1. INTRODUCTION, BACKGROUND, AND MAJOR OBJECTIVES FOR ODP LEG 117 (WESTERN ARABIAN SEA) IN SEARCH OF ANCIENT MONSOONS[1]

Shipboard Scientific Party[2]

The primary goal of Leg 117 was to explore the origin, evolution, and variability of the Indian Ocean Monsoon and its effect on the oceanic environments of the western Arabian Sea and the paleoclimates of tropical Africa, Arabia, India, and Asia. Briefly, the monsoon is characterized by seasonal changes in precipitation and in the direction and strength of the low-level winds over the northwest Indian Ocean and the adjacent continents. During the summer monsoon (June through August), the winds are from the southwest, are quite strong (consistently >15 m/s), and are associated with maximum seasonal precipitation over much of India and southern Asia. The causes of the monsoon are complex and include interactions between marine and continental tectonics, atmospheric and oceanic circulation, and variations of solar radiation. These factors, which cause changes in monsoon circulation, vary on different time-scales to produce a complex monsoonal response. One goal of ODP Leg 117 was to define more clearly the roles of these factors as causes of the evolution and variability of the Indian Ocean Monsoon. This goal is feasible because the monsoon leaves an indelible imprint on the climatic and oceanographic history of the western Arabian Sea that is recorded in its marine sediments. Below we summarize the tectonic, oceanographic, and climatic framework of the western Arabian Sea to illustrate how they are related to the monsoon and to suggest how the sediment record can produce a reliable record of monsoonal history.

TECTONIC FRAMEWORK OF THE WESTERN ARABIAN SEA

The major tectonic and depositional features of the western Arabian Sea include the Indus Fan, the Owen Ridge, the Owen Basin, and the Arabian margin off Oman (see Figs. 1 and 2). All of these features reflect the long, complex tectonic history of the Northern Indian Ocean. In most plate reconstructions, the initial separation of India, Madagascar, and Antarctica from Africa is thought to have begun in the late Jurassic (about 160 Ma) and halted in Early Cretaceous (about 102 Ma) (Rabinowitz et al., 1983; Cochran, 1987, in press). Most workers assume that the ocean crust along the African and Arabian margins was formed during this interval of spreading, an inference that implies that the Oman margin has been passive since its breakup and that the age of the Owen Basin is Jurassic (Whitmarsh, 1979; Beydoun, 1982; Stein and Cochran, 1985; Larson et al., 1985). The separation of India from Madagascar occurred on a new spreading ridge in the Late Cretaceous (at about 90 Ma). During this phase of spreading, the Owen Ridge is thought to have been the major transform fault that connected the ridge between India and Arabia with the east-west trending spreading center located to the north of Arabia (McKenzie and Sclater, 1971; Whitmarsh, 1974, 1979; Norton and Sclater, 1979; Stein and Cochran, 1985). During the Late Cretaceous (about 89 to 75 Ma), the Semail ophiolites were emplaced on the northern Arabian margin (Coleman, 1981). Similar ophiolitic sequences, but with less well known ages, are found striking southwestward on the Masirah Island, indicating possible emplacement from the Owen Basin (Moseley and Abbotts, 1979). Recent survey of the Oman margin (Mountain and Prell, 1987, in press) suggests that its history is more complex than a simple passive margin model would indicate.

The continental collision of India with Asia is thought to have occurred in the Eocene (about 50 Ma) (Patriat and Achache, 1984). Continued subduction and crustal thickening began the uplift of Asia and reduced the convergence rate between India and Asia. In the middle to late Oligocene (about 30–25 Ma), a major reorganization of plate geometry occurred in the Indian Ocean (McKenzie and Sclater, 1971; Sclater and Fisher, 1974; Sclater et al., 1976; Johnson et al., 1976; Johnson et al., 1980; Norton and Sclater, 1979; Schlich, 1982). The present Carlsberg Ridge was formed and began its progression into the Gulf of Aden, where the first emplacement of true oceanic crust occurred about 10 Ma (Laughton et al., 1970; Cochran, 1981). During this Oligocene to Holocene spreading phase, the Owen Ridge has been uplifted due to a component of compression along the Owen transform (Whitmarsh, 1979) (See "Background and Summary of Drilling Results—Owen Ridge chapter," this volume, for details).

Previous DSDP drilling in the Owen Basin (Site 223) and on the Owen Ridge (Site 224) (see Fig. 2 for locations) established igneous basement(?) ages of Paleocene to Eocene (Site 223) and pre-early Eocene (Site 224) for this area. These ages are inconsistent with the proposed Jurassic age for the Owen Basin.

OCEANOGRAPHIC FRAMEWORK OF THE WESTERN ARABIAN SEA

The oceanography of the Arabian Sea is characterized by three major divisions: (1) a seasonally changing monsoonal gyre in the surface waters, (2) a high-salinity, oxygen-poor intermediate water, and (3) the Indian Deep Water. In the following, we briefly review the characteristics of these circulation systems as they relate to the formation or modification of the sediment record in the western Arabian Sea.

The western Arabian Sea is characterized by large seasonal variations in current direction, upwelling intensity, and mixed-layer properties such as temperature, nutrient content, and productivity (Wyrtki, 1971, 1973). These seasonal changes represent a unique oceanic response that is forced by the large-scale monsoonal winds, especially by the intense southwesterly monsoon winds (see monsoon disscussion below). Along the coasts of northeastern Africa (Kenya and Somalia) and the Arabian Peninsula (Oman) (Fig. 3), the strong southwesterly winds are nearly parallel to the coast and cause Ekman transport of surface waters away (offshore) from the coasts and thus cause intense centers of seasonal coastal upwelling (Currie et al., 1973; Bruce, 1974; Wyrtki, 1973; Hastenrath and Lamb, 1979). This seasonal upwelling brings nutrient-rich, oxygen-poor, and cold

[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.

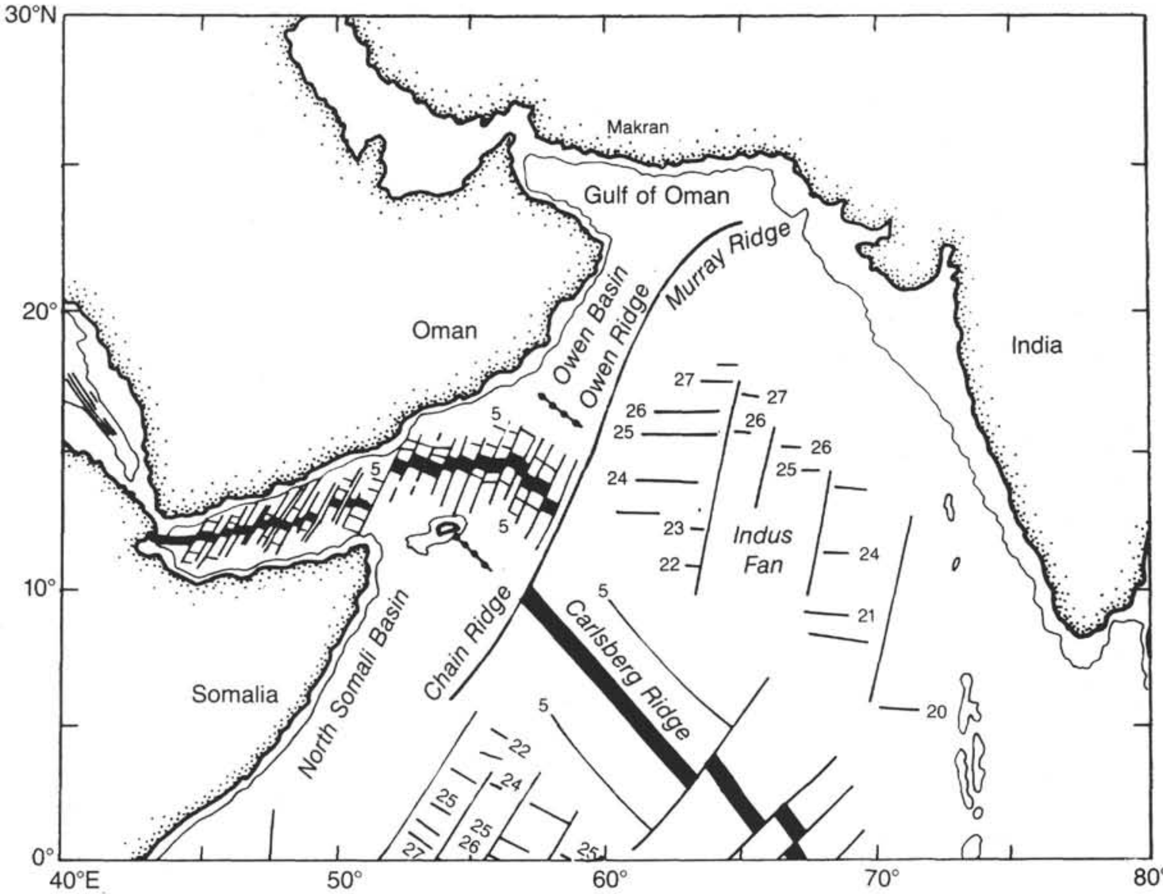

Figure 1. Tectonic features and magnetic anomalies in the northern Indian Ocean. Modified after Mountain and Prell (in press). Numbers = magnetic anomalies recognized on oceanic crust.

waters from several hundred meters depth to the surface and triggers high productivity in the euphotic zone (Krey and Babenerd, 1976). Since these upwelling events are largely driven by Ekman transport (Wyrtki, 1973; Prell and Streeter, 1982), their duration and intensity must reflect the intensity of the monsoonal winds. Thus, a direct and coherent link is established between monsoonal wind intensity, the intensity of coastal upwelling, biogenic productivity, and sediment input to underlying seafloor. This uniquely seasonal system differs sharply from other important upwelling systems such as off Peru and off the west coast of Africa, which are embedded in eastern boundary currents and are forced by large-scale, persistent atmospheric and oceanic circulation.

The intermediate waters of the Arabian Sea, named the North Indian Intermediate Water (NIIW) by Wyrtki (1973), are characterized by their high salinity, stability, and low oxygen concentrations. The source of the NIIW is the restricted marginal basins (Red Sea and Persian Gulf) adjacent to the Arabian Sea as well as the Gulf of Aden and the northern Arabian Sea. All of these sources produce relatively high salinity waters which combine to give the NIIW a density that is similar to the Antarctic Intermediate Water (Wyrtki, 1971, 1973). As a result, the meridional advective exchange with central Indian Ocean waters is restricted, and the NIIW in the Arabian Sea is relatively isolated and has a long residence time. This lack of advective recharge combined with the stability of the intermediate waters, and the high productivity of the surface waters (see below), results in extremely low oxygen concentrations (0.2 mL/L) between the depths of about 200 m and 1500 m. The NIIW thus forms a distinctive oxygen-minimum zone (OMZ) in the Arabian Sea and the entire northern Indian Ocean. Understanding the interactions of productivity and circulation on the OMZ and the effects of the OMZ on the sediments of the Oman margin are important goals for research associated with Leg 117.

The deep waters of the Arabian Sea are relatively homogeneous and are formed by elements of North Atlantic Deep Water (NADW), Circumpolar Deepwater (CD), and Antarctic Bottom Water (AABW). Global circulation of deep waters requires that some regional upwelling of deep water must occur in the northern Indian Ocean, but its influence on the intermediate waters is largely unknown. The deep waters of the Arabian Sea are saturated with carbonate above 3500 m (Broecker and Peng, 1982); thus they should have minimal influence on the dissolution of carbonate sediments on the crest of the Owen Ridge and the Oman margin.

MONSOONAL CLIMATE FRAMEWORK OF THE WESTERN ARABIAN SEA

The term "monsoon" is derived from the Arabic word "mausim," which means season and is usually applied to the seasonal reversals of wind direction around the Arabian Sea (Webster, 1987). The seasonal reversal of monsoonal winds strongly affects the Arabian Sea, and below we shall examine the fundamental boundary conditions that cause the monsoon and control its variability on geologic time scales.

The winter circulation of the northern Indian Ocean–Asian atmosphere is dominated by a high-pressure cell over the Tibetan Plateau, which is caused by cooling over Asia (Fig. 3). The resulting pressure gradient causes northeasterly winds to flow from the Asian continent over the Arabian Sea. These con-

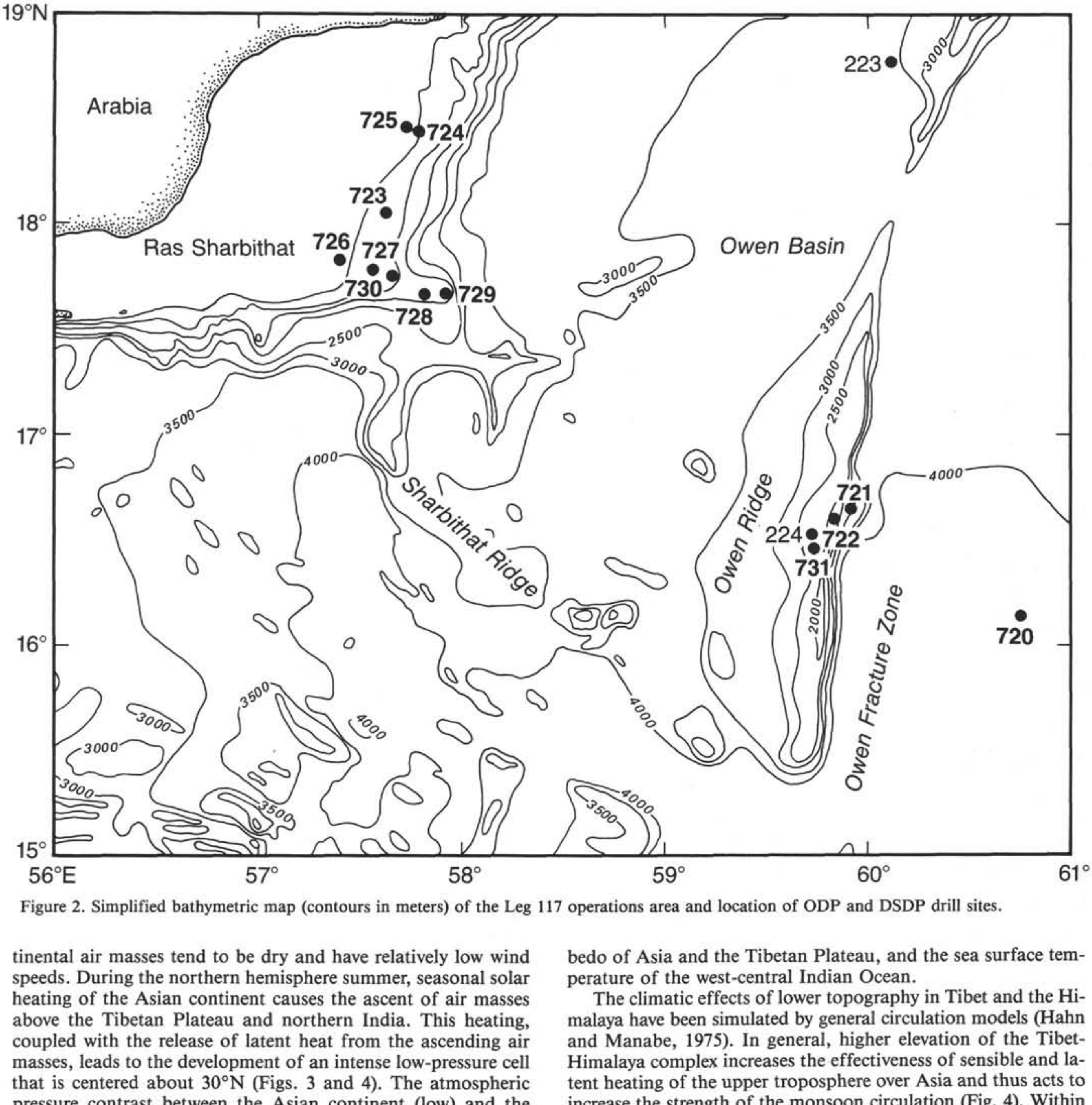

Figure 2. Simplified bathymetric map (contours in meters) of the Leg 117 operations area and location of ODP and DSDP drill sites.

tinental air masses tend to be dry and have relatively low wind speeds. During the northern hemisphere summer, seasonal solar heating of the Asian continent causes the ascent of air masses above the Tibetan Plateau and northern India. This heating, coupled with the release of latent heat from the ascending air masses, leads to the development of an intense low-pressure cell that is centered about 30°N (Figs. 3 and 4). The atmospheric pressure contrast between the Asian continent (low) and the cooler southern Indian Ocean (the Madagascar high) causes the strong low-level southwesterly winds that are characteristic of the summer monsoon in the western Indian Ocean. The convergence of these air masses over the Indian subcontinent and their uplift due to heating and orographic factors is the primary cause of the seasonal monsoon precipitation (Hastenrath, 1985; Fein and Stephens, 1987; Chang and Krishnamurti, 1987).

On the basis of this general mechanism of monsoonal circulation, climate model simulations and paleoclimatic reconstructions have identified four separate, but interrelated, factors that could potentially cause changes in the intensity of the monsoon. These are changes in the elevation of the Tibetan Plateau, the variation of northern hemisphere summer insolation, the albedo of Asia and the Tibetan Plateau, and the sea surface temperature of the west-central Indian Ocean.

The climatic effects of lower topography in Tibet and the Himalaya have been simulated by general circulation models (Hahn and Manabe, 1975). In general, higher elevation of the Tibet-Himalaya complex increases the effectiveness of sensible and latent heating of the upper troposphere over Asia and thus acts to increase the strength of the monsoon circulation (Fig. 4). Within the late Neogene, uplift rates of the Himalaya are thought to increase dramatically, especially in the Pliocene-Pleistocene (Mercier et al., 1987). Thus, if the "mountain" hypothesis and uplift estimates are correct, the monsoon should increase in intensity during this interval. If the monsoon response is not dependent on a "critical" elevation, one would expect the "uplift" trend to be long-term and relatively continuous.

Variations in the seasonal distribution of solar radiation due to changes in the earth's orbit (i.e., the Milankovitch mechanism) have long been thought to be an important factor in the cause and timing of the Ice Ages (for summaries see Berger et al., 1984). More recently, researchers have found that the Milankovitch mechanism also has strong effects on the hydrologic

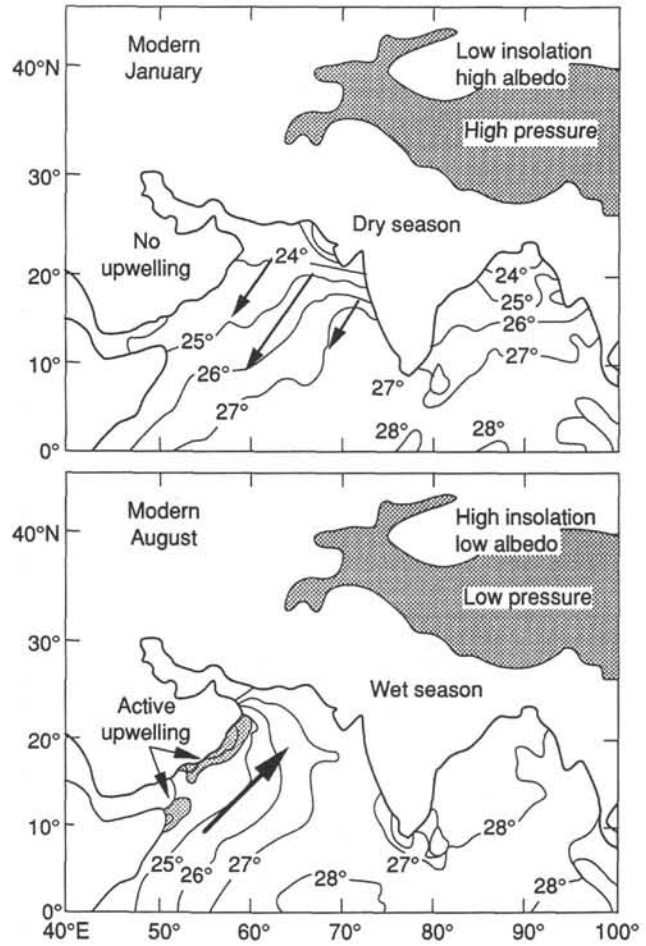

Figure 3. Seasonal changes in the boundary conditions of monsoonal circulation in the northern Indian Ocean and in Asia. Upper: During the northeastern monsoon in modern January. Lower: During the southwestern monsoon in modern August. Shaded area is the Tibetan Plateau and the Himalaya. Arrows denote wind directions; sea surface temperatures are given in °C. During the southwestern monsoon, upwelling offshore Somalia and Oman (shaded pattern) lowers the sea surface temperatures to between 22° and 24°C. Redrawn after Prell (1984a).

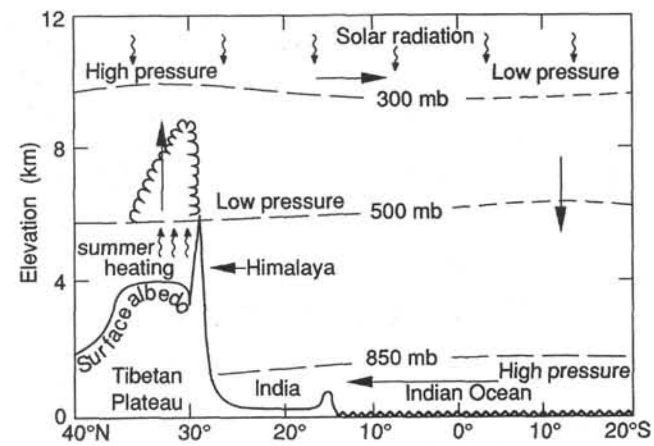

Figure 4. Schematic boundary conditions of monsoonal atmospheric and oceanic circulation in the northwest Indian Ocean during the summer monsoon. Heating of air masses over the highlands of Asia creates a low-pressure cell which induces intense southwesterly winds in the lower atmosphere over the northwest Indian Ocean. mb = atmospheric pressure surfaces (exaggerated) in millibars; arrows denote wind direction. Redrawn after Prell (1984a).

budgets and wind fields of the tropics and in particular on the Indian-African summer monsoon (Kutzbach, 1981; Prell, 1984a, 1984b; Kutzbach and Street-Perrott, 1985; Prell and Kutzbach, 1987). A combination of climate model simulations and paleoclimatic observations has established that increased summer radiation over Asia, especially changes associated with the precessional component of the earth's orbit, result in stronger monsoons. These radiation changes are induced by specific orbital components that have distinct periodicities (precession at 19 kyr and 23 kyr, tilt at 41 kyr, and eccentricity at 100 kyr and 414 kyr) that can be calculated over the past several million years. If these orbital-radiation components are important in forcing the monsoon response, then the temporal changes in the amplitude and timing of these components and their distinct spectral signatures should be reflected in the monsoon-related sediment record.

Changes in the albedo of the Asian continent (Fig. 4), especially due to increased extent or duration of snow and ice cover, have long been assumed to be important in determining the timing and strength of the modern monsoon (Blanford, 1884; Hahn and Shukla, 1976; Prell 1984a, 1984b). Although this mechanism is still somewhat controversial, increased albedo (i.e., more snow) is thought to delay the seasonal heating cycle over Asia and thus to retard and weaken the monsoon. During glacial periods, several researchers have inferred higher albedo and even ice-caps on the Tibetan Plateau (CLIMAP Project Members, 1981). Although this albedo increase is not well documented, it would lead to weaker monsoons during glacial conditions.

Changes in the pattern of sea surface temperature (SST) of the central and southern Indian Ocean have also been correlated with the strength of the monsoon (Fig. 4; Shukla, 1987). Glacial boundary conditions (CLIMAP Project Members, 1981) may have led to higher SST in the west-central Indian Ocean relative to modern SST. The effect of higher SST is to decrease the pressure gradient between Asia and the Indian Ocean and thus to decrease the monsoon response. This effect has been inferred in some studies of the last glacial maximum (Prell and Kutzbach, 1987) while others failed to find an SST effect (Manabe and Hahn, 1977).

All of the above factors vary on timescales from 10^3 to 10^6 yr and potentially affect the sediments deposited on the Owen Ridge and the Arabian margin. Below, we suggest how such changes might be observed in Neogene sediments of the Western Arabian Sea.

ENVIRONMENTAL EFFECTS OF THE MONSOON

The Indian Ocean monsoon imposes large seasonal variations, especially pronounced in the summer, on the environments of the western Arabian Sea. These variations include changes in current direction, upwelling intensity, depth of the mixed layer, structure of the OMZ, sea surface temperature, nutrient content, primary and secondary productivity, the composition of plankton assemblages, and in the concentration and source of eolian material. All of these phenomena respond to changes in the monsoon intensity; we recognize, however, that they are also affected by other oceanic and atmospheric processes.

On the basis of the above observations and rationale, past changes in the strength of the monsoonal circulation might be represented in the sediments of the western Arabian Sea by the following types of records:

Changes in productivity: Increased/decreased monsoonal winds might be expected to cause increased/decreased upwelling and hence productivity of the surface waters. Sedimentary records of a change in productivity could include changes in the following: organic carbon content, biogenic accumulation rates, and specific biotic indicator species.

Changes in faunal and floral assemblages: Increased/decreased upwelling would be expected to affect the distribution of plankton (such as Radiolaria vs. Foraminifera) and the relative abundance of species within those groups. Variations and trends between "tropical" versus "upwelling" assemblages should reflect changes in the monsoonal upwelling as well as of related oceanic processes. The amplitude and timing of cyclic variations of faunal and floral upwelling components may be quantitatively compared to the hypothetical record of monsoonal forcing to establish "causal" links.

Changes in eolian sediment components: Increased/decreased monsoonal winds might be expected to change the amount, size, and composition of eolian material transported into the western Indian Ocean. Those components that can be correlated with southwestern sources on the basis of mineralogy or pollen content could be interpreted in terms of strength of the southwestern monsoon. Components that are associated with more northern sources might reflect the winter monsoon. The usefulness of these eolian components in interpreting the monsoon patterns will largely depend upon the identification of distinct regional source areas.

Changes in pollen assemblages: Increased/decreased aridity and temperature on the adjacent continental land masses greatly affects the composition and amount of vegetation. The transport of pollen from these vegetational assemblages into the marine record offers the opportunity to directly compare the response of the terrestrial and marine environments to various climatic forcing mechanisms.

Changes in surface water temperature and chemistry: Increased/decreased upwelling would produce lower/higher SST and changes in the carbon budget of the surface waters. Such changes should be recorded by the oxygen and carbon isotopic composition of various species of planktonic foraminifera, as well as by temperature-dependent organic compounds and biomarkers, such as the ratios of unsaturated ketones from coccolithophorids. Estimates of SST from biotic data should also help to identify upwelling-related temperature changes.

Changes in the oxygen-minimum zone: Increased/decreased upwelling might be expected to change the structure and intensity of the OMZ. Two competing mechanisms that might modify the OMZ are: (1) increased/decreased productivity leading to increased/decreased oxygen demand, which would result in a stronger/weaker OMZ; and (2) increased/decreased vertical advection of deeper oxygen-rich waters below the OMZ is required by the upwelling and could lead to increased/decreased oxygen supply which would result in a weaker/stronger OMZ.

Some of the above measures have been useful in interpreting the environmental history of the western Arabian Sea. For example, the onset of upwelling in this area was suggested as having occurred at middle Miocene time on the basis of the increased abundance of siliceous microfossils (Whitmarsh, Weser, Ross, et al., 1974). Previous work on Owen Ridge sediments of late Quaternary age (Prell, 1984a; 1984b) has shown that planktonic foraminifer species can be used as indices of upwelling and that their abundance varies coherently with the 23-kyr precessional component of the earth's orbit, which is thought to be the solar radiation component forcing the monsoon. These studies show that the history of the monsoon can be reconstructed from the sediments and can be used to test hypotheses about the mechanisms that control the strength of the monsoon and cause changes in global climate.

GOALS AND DRILLING STRATEGY FOR LEG 117

Given the above observational and theoretical background, the major goal of Leg 117 was to sample a diversity of depositional environments that represent different atmospheric, oceanic, and sedimentologic regimes of the Indian Ocean monsoon system. Our sampling strategy was to drill on the Indus Fan to recover a clastic record related to uplift of the Himalayas and climatic/sea level changes. We drilled the crest of the Owen Ridge to recover a continuous section of upper Neogene pelagic sediments to establish both long-term tectonic and short-term Milankovitch variations in the biotic, sedimentologic, and chemical response to monsoonal changes. Lastly, we drilled the Arabian margin to recover the organic-rich sediments that accumulated rapidly in the zone of high productivity and detrital input and are associated with the oxygen minimum. These three distinct depositional environments allowed us to examine different aspects of the depositional response to changing monsoonal conditions that are embedded in changing global climates and sea levels.

Our interests in tectonic problems were focused on the uplift history of the Owen Ridge and how it is related to the reorganization of spreading centers and the growth of the Gulf of Aden. We also sought to understand the apparently complex tectonic and depositional history of the Arabian margin and how the timing of its tectonic features is related to the uplift of the Owen Ridge. Within the framework of these broad goals, we present the more detailed site-specific objectives for these areas in "Owen Ridge" and "Oman Margin" introductory chapters and in the respective site chapters (this volume).

REFERENCES

Berger, A., Imbrie, J., Hays, J., Kukla, G., and Saltzman, B., 1984. *Milankovitch and Climate*: Dordrecht (D. Reidel).

Beydoun, Z. R., 1982. The Gulf of Aden and northwest Arabian Sea. *In* Nairn, A.E.M., and Stehli, F. G. (Eds.), *The Ocean Basins and Margins: The Indian Ocean*: New York (Plenum Press), 253–313.

Blanford, H. F., 1884. On the connexion of the Himalaya snowfall with dry winds and seasons of droughts in India. *Proc. R. Soc. London*, 37:3.

Broecker, W. S., and Peng, T. H., 1982. Tracers in the Sea: Palisades, NY (Eldigio Press).

Bruce, J. G., 1974. Some details of upwelling off the Somali and Arabian coasts. *J. Mar. Res.*, 32:419–423.

Chang, C.-P., and Krishnamurti, T. N. (Eds.), 1987. *Monsoon Meteorology*: New York (Oxford Univ. Press).

CLIMAP Project Members, 1981. Seasonal reconstructions in the earth's surface at the last glacial minimum. *Geol. Soc. Am. Map/Chart*, MC-36.

Cochran, J. R., 1981. The Gulf of Aden: structure and evolution of a young ocean basin and continental margin. *J. Geophys. Res.*, 86: 263–288.

________, in press. The North Somali Basin, Chain Ridge, and the origin of the Somali Basin geoid/gravity low. *J. Geophys. Res.*

Coleman, R. G., 1981. Tectonic setting for ophiolite obduction in Oman. *J. Geophys. Res.*, 84:2497–2508.

Currie, R. I., Fisher, A. E., and Hargraves, P. M., 1973. Arabian Sea upwelling. *In* Zeitzschel, B., and Gerlach, S. A. (Eds.), *The Biology of the Indian Ocean*: New York (Springer-Verlag), 37–52.

Fein, J. S., and Stephens, P. L. (Eds.), 1987. *Monsoons*: New York (Wiley).

Hahn, D. G., and Manabe, S., 1975. The role of mountains in the South Asian monsoon circulation. *J. Atmos. Sci.*, 32:1515–1541.

Hahn, D. G., and Shukla, J., 1976. An apparent relationship between Eurasian snow cover and Indian monsoon rainfall. *J. Atmos. Sci.*, 33:2461–2463.

Hastenrath, S., 1985. *Climate and Circulation of the Tropics*: Boston (Reidel).

Hastenrath, S., and Lamb, P. J., 1979. *Climatic Atlas of the Indian Ocean*: Madison (Univ. Wisconsin Press).

Johnson, B. D., Powell, C. McA., and Veevers, J. J., 1976. Spreading history of the eastern Indian Ocean and greater India's northward flight from Antarctica and Australia. *Geol. Soc. Am. Bull.*, 87: 1560-1566.

________, 1980. Early spreading history of the Indian Ocean between Antarctica and Australia. *Earth Planet. Sci. Lett.*, 47:131-143.

Krey, J., and Babenerd, B., 1976. *Phytoplankton Production; Atlas of the International Indian Ocean Expedition*: Kiel (Institut für Meereskunde).

Kutzbach, J. E., 1981. Monsoon climate of the early Holocene: climate experiment with the earth's orbital parameters for 9000 years ago. *Science*, 214:59-61.

Kutzbach, J. E., and Street-Perrott, F. A., 1985. Milankovitch forcing of fluctuations in the level of tropical lakes from 18 to zero kyrBP. *Nature*, 317:130-134.

Larson, R. L., et al., 1985. *The Bedrock Geology of the World*: New York (W. H. Freeman).

Laughton, A. S., Whitmarsh, R. B., and Jones, M. T., 1970. The evolution of the Gulf of Aden. *Philos. Trans. R. Soc. London, A*, 267: 227-266.

McKenzie, D., and Sclater, J. G., 1971. The evolution of the Indian Ocean since the Late Cretaceous. *Geophys. J. R. Astron. Soc.*, 24: 437-528.

Manabe, S., and Hahn, D. G., 1977. Simulation of the tropical climate of an ice age. *J. Geophys. Res.*, 82:3889-3911.

Mercier, J.-T., Armijo, R., Tapponnier, P., Carey-Gailhardis, E., and Lin, H. T., 1987. Change from late Tertiary compression to Quaternary extension in Southern Tibet during the India-Asia collision. *Tectonics*, 6:275-304.

Mountain, G., and Prell, W. L., 1987. Leg 117 ODP site survey: a revised history of Owen Basin. *Eos, Trans. Am. Geophys. Union*, 68: 424.

________, in press. A multiphase plate tectonic history of the southeast continental margin of Oman. *In* Robertson, A.H.F., Searle, M. P., and Ries, A. C. (Eds.), *The Geology and Tectonics of the Oman Region*, Geol. Soc. Am. Spec. Publ.

Norton, I. O., and Sclater, J. G., 1979. A model for the evolution of the Indian Ocean and the breakup of Gondwanaland. *J. Geophys. Res.*, 84:12.

Patriat, P., and Achache, J., 1984. India-Eurasia collision chronology has implications for crustal shortening and driving mechanism of plates. *Nature*, 311:615-621.

Prell, W. L., 1984a. Variation of monsoonal upwelling: a response to changing solar radiation. *In* Hansen, J. E., and Takahashi, T. (Eds.), *Climatic Processes and Climate Sensitivity*: Washington (American Geophysical Union), Geophys. Monogr. 29, Maurice Ewing Series, 5:48-57.

________, 1984b. Monsoonal climate of the Arabian Sea during the late Quaternary: a response to changing solar radiation. *In* Berger, A., and Imbrie, J. (Eds.), *Milankovitch and Climate*: Dordrecht (D. Reidel), 349-366.

Prell, W. L., and Kutzbach, J. E., 1987. Monsoon variability over the past 150,000 years. *J. Geophys. Res.*, 92:8411-8425.

Prell, W. L., and Streeter, H. F., 1982. Temporal and spatial patterns of monsoonal upwelling along Arabia: a modern analogue for the interpretation of Quaternary SST anomalies. *J. Mar. Res.*, 40:143-155.

Rabinowitz, P. D., Coffin, M. F., and Falvey, D., 1983. The separation of Madagascar and Africa. *Science*, 220:67-69.

Schlich, R., 1982. The Indian Ocean: aseismic ridges, spreading centers, and oceanic basins. *In* Nairn, A.E.M., and Stehli, F. G. (Eds.), *The Ocean Basins and Margins, The Indian Ocean* (Vol. 6): New York (Plenum Press), 51-148.

Sclater, J. G., Luyendyls, B. P., and Meinke, L., 1976. Magnetic lineations in the southern part of the Central Indian Basin. *Geol. Soc. Am. Bull.* 87:371-376.

Sclater, J. G., and Fisher, R. L., 1974. The evolution of the east-central Indian Ocean, with emphasis on the tectonic setting of the Ninetyeast Ridge. *Geol. Soc. Am. Bull.* 85:683-702.

Shukla, J., 1987. Interannual variability of monsoons. *In* Fein, J. S., and Stephens, P. L. (Eds.), *Monsoons*: New York (Wiley), 399-463.

Stein, C. A., and Cochran, J. R., 1985. The transition between the Sheba Ridge and Owen Basin: rifting of old oceanic lithosphere. *Geophys. J. R. Astron. Soc.*, 81:47-74.

Webster, P. J., 1987. The elementary monsoon. *In* Fein, J. S., and Stephens, P. L. (Eds.), *Monsoons*: New York (Wiley), 3-32.

Whitmarsh, R. B., 1974. Some aspects of plate tectonics in the Arabian Sea. *In* Whitmarsh, R. B., Weser, O. E., Ross, D. A., et al., *Init. Repts. DSDP*, 23: Washington (U.S. Govt. Printing Office), 527-536.

________, 1979. The Owen Basin off the southeast margin of Arabia and the evolution of the Owen Fracture Zone. *Geophys. J. R. Astron. Soc.*, 58:441-470.

Whitmarsh, R. B., Weser, O. E., Ross, D. A., et al., 1974. *Init. Repts. DSDP*, 23: Washington (U.S. Govt. Printing Office).

Wyrtki, K., 1971. *Oceanographic Atlas of the International Ocean Expedition*: Washington (National Science Foundation).

________, 1973. Physical oceanography of the Indian Ocean. *In* Zeitschel, B., and Gerlach, S. A. (Eds.), *The Biology of the Indian Ocean*: New York (Springer-Verlag), 18-36.

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