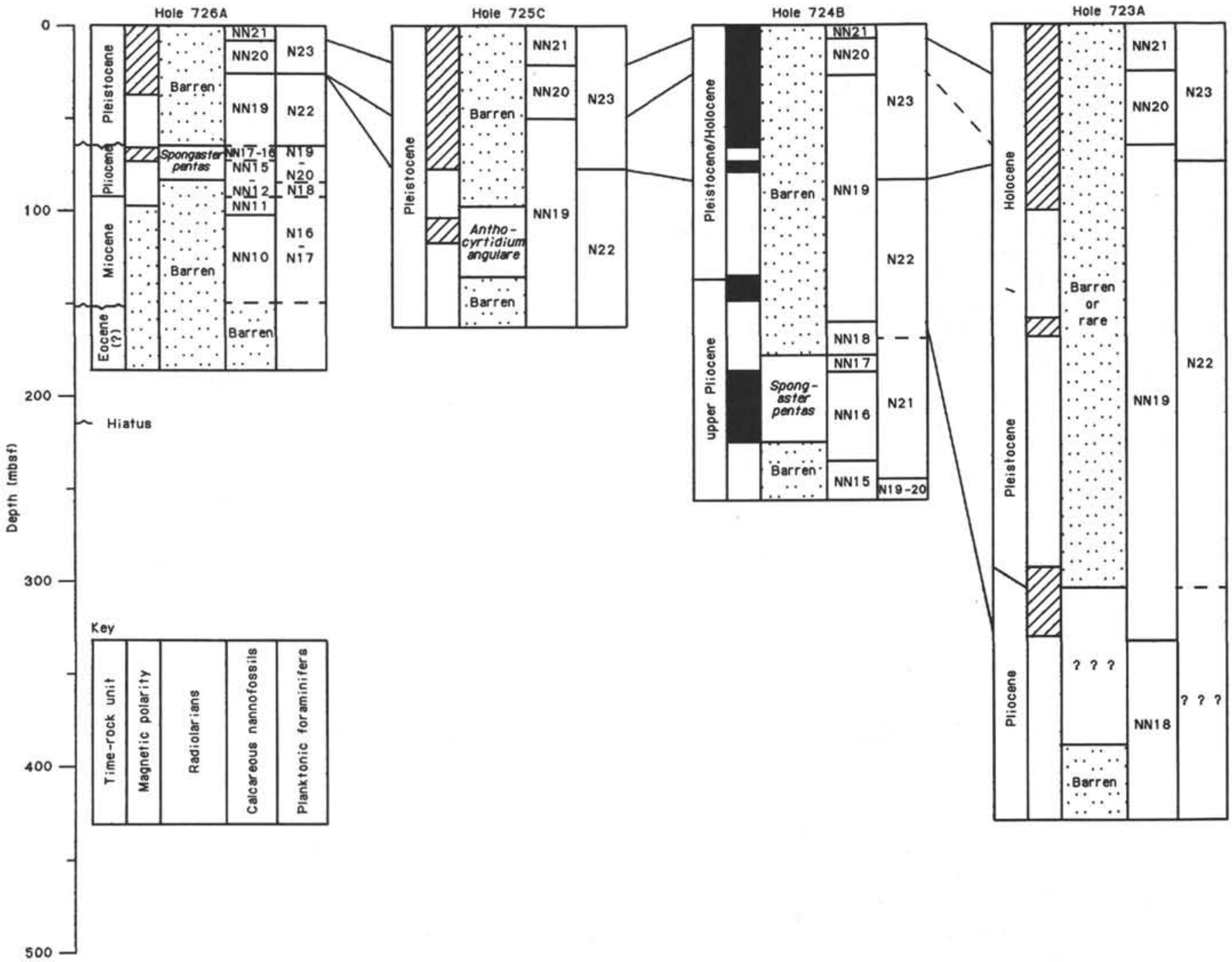

Figure 5. Correlation of margin sites based on stratigraphic evidence. Note that the sediment succession discussed in the text is a composite from all sites.

include laminated, diatom-bearing intervals rich in organic matter (>5%) at sites in the center of the upwelling zone (Site 724 at 600 m and Site 723 at 800 m). Intervals of abundant sand-sized detrital material at near-shore sites (726, 725, 724) are thought to indicate terrestrial input, while phosphorite-rich lag deposits at the shallowest site (726) are interpreted to record the effects of current winnowing. A schematic representation of the lateral and temporal variations in sediment facies on the Oman margin is shown in Figure 3.

The oldest coherent signal observed in these sections is the increased preservation of organic matter during the late Miocene to early Pliocene. The effect of an intensified OMZ on the sediments is seen in the laminated, organic-carbon-rich sediments that occur in the upper Pliocene and lower Pleistocene of the four landward sites. The preservation of laminae is paralleled to some extent by an increase in the abundance of sand-sized detrital material in nearshore Sites 724, 725, and 726. The increase in the abundance of coarse clastics may be a result of lower sea level or increased wind strength and enhanced eolian input. A further characteristic of the laminated and organic-carbon-rich sediments is the preservation of opaline microfossils. Upper Pleistocene sediments are uniform in fossil and organic carbon content at all sites, indicating that the significant climatic and sea-level fluctuations known from the late Pleistocene glacial phases did not affect sedimentation patterns to any noticeable extent.

In general, the margin sediments bear a continuous imprint of constant high-surface productivity, while facies changes signify changes in the depositional environment. The complex interaction between the tectonic evolution of the margin and slope basins and the deposition and preservation of organic-rich, opal-rich, and laminated facies results in patterns of deposition that are summarized in Figure 4. In this illustration the abundance of organic carbon in the sediments is contoured on a plot of paleodepth vs. time. The plot reveals a striking coincidence of organic-carbon-rich, opaline, and laminated facies near 800-m paleowater depth in the upper Pliocene and lower Pleistocene. The late Pliocene mode of deposition and preservation of laminated sediments may reflect an intensified and stable OMZ. Sediments of late Pleistocene and Holocene age also contain high organic-carbon concentrations, but these sediments are not laminated and lack opal.

The abundance of organic carbon in the Oman margin sediments leads to diagenetic changes in those sediments, and indications of microbial activity deep in the sediment column were pronounced. Biogenic methane gas was found in high concen-

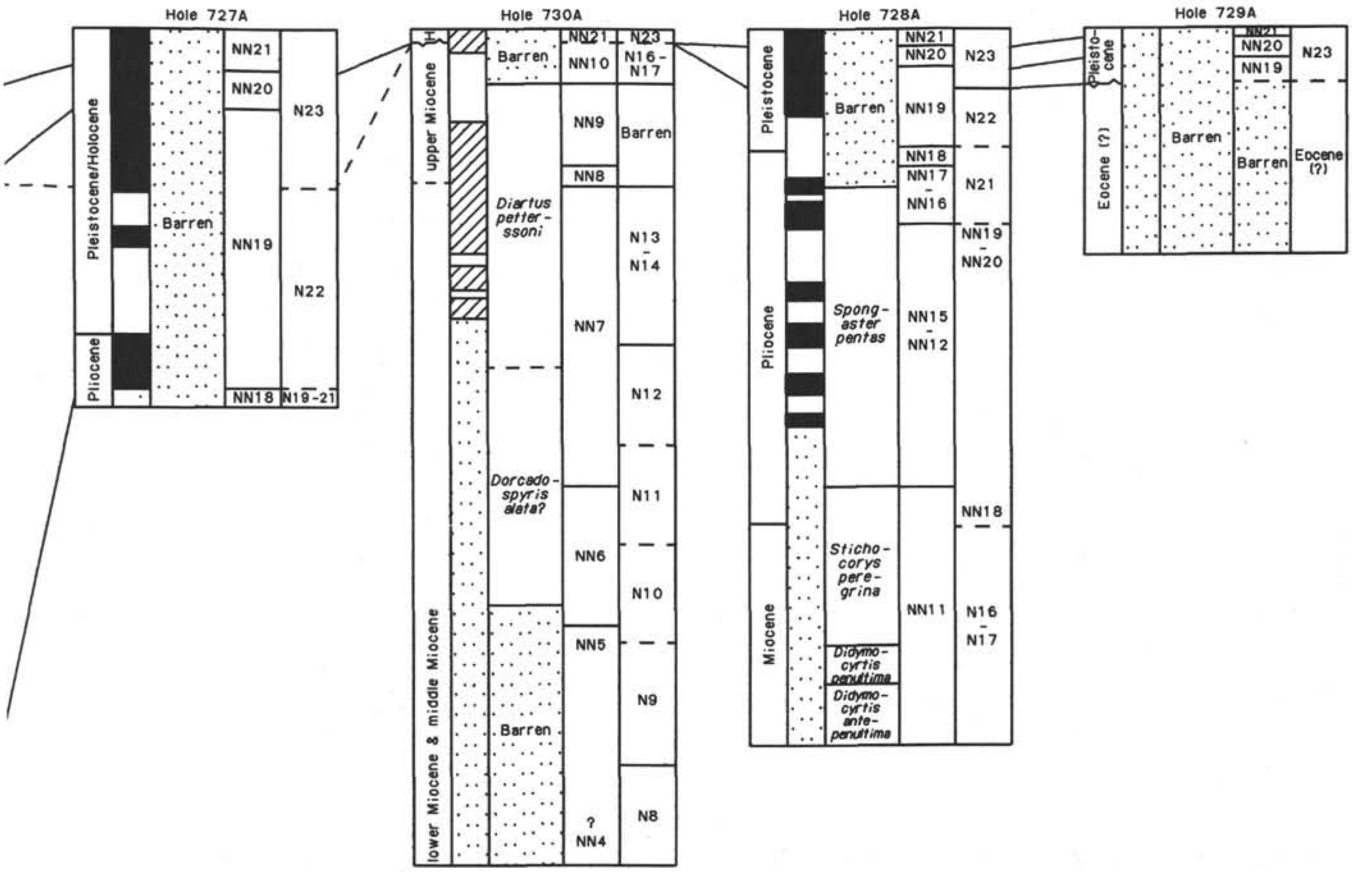

Figure 5 (continued).

trations at all sites and reached up to 0.29 L/L of sediment. High bottom-water temperatures and shallow water depths precluded the formation of gas hydrates at these sites. In addition to the high methane content, thermogenic gas was observed in low concentrations at Sites 723, 724, 725, 727, and 728. Interestingly, Sites 723 and 724 displayed pore-water profiles that suggest an advective supply of sulfate-bearing waters from some deep source, similar to the situation in the Peru slope basins (Suess, von Huene, et al., 1988). The additional supply of sulfate fuels microbial sulfate reduction beyond the range usually found in deep-sea sediments and creates very high concentrations of alkalinity (107 mmol/L) and ammonia (40 mmol/L) in pore waters. High alkalinity and interstitial calcium and magnesium ions combine to form diagenetic dolomites at depth at Site 723.

Biostratigraphic zonations showed that Sites 725 and 727 have expanded Pleistocene sections and that Sites 723 and 724 are expanded in the Pleistocene and upper Pliocene (Fig. 5). Calcareous nannofossils are abundant in most samples, but they exhibit low species diversity. Planktonic foraminifers are abundant in Pleistocene sediments, but their abundance and preservation declines near the Pliocene/Pleistocene boundary. Benthic foraminifers are abundant and highly diverse in the relatively shallow sites on the margin, and benthic assemblages reveal the subsidence history on the margin. This history is marked by rapid subsidence events from <300 m water depth in the middle Pliocene to >800 m at present. Radiolarian faunas were found in upper Miocene and Pliocene strata only. In general, the microfossil assemblages reveal a trend from more siliceous sediments in the Miocene and Pliocene to more calcareous sediments in the Pleistocene.

Intensities of natural remanent magnetization (NRM) in the margin sediments were commonly less than 1 mA/m and decreased with sediment depth, so that the use of paleomagnetic methods for stratigraphy was somewhat limited. These problems are partially offset by the unusually detailed correlation between holes and even sites using records of magnetic susceptibility measured with high resolution on whole cores.

In summary, some of the most important findings of ODP Leg 117 pertain to the tectonic history of the Oman margin and the evolution of monsoonal circulation since the middle Miocene:

1. Parts of the Arabian margin have subsided as much as 1000 m during the late Neogene. This can be deduced from unconformities, sedimentation rates, and benthic faunas.
2. The geometry of slope basins and the occurrence of shallow-water platform carbonates similar to those overlying the ophiolitic rocks in Masirah Island suggest that much of the margin is underlain by ophiolitic rocks. The occurrence of thermogenic gas and interstitial water sulfate profiles further suggest that advective subsurface flow and gas migration occurs from deep geologic structures, possibly from beneath the ophiolitic rocks.
3. The organic-carbon-rich margin sediments are dominantly calcareous mudstones that include eolian and diagenetic minerals but are poor in opal. This composition is unusual when compared with opal-rich sediments typical of other major upwelling systems.
4. Faunas and floras indicative of upwelling appear in the early middle Miocene on the margin; variations in the intensity of the monsoon during the Neogene were not immediately discernible from the microfossil data.
5. Laminated organic-carbon-rich sediments that contain siliceous microfossils are restricted to the upper Pliocene and lower Pleistocene, suggesting that during that time a different

Table 1. Sites and holes drilled on the Oman margin during Leg 117.

Site	Latitude	Longitude	Water depth (m)	Drilled (m)	Recovery (%)	Nature and age of oldest strata
723A	18°03.079′N	57°36.561′E	807.8	432.3	68	Dolomite biscuits; late Pliocene
723B	18°03.079′N	57°36.561′E	807.8	429.0	73	Nannofossil clayey silt; late Pliocene
723C	18°03.079′N	57°36.561′E	807.8	76.8	107	Nannofossil clayey silt; Pleistocene
724A	18°27.713′N	57°47.147′E	592.8	44.5	100	Foraminifer nannofossil ooze; Pleistocene
724B	18°27.713′N	57°47.147′E	592.8	257.7	83	Calcareous clayey silt; early Pliocene
724C	18°27.713′N	57°47.147′E	592.8	252.4	96	Calcareous clayey silt; early Pliocene
725A	18°29.200′N	57°42.080′E	311.5	4.5	100	Nannofossil-foraminifer sandy silt; Pleistocene
725B	18°29.200′N	57°42.080′E	311.5	93.8	11	Foraminifer-rich calcitic sandy silt; Pleistocene
725C	18°29.200′N	57°42.080′E	311.5	162.8	60	Nannofossil-rich calcitic sand, silt, and clay; Pleistocene
726A	17°48.965′N	57°22.290′E	330.8	186.3	59	Limestone; Eocene (?)
727A	17°46.096′N	57°35.216′E	914.8	182.2	103	Calcareous clayey silt; late Pliocene
727B	17°46.096′N	57°35.216′E	914.8	27.1	103	Calcareous clayey silt; late Pleistocene
728A	17°40.790′N	57°49.553′E	1427.8	346.4	99	Foraminifer-nannofossil ooze; late Miocene
728B	17°40.790′N	57°49.553′E	1427.8	347.7	100	Claystone; late Miocene
729A	17°38.715′N	57°57.221′E	1398.8	109.1	29	Limestone; Eocene (?)
730A	17°38.885′N	57°42.519′E	1065.8	403.9	80	Foraminifer-nannofossil chalk; late early Miocene

oceanographic regime produced a more pronounced OMZ. The absence of benthic macroorganisms in the suboxic/anoxic bottom waters of an intensified OMZ would explain the preservation of primary sedimentary features.

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