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Subsurface Geology off Bombay with Paleoclimatic Inferences Interpreted from Shallow Seismic Profiles[1]

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ABSTRACT

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High resolution seismic reflection profiles of nearshore areas off Bombay provide information on subsurface geology and permit certain paleoclimatic inferences. Three sedimentary units overlie the acoustic basement: late Pleistocene consolidated sediment, early Holocene layered sediment (about 7 m thick) and Modern Clay (2.5 - 3 m thick). An unconformity probably due to subaerial erosion during the Pleistocene lowered sea level stand separates the consolidated sediments from the overlying layered sediments. The latter were probably deposited during the early Holocene marine transgression, when the precipitation pattern was different from the present (wetter). The Modern Clay conformably overlies them and was deposited during the last 600-700 years, during which the climate was similar to that of the present day. The bedrock appears to be fractured, tilted and eroded but no evidence was observed for any Holocene disturbance.

ADDITIONAL INDEX WORDS: *Offshore high resolution, seismology, subsurface geology, stratigraphy, Bombay harbour*

INTRODUCTION

The city of Bombay, on the west coast of India, is located on a group of islands separated by marshy tidal flats and creeks. The islands represent the western (onshore) limit of the Deccan Traps. The geology, especially the petrology, of the Deccan Traps (Paleocene) of Bombay has been studied by several researchers (SUKESHWALA and POLDERVAART, 1958; SETHNA and MERCHANT, 1976; SETHNA, 1981). Extensive geophysical investigations including multichannel seismic surveys have been carried out on the continental shelf off Bombay and the giant offshore Bombay High oil field (SAHAY, 1978; RAMASWAMY and RAO; 1980). However, until recently, little work on the marine geology of the nearshore areas has been carried out.

The National Institute of Oceanography has conducted several integrated high resolution geological and geophysical surveys of the Bombay harbour and the adjacent offshore areas to study the surficial and shallow subsurface geology. The study area extends from shallow tidal flats to about the 14 m isobath. About 650 lkm are covered by echo sounding, side-scan sonar and shallow seismic profiling. This was followed by surficial sediment sampling with grab and piston gravity corers. The paper presents analyses of the high resolution seismic profiling to describe the subsurface geology and stratigraphy, and to make some inferences about the Holocene paleoclimates.

GEOLOGICAL SETTING

The western side of the Bombay harbour is bordered by the Bombay group of islands with the mainland lying to the north and east. The coastline is characterised by numerous bays, beaches, cliffs, stacks, marine platforms, marshy tidal flats, and creeks (SUBRAMANYAN, 1981). Several small shoals, islets and few islands appear in the inner harbour. The rivers Ulhas in the north, Panvel in the east and Amba in the southeast discharge into the harbour (Figure 1).

Basalts and associated rock types (about 60 - 65 Myr old) interbedded with tuffs are exposed on the islands and the mainland. The Deccan Traps re-

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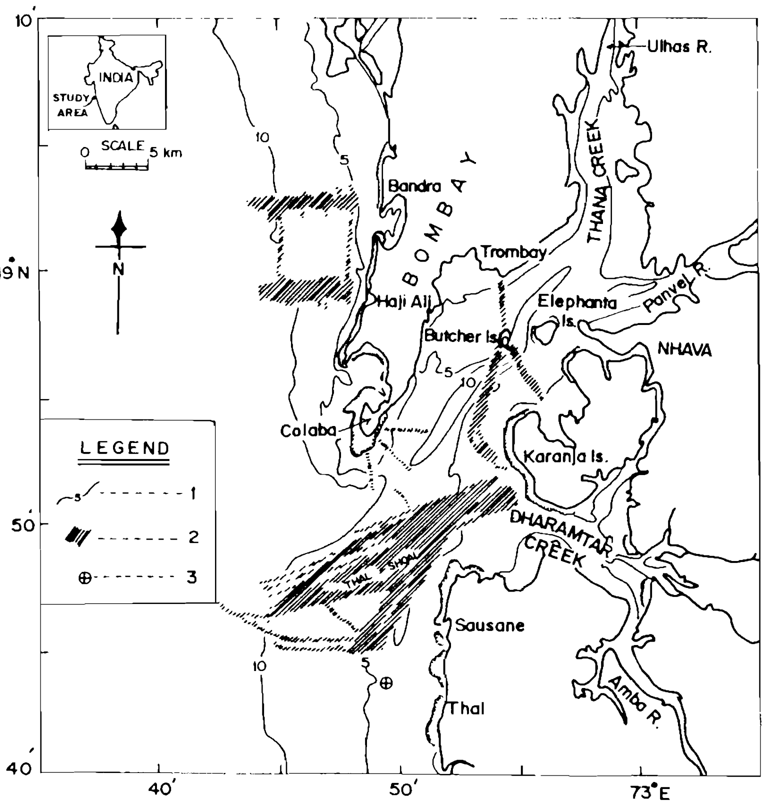

Figure 1. Map showing the areas surveyed and the bathymetry. 1—simplified bathymetric contours (in m); 2—the area covered by Side-Scan Sonar; 3—location of core sample off Thal. Bathymetric contours are partly from the published hydrographic charts.

sulted from fissure eruptions and consequently pyroclastic deposits are not common, but the traps of the Bombay Island are associated with pyroclastics which indicate that in this area fissure eruptions were accompanied by a central type of volcanic activity (SUKESHWALA and POLDERVAART, 1958). The lava flows are generally almost horizontal but around Bombay the traps dip about 10° towards west (SETHNA, 1981).

METHODS

The positions during the surveys were obtained with a Motorola Miniranger III system and in some areas with the conventional sextant angles of shore features. The echosounding was carried out with an Atlas Deso 10 or a Raytheon echosounder. Side-Scan Sonar profiling was carried out using an EG&G Mark 1B system with tow fish model 272. The sub-bottom profiling was carried out with a Huntec Hydrosonde 2A system. A Boomer with a predominant frequency of the main beam pulse as 5 KHz was used as the energy source. The echograms obtained were used not only for preparation of bathymetric maps but also to identify the rock outcrops on the seabed and the nature of the sediment cover. The side-scan sonar records (sonographs) were used to map the distribution of sediments and rocks on the seabed, periodic bedforms in sediments and also trends of the rocks. All the seismic recordings were carried out at 62.5 millisecond-sweep rate and the seismic sections have been prepared with 1500 m/s as the conversion factor. The depth is shown in meters.

ACOUSTIC STRATIGRAPHY

The seismic reflection records show four distinct reflectors (Figure 2). The lowermost is the acoustic basement mainly representing the seaward extension of the Deccan Traps and locally representing the upper weathered/altered or reworked surface.

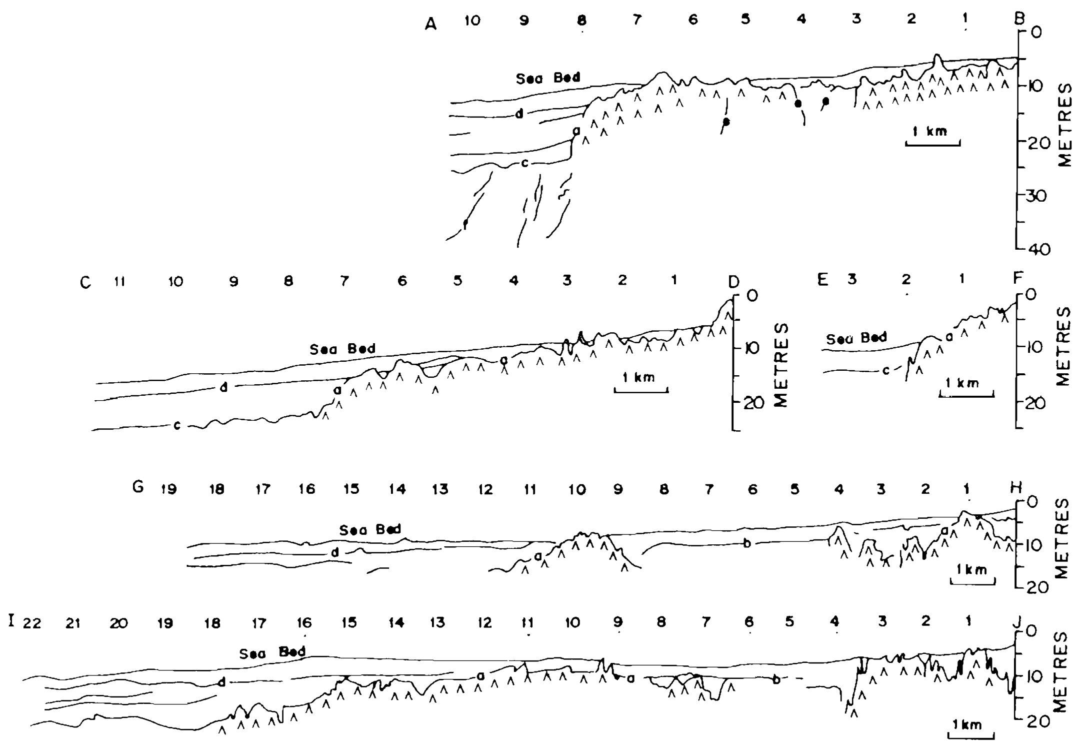

Figure 2. Line drawings of seismic profiles along the traverses AB, CD, EF, GH and IJ. (a) Bedrock surface; (b) conspicuous flat reflector; (c)– unconformity forming the top of the westward dipping reflectors; (d) - unconformity (top of the layered sequence); (e) faint reflectors below the acoustic basement; and (f) westward-dipping reflectors. Positions of these traverses are shown in Figure 3.

The second one is the top of a westward dipping sequence representing an erosional surface of unconformity. The third is the top of a sequence of parallel reflectors which appear west of Thal Shoal and about 8 km offshore from Bandra and Haji Ali. Finally the uppermost reflector represents the present-day seafloor.

Acoustic and subacoustic basement

The lowermost strong reflector, which is acoustically opaque to the seismic energy used represents the acoustic basement. The seismic records show that the acoustic signature from this reflector is not consistent and shows some lateral variation. Where the acoustic basement shows characteristics of high relief, exceptional strong reflection and complete opacity, it is presumed to represent the bedrock. However, where faint reflectors are seen below the basement, it is considered as the subacoustic basement, which possibly represents the dense consolidated or cemented overburden or weathered/altered or reworked basalts.

The bedrock reflector off Colaba can be traced to about 2 km offshore and about 10 m below the seabed (line EF in Figure 3). However to the west, off Haji Ali and Bandra the acoustic basement shows lateral variation (Figure 4) and could be traced to about 8 km offshore and about 10-12 m below the seabed. A N - S trend of the bedrock outcrops was revealed from the sonographs. Inside the harbour, off Karanja Island (line GH in Figure 3), the bedrock can be traced about 3 to 4 km offshore. From 4 km to about 8.5 km the acoustic basement is conspicuously flat (Figure 5). The flat reflector is confined more or less to the Amba river mouth (Dharamtar creek). The bedrock shows considerable relief and appears to have undergone fracturing and erosion whereas the flat reflector does not. Further from 8.5 to 12 km offshore, the bedrock is characteristically rugged and outcrops at the Thal Shoal. Subsequently, the bedrock rapidly deepens

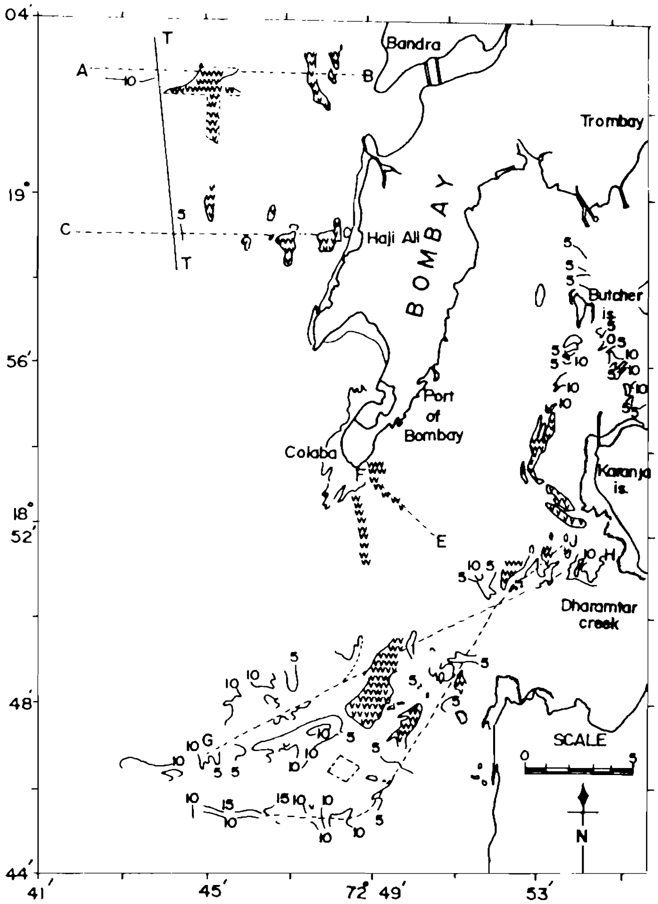

Figure 3. Map showing the isopachs of unconsolidated sediments and distribution of rock outcrops in the area surveyed.

and it could not be traced owing perhaps to increased overburden thickness. The submarine outcrops inside the harbour trend NNE - SSW. At the northern end of the harbour between Trombay and Butcher Island the bedrock rises to a shallow depth (about 5 m) below the seabed.

Westward dipping reflector

About 8 km offshore from Bandra, several westward dipping reflectors are observed (Figure 6). The upper surface of the westward dipping reflectors is an angular unconformity and appears to have been caused by subaerial erosion.

Layered sequence

The erosional unconformity on top of the westward dipping reflector is overlain by a series of faintly stratified parallel reflectors having a total thickness of about 7 m (Figure 6). As these reflectors approach the shore they onlap the acoustic basement. Seismic signals within this layer indicate alternate bands of strong and weak reflections and localised discontinuities.

Present day seafloor

Based on the seismic records the seabed could be divided into three distinct zones, *i.e* (1) bedrock outcrops, (2) a thin layer of sand or shells on clay and (3) clay.

Almost over the entire area the seabed is covered by 2.5 to 3 m thick unconsolidated acoustically transparent clay, which was confirmed from several

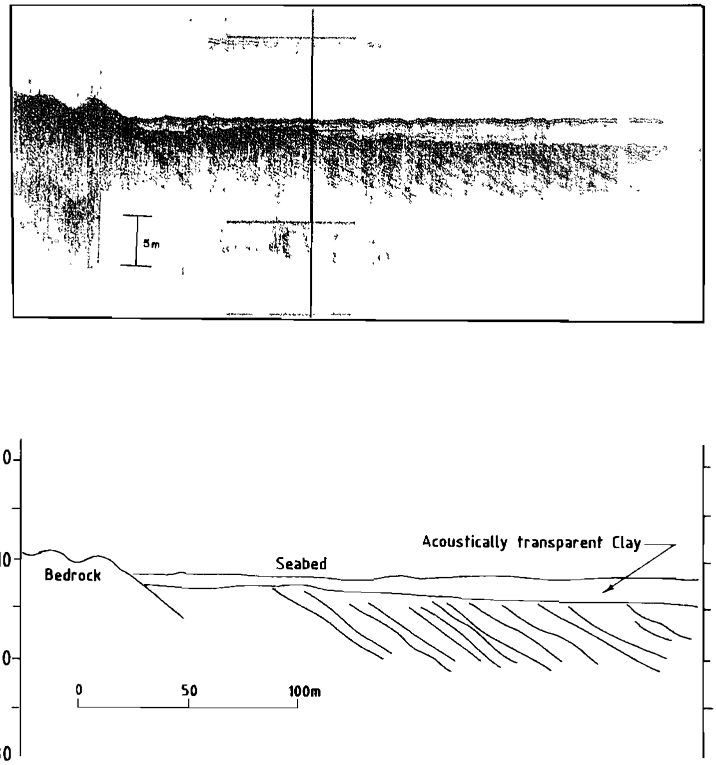

Figure 4. Seismic record off Bandra showing bedrock reflector and the lateral variation in the character of the acoustic basement

seabed samples to be an olive-gray clay (ALMEIDA *et al.*, 1978) It was noticed that this clay unit is thicker in the bedrock troughs and in the northern part of the inner harbour, and thinner in pockets on top of the bedrock highs.

DISCUSSION

The rocks, surficial sediment distribution and the isopachs (Figure 3) show that the submarine outcrops follow a N - S trend on the western offshore areas off Bandra and Haji Ali and a NNE - SSW trend in the harbour. These trends are similar to the predominant N - S trend of the major structural elements observed in the adjoining coastal areas (POWAR, 1981). Basalts and associated rocks and tuffaceous sediments of the Upper Deccan Group are exposed on land in the vicinity of the study area. Therefore it can be concluded that the bedrock identified in the offshore seismic sections represents the extension of the onshore Deccan Traps and associated rock types.

According to SETHNA and BATTIWALA (1974) the tuffs are eroded easily and therefore form mud flats while crystalline rocks stand out as hillocks and ridges. Exposure of different varieties of basalts at the same level even on the flanks of the same hill without the slightest indication of faulting between the two is a not uncommon feature of the Deccan Traps (AGASHE and GUPTE, 1968). A situation very similar to this can also be expected in the adjacent offshore areas. Therefore, the cause for the ridge and trough features observed in the bedrock at or below the seabed, can be attributed similarly to differential erosion.

From the seismic sections (off Bandra and Haji Ali) it was observed that, the bedrock slopes gently (about 1:1,100) as far as about 7.5 km from the shore (line AB in Figure 2). Immediately westwards, the slope increases sharply to about 1:100. This zone of abrupt change in bedrock slope is inferred to reflect a lineament shown as TT in Figure 3. The geological setup on either side of the lineament is different. Shorewards of it, the bedrock

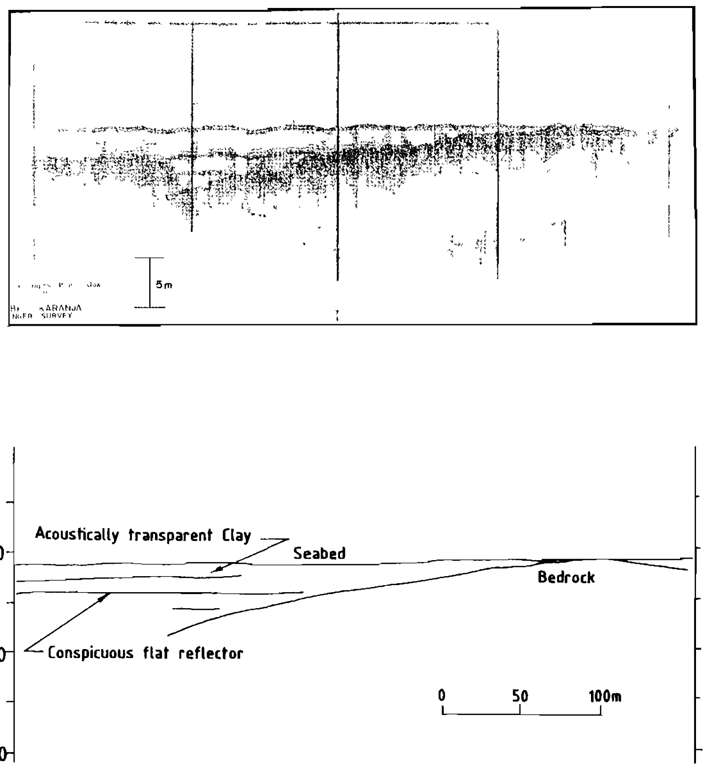

Figure 5. Seismic record off Karanja Island showing the conspicuously flat strong reflector on the left. This reflector is identified as Amba River deposit.

reflector can be traced with a characteristic undulating surface representing the Deccan Traps, whereas seawards, there are steeply westward dipping reflectors topped by the unconformity. It is inferred that the steep slope and subsequent discontinuity of the bedrock off Bandra and Haji Ali is a fault-controlled feature. During lowered sea level the fault scarp might have faced wave action which developed sea cliffs and caused the scarp to migrate shorewards. Therefore we consider that the lineament TT represents a fault.

The conspicuously flat reflector near Dharamtar creek (Figure 5) characterised by strong seismic reflection signals perhaps represents thick shelly/sandy deposit at the mouth of the Amba river. The unit is opaque to the seismic energy used in the present survey and therefore masks the reflectors below it.

In the absence of borehole data it is difficult to identify the lithology of the westward dipping reflectors. However, these reflectors show remarkable continuous subparallel reflection and the fact that seismic energy could penetrate through, possibly indicate that these are of sedimentary origin. Shallow penetration subbottom profiles taken from nearshore across the shelf as far as the Bombay High indicate that the sedimentary unit overlying the westward dipping reflector outcrops at the outer shelf around 60 - 90 m water depth (SIDDIQUIE *et al.*, 1977). These outcrops were identified to be relict carbonate sediments of the late Pleistocene to early Holocene time of glacially lowered sea level and was radiocarbon dated to be around 9,000-11,000 years old (HASHIMI *et al.*, 1978; NAIR and HASHIMI, 1980). The lithological log of an exploratory well drilled on the inner continental shelf off Bombay (SAHAY, 1978) indicates that, shallow marine clay and claystone were deposited in this area during the Pliocene to Holocene interval. The erosional truncation of the upper surface of the westward dipping reflectors indicates subaerial erosion which is possible only during a lower seastand and most likely

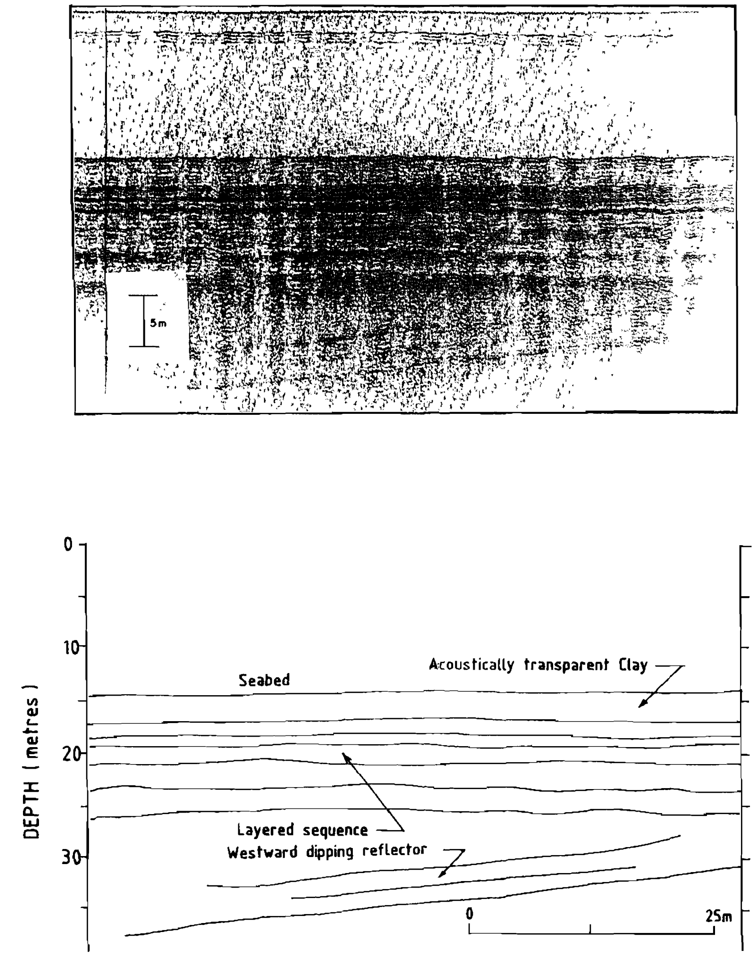

Figure 6. Seismic record off Bandra showing (1) unconsolidated Modern Clay on the top, (2) faintly stratified parallel reflectors and (3) westward dipping reflector.

during a Pleistocene regression. It is therefore inferred that the westward dipping sequence is the shoreward edge of the late Pleistocene consolidated deposits.

The relict early Holocene carbonate sediments provide the base above which the layered sequence and the acoustically transparent top clay were deposited. These sedimentary units onlap the bedrock as they approach the shore. The last glacial maximum in the Indian Ocean was around 18,000 yrs BP (PRELL *et al*, 1980), and about 14,000 yrs BP the global transgression commenced (MILLIMAN and EMERY, 1968). Therefore it is concluded that the sedimentary unit overlying the relict carbonate sediments was deposited during the last 10,000 years. A certain degree of stratification within the unit is indicative of a relatively slow sedimentation rate. Local discontinuities of the minor reflectors perhaps indicate small scale lateral facies variation. The alternate banding of the weak and strong seismic reflection signals are indicative of vertical variation in the sedimentary facies and this shows a certain cyclicity which appears to be significant. This may be related to environmental variation. The strong reflectors represent the coarse-grained material and the intervening acoustically transparent layers are fine-grained sediments. Examination of similar shallow seismic records elsewhere on the continental shelf (off Bassein about 99 km and off Umbhrat about 200 km, WNW and NW respectively of the study area) indicated the presence of layered sequence underlying the acoustically transparent Modern Clay (N.I.O., 1978). Therefore it appears that this layered sequence is a regional depositional unit, which possibly reflects the prevailing climatic conditions.

Increased runoff due to greater rainfall generate large supplies of this coarse-grained material. Rainfall in this part of the world is mostly during the northern summer monsoon and the average annual precipitation of almost twice the present value during the early Holocene (10,000 to 5,000 yr BP) was indicated by KUTZBACH (1980) and SINGH *et al.*, (1972). Long-distance transport of coarse-grained material on the continental shelf in this area was attributed to flash floods caused by heavy, shortlived and sporadic rain during Holocene (NAIR and HASHIMI, 1980). The alternate bands of coarse and fine-grained material were perhaps deposited in the early Holocene when the climate was wetter than the present and over this was superimposed the second-order cycle of intensified shortlived, heavy spells of the monsoon.

The top 2.5 to 3 m of acoustically transparent clay which forms the present day seafloor except where rocks outcrop is in the process of covering all the irregularities of the bedrock and represents a submergent phase of the coastal plain. According to AHMED (1972) this littoral appears to represent a stage intermediate between the initial crenulate and subsequent youth stage of an irregular terrain subjected to submergence. The absence of any stratification within this unit is attributed to relatively faster rate of deposition. The sediment rate computed by various researchers (HASHIMI *et al.*, 1978; BOROLE *et al.*, 1982; PATEL *et al.*, 1975) varies from 3 m to 19 m/1,000 yr off Bombay. Large variations in depositional rates could be attributed to the variations in the environment from where core samples were collected and different methods used for their determination. From one of the cores off Thal, an area not highly influenced by the activities of the harbour, the depositional rate was calculated to be about 4.3 m/1,000 yr (BOROLE, personal communication, 1986). Based on this rate it appears that the top sedimentary unit consisting of acoustically transparent clay (about 2.5 -3 m thick) was deposited during the last about 600 - 700 yr. The beginning of the deposition of this unit, perhaps marks a change in the precipitation pattern from heavy to low rainfall.

On the east of the Bombay Islands a large number of tree trunks with the roots *in situ* embedded in the clay and submerged to a depth of about 6 m below the mean sealevel were excavated in 1878 (SAHASRABUDHE and DESHMUKH, 1970). On the west of the Bombay Islands beach deposits were reported at about 4 m above the high water level (PASCOE, 1962). He interpreted this to be due to the eastward tilting of the bedrock towards the inner harbour caused by tectonic movement. However, later researchers (AGRAWAL *et al.*, 1979) preferred to explain these raised beaches and submerged forests by glacio-eustasy. The radiocarbon dating of the raised beach material indicates them to be not older than 5,000 yrs BP (AGRAWAL *et al.*, 1979). If the emergence and submergence of the Bombay Islands is to be attributed to a tectonic cause, then it should have happened around 5,000 yrs BP. The seismic profiles which contain the sedimentary record of the past 10,000 yr do not show any indication of offset in the layers. It is therefore concluded, that no tectonic movement took place in this area since the early Holocene and only the process of marine transgression and regression is responsible for the emergence and submergence of the coastal plain around Bombay.

SUMMARY AND CONCLUSIONS

Based on the analyses of the acoustic stratigraphy, and the character and inter-relationships of the different reflectors, a shallow stratigraphic sequence is prepared (Table 1). Further the subsurface geology and the geological history of the Bombay Harbour area and certain paleoclimatic inferences derived from the present study are summarised as follows.

(1) The onshore Deccan Traps of the Bombay Island extend well offshore and are terminated by a sharp boundary, possibly a fault scrap, modified by later cliffing.

(2) Above the acoustic basement three main sedimentary units could be identified. The units are interpreted as late Pleistocene consolidated sediments, Holocene layered sediments and the Modern Clay.

(3) The consolidated sediments characterised by westward dipping reflectors were deposited above the bedrock before the Pleistocene regression.

(4) During the Pleistocene glacially lowered sea stands, the top of the consolidated sediments was eroded forming an unconformity. Above this unconformity, faintly stratified sediments were deposited during an early Holocene transgressional phase.

(5) The Modern Clay was deposited at a com-

Table 1. Inferred stratigraphic sequence of the Bombay Harbour area

Age	Acoustic signature	Lithology	Thickness (approximately)	Paleoclimate
Modern	Acoustically transparent	Olive gray clay, silty clay with shells	3 m	Warm and humid
Holocene	Alternate bands of strong and weak reflections	Faintly stratified fine and coarse sediments	7 m	Relatively moister than present, accompanied with periodically intensified and shortlived monsoon
	— —	UNCONFORMITY —	———	———
Late Pleistocene	Fairly continuous subparallel reflections	Consolidated sediments		
	— —	— UNCONFORMITY —	———	———
Paleocene	Acoustic basement	Mostly Deccan Trap		

paratively faster rate during the last 600 - 700 yr. Its attitude, covering of all the irregularities in the sea floor, represents the contemporary submergent phase of the coastal plain.

(6) There was perhaps no major climatic change during about the last 600 - 700 yr, but before this the monsoon must have been periodically much more vigorous.

(7) The sedimentary units do not indicate any evidence of faulting or other tectonic disturbance since the Pleistocene.

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□ ZUSAMMENFASSUNG □

Seismische Rückstrahlungsprofile mit höhen Auslösung, die in der Nähe der Strände Bombays genommen wurden, liefern Auskunft über die Geologie unter der Oberfläche und lassen besondere paleoklimatische Folgerungen. Drei Sedimentteile legen überm akustischen Fundament: spätholozäne zusammengefasstete Sedimente, frühholozäne geschichtete Sedimente (7 m dick) und moderne Ton (2,5 - 3 m dick). Die zusammengefasstete Sedimente und die Geschichtete werden von einer Unübereinstimmung getrennt, die vielleicht von Unterluftauswaschung während der pleistozänen niedrigen Meeresspiegelumstände verursacht wurde. Es gibt die Möglichkeit, dass die geschichtete Sedimente stammen aus der frühholozänen Überschreitung. Das moderne Ton legt darüber, und stammt aus den letzten 600 - 700 Jahre. Die Grundgebirge scheinen gebrochen, gekippt und ausgewaschen, aber kein Beweis von holozäne Störungen wurde beachtet.--*Stephen A. Murdock, CERF, Charlottesville, Virginia, USA*

□ RÉSUMÉ □

Des profils sismique-réflexion à haute résolution de zones prélittorales au large de Bombay nous informent sur la géologie de surface et les paléoclimats. Trois unités sédimentaires dominent: les sédiments pléistocènes consolidés, des sédiments stratifiés holocènes anciens (7 m d'épaisseur) et des argiles modernes (2,5 - 3 m d'épaisseur). La séparation entre les sédiments consolidés et les sédiments stratifiés est souvent non conforme. On devrait ce fait à l'érosion subaérienne au cours de stations du niveau de la mer en baisse pendent le Pliocène. Les sédiments stratifiés se sont probablement déposés au cours de premières transgressions marines de l'Holocène, alors que le régime des précipitations était plus humide que l'actuel. La position de l'argile moderne déposée au cours des 600 - 700 dernières années est conforme. Le climat était alors trés semblable à l'actuel. Le lit rocheux est fracturé, incliné et érodé, sans qu'il soit possible d'y observer de perturbation holocène.--*Catherine Bressolier, EPHE, Montrouge, France*