Exploring the oceans — The geophysical way

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The evolution of the eastern continental margin of India (ECMI), the Bengal Fan and the Central Indian Basin (CIB) is a consequence of the breakup of India from the eastern Gondwanaland in Late Jurassic to Early Cretaceous. Recent marine geophysical studies provided some new information about the structure, tectonics and the evolutionary history of this region and also helped in identifying some target areas for offshore exploration of ECMI.

MARINE geophysics deals with the physics of the earth beneath the oceans. Though the ultimate goal of marine geophysical studies is to explore the non-living resources of the oceans, a marine geophysicist is interested in certain basic aspects related to the nature and origin of the oceanic crust, evolution of continental margins, oceanic basins, etc. This Regional Centre of NIO has been engaged in such studies for some time and has contributed to the marine geophysical investigations over the eastern continental margin of India (ECMI), Bengal Fan and Central Indian Ocean Basin (CIOB). The marine geophysical work is primarily on (i) nearshore heavy minerals, (ii) geomorphology of the shelf, (iii) shelf stratigraphy in relation to sea level changes, (iv) tectonics of the eastern continental margin and Bengal Fan, (v) crustal deformation in the central Indian Basin, and (vi) marine archaeology.

Nearshore heavy minerals

Placer deposits constitute the major component of nearshore minerals and are mostly confined to the inner shelf (less than 30 m water depth) of the continental margins. These are mechanically concentrated detrital minerals derived from the erosion of onshore rocks. Rivers and other drainage channels are the main carriers of these placers, which contain heavy minerals like magnetite, ilmenite, garnet, zircon, monazite, rutile, etc. These heavy minerals generally concentrate in the nearshore areas as they cannot be transported for long distances. Sea level changes play an important role in the accumulation of heavy mineral concentrations. During periods of lowered sea levels, the rivers flowed for a considerable distance from the shore and might have deposited placers on the presently submerged shelf. These drowned valleys are therefore important targets in the exploration of offshore placer deposits. Stable or passive continental margins are ideal locations for the accumulation of placer deposits and some parts of east coast of India are an example.

Placer deposits in the form of black sands are found along the beaches of east coast of India, for example off Orissa coast near Gopalpur, off Bhimunipatnam and Visakhapatnam coasts in Andhra Pradesh and off Kanyakumari (Manavalakurchi) in Tamil Nadu. Some of these deposits are already being explored by the Indian Rare Earths Limited.

A systematic geophysical coverage of the innershelf off Visakhapatnam and Bhimunipatnam was carried out to study the nature and origin of these placer deposits. Magnetic and acoustic (shallow seismic profiling) methods are widely used for the location of placer deposits. Research work including modelling of marine magnetic anomalies of these bays[1–3], revealed that (i) the innershelf (below 30 m water depth) is associated with heavy mineral concentrations, (ii) in some cases, placers are associated with structural lineaments like fracture zones and intrusives extending from coast to the innershelf, and (iii) in majority cases, the source for these placers appeared to be the on shore drainage channels, either active or inactive.

One of the significant findings from the shallow seismic surveys is the presence of buried river channels off (a) Bhimunipatnam and (b) Pudimadaka near Visakhapatnam (Figure 1). These channels having widths of nearly 2 to 3 km are located nearly 40 to 50 m below the seabed in the innershelf (at water depths of nearly 30 m) and might have been active during lowered sea levels of late Pleistocene (around 18,000 yrs age).

Sediment samples of the inner shelf (< 15 to 20 m water depth) indicated that the bulk concentration of heavy minerals varied from 20 to 40% at a few places[1,3]

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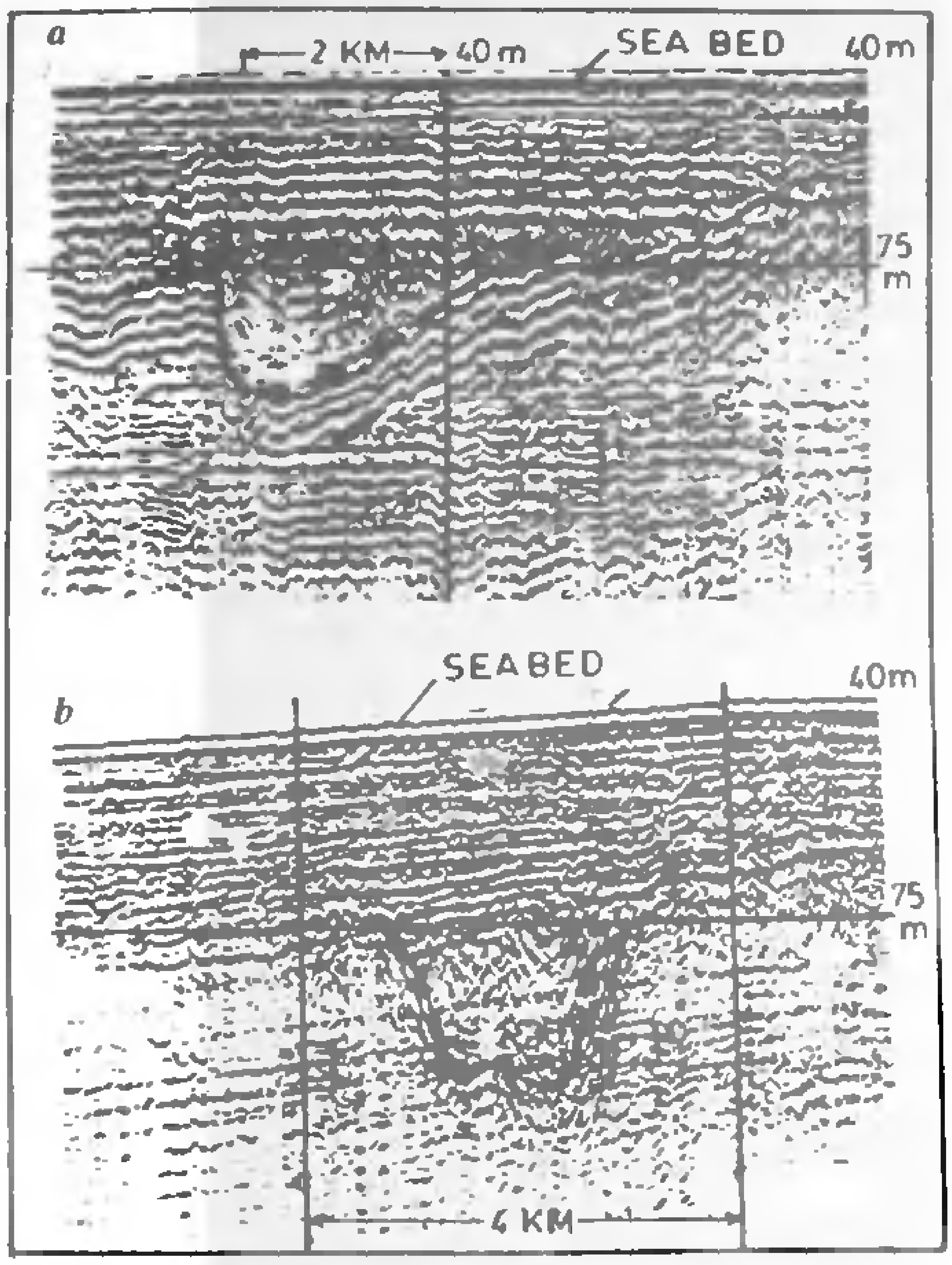

Figure 1 *a* and *b*. Buried river channels. ***a***, Off Bhimunipatnam. ***b***, Off Pudimadaka near Visakhapatnam.

Geomorphology

Geomorphology of a continental shelf to a large extent depends on coastal geology. The land geology of east coast of India mainly comprises of khondalite hills (a variety of metamorphic rock) aligned in NE–SW and NW–SE direction, though charnockites (a variety of granite) are also found as intrusives into the khondalite massif.

Magnetic data of the eastern continental shelf revealed seaward extension of several coastal features. Models derived at this Regional Centre from the magnetic data delineated offshore extension of major folds, for example the one derived from Tuni to Visakhapatnam, extending up to 10 km into the sea in the form of basement uplift[2]. These models also suggest charnockitic intrusions beneath the innershelf. These structural lineaments play a vital role in the shelf mineralization, as they often form as source rocks for the offshore mineral concentrations.

Another significant observation is the presence of gas-mixed sediments and gas seepages within the shelf sediments of Krishna, Godavari and Mahanadi river basins[4]. These gas seepages are due to migration of gas/oil from deeper depths and are reflected as acoustic wipeouts or chaotic reflections on seismic records (Figure 2) of the river basins. They are considered as good indicators of the potential hydrocarbon deposits of the offshore basins.

Sea level changes and seismic stratigraphy

The world had experienced a series of warm and cold climates with at least five Ice Ages reported during the last 2300 million years. These climatic changes had a profound effect on the sea levels all over the world. During the Ice Ages, glaciers or huge masses of ice occupied much of the present oceanic and land regions and the sea levels dropped by as much as hundred meters, while during the warm climates, the glaciers melted raising the sea levels.

It is of course not possible to trace the history of sea levels for periods more than a few hundred million years, due to the absence of valid data. However, sea level changes during the Quaternary period, spanning a little more than two million years can be inferred from seismic sequence analysis of shelf sediments. The regressions and transgressions of sea levels made an impact on the shelf morphology. A sea level drop, for example exposes the shelf to weathering while a subsequent rise covers this eroded shelf by transgressive sediments.

Shallow seismic profiling, a low energy acoustic propagation technique records the subsurface stratigraphy up to a depth of about 150 to 200 m below the sea bed and is widely used to study the interrelation between the sea level changes and stratigraphy.

Seismic stratigraphy of the eastern continental shelf revealed a major sea level regression around 18,000 years (late Pleistocene)[5]. A relict shore line parallel to the east coast was located at about 130 m water depth corresponding to the late Pleistocene glaciation (Figure 3). Seismic sequence analysis adopted at the Institute

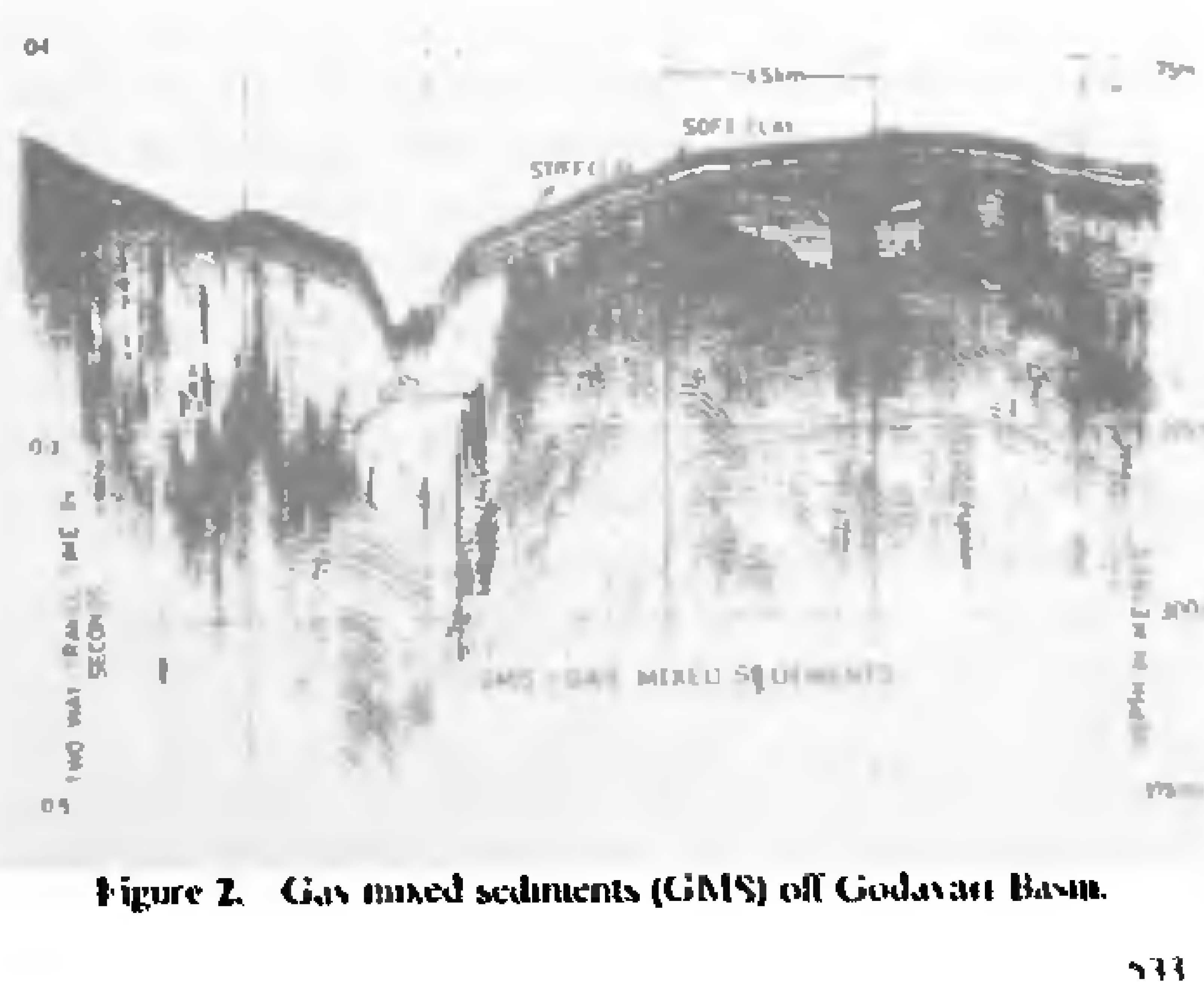

Figure 2. Gas mixed sediments (GMS) off Godavari Basin.

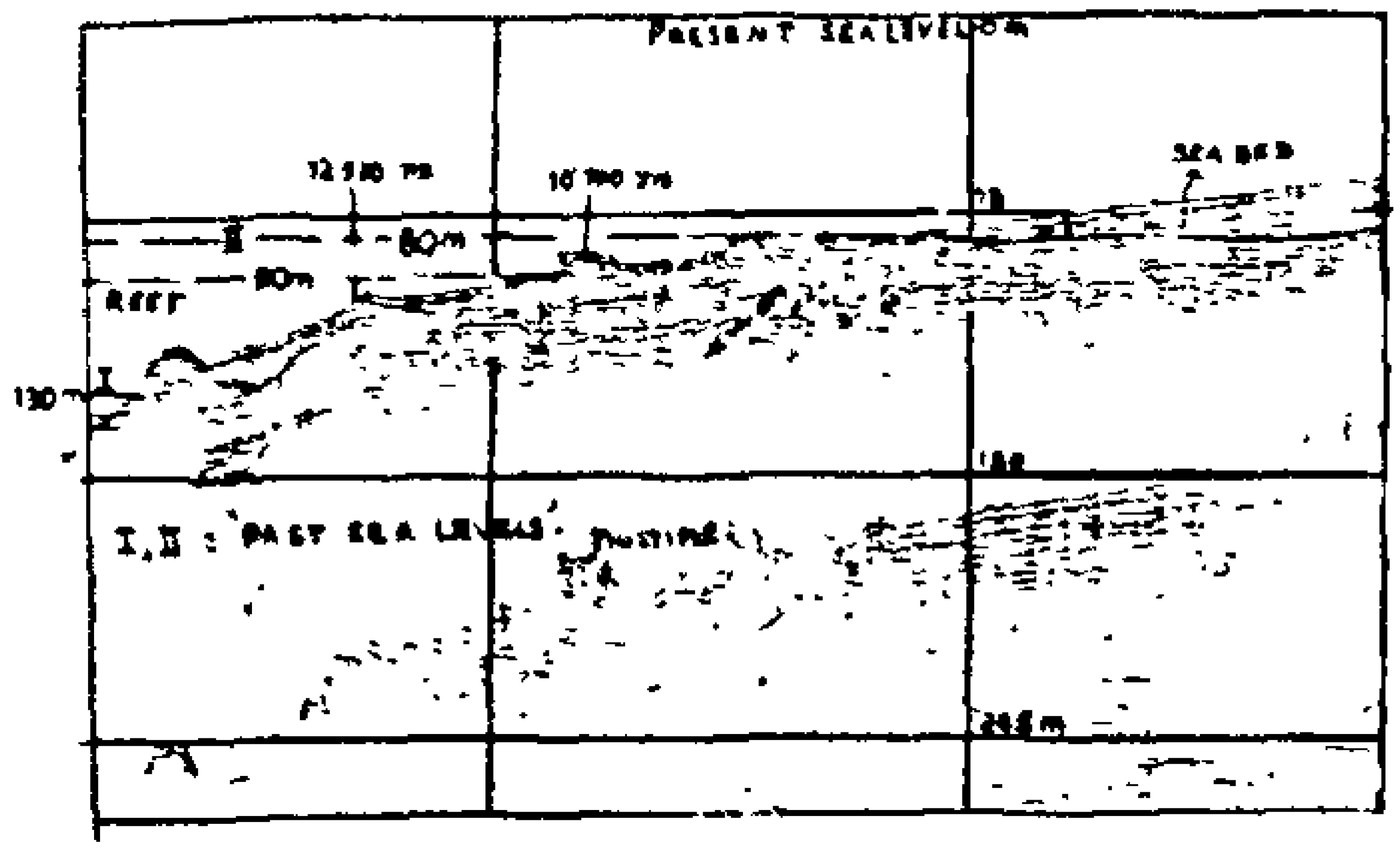

Figure 3. Seismic record indicating sea level changes (I & II) for the last 18,000 years.

also revealed that the sea level transgression between 18,000 years till date has not been continuous and there are at least four still stands[6] (periods during which the sea level is steady). These still stands have made imprints on the shelf morphology (Figure 3). Radiocarbon dating of the samples collected over the different relict shoreline features helped in estimating the sea level history of the Quaternary period. Locations of these relict features are economically potential areas for the exploration of carbonate deposits.

Tectonics

The evolution of eastern continental margin of India (ECMI) and Bengal Fan is a consequence of the breakup of Gondwanaland around 130 million years ago (Cretaceous period). This huge landmass at that time comprised of the present-day continents of Africa, South America, Australia, Antarctica and the Indian subcontinent. The breakup of Gondwanaland occurred across three major midoceanic spreading centres called the south east Indian (SEIR), south west Indian (SWIR) and central Indian (CIR) ridges. New oceanic crust was formed across these three spreading centres and thus the Indian ocean came into existence. The Indian plate moved in a northward direction at a faster rate since the Cretaceous period and around Eocene time (54 million years) the Indian subcontinent or landmass collided with Asia land mass, thereby closing the Tethys sea existing between them. Further collision of Indian and Asian plates resulted in the Himalayan uplift and Fan sedimentation into the Bay of Bengal.

Though this overall scenario has been accepted by many, some intriguing problems about the evolution of ECMI and Bengal Fan remain unsolved. Some of the major problems are (i) location of the boundary between the oceanic and continental crust (OCB) in the Bengal Fan, an important aspect in plate reconstructions, (ii) the nature and origin of the two major aseismic (presently inactive) ridges in the Bengal Fan, viz. the Ninety East Ridge and 85° E Ridge, and (iii) the mode of subduction of oceanic crust near Andamans and opening of Andaman back-arc basin.

A systematic geophysical coverage of ECMI and Bengal fan by bathymetry, magnetic and gravity surveys, has been made to understand some of these problems. The data have been used to derive models for the evolution of ECMI and Bengal Fan.

Preliminary results of the analysis/models indicate that the transition between the continental and oceanic crust in the Bengal Fan (Figure 4) occurs at the foot of the continental slope (around 3000 m water depth)[7]. The study also gives evidence for rift phase volcanism along the east coast, associated with the initial breakup of India and Antarctica. Models generated from magnetic data also indicate block faulting and horst and graben basement configuration beneath the northeastern continental shelf which was also a consequence of the rifting process[7].

Models have also been worked out for the Ninety East Ridge and 85° E at NIO[7,8]. The study reveals the northern extension of the 85° E ridge towards the continental shelf off Chilka lake in Orissa (Figure 4). Scientists now believe that these two ridges and the Chagos-Laccadiv Ridge in the Arabian sea are traces of hotspots over which the Indian plate moved northward from Antarctica to the present position.

These results are very useful not only in plate recon-

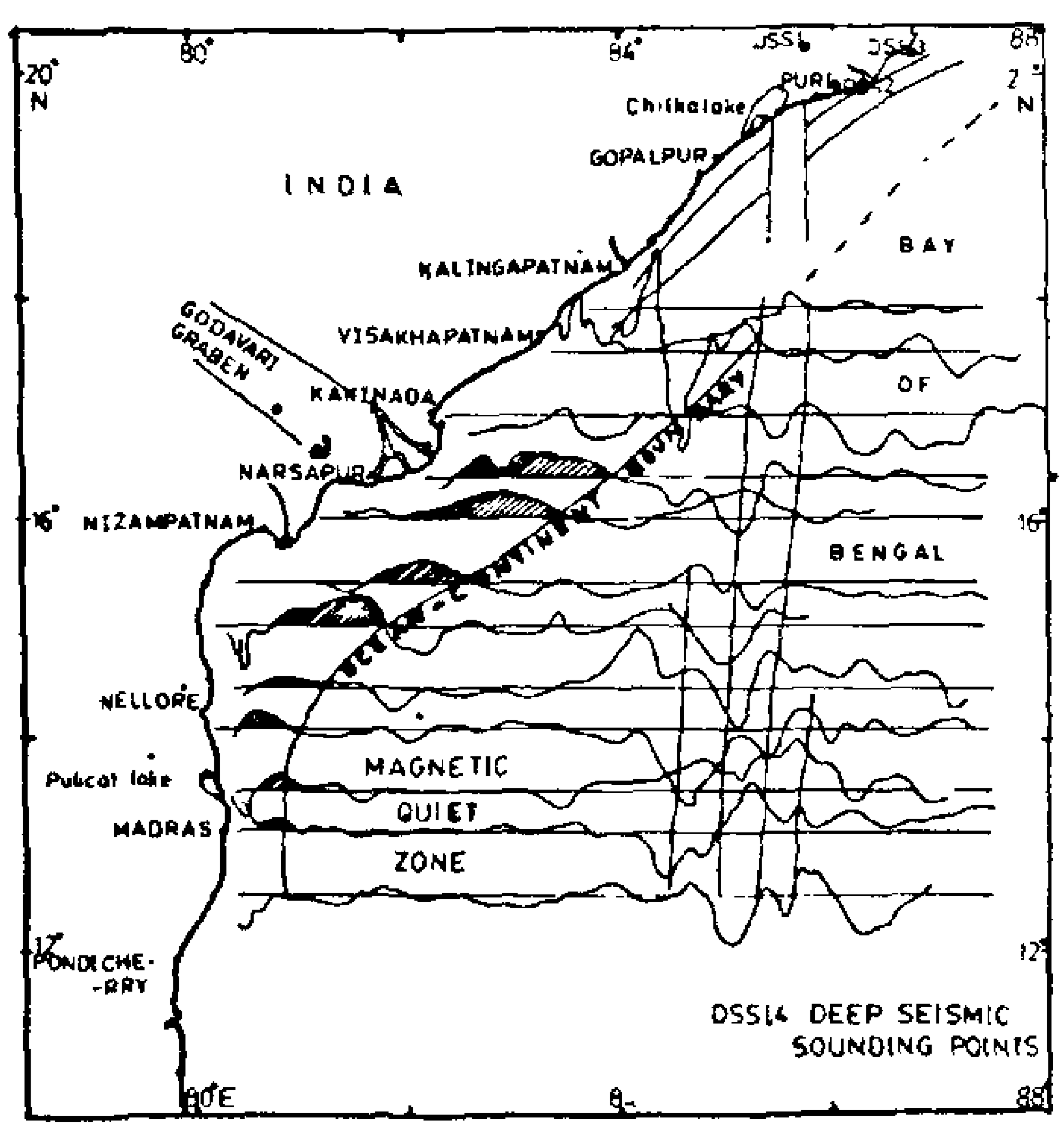

Figure 4a. Magnetic sections and ocean continent Boundary off ECMI.

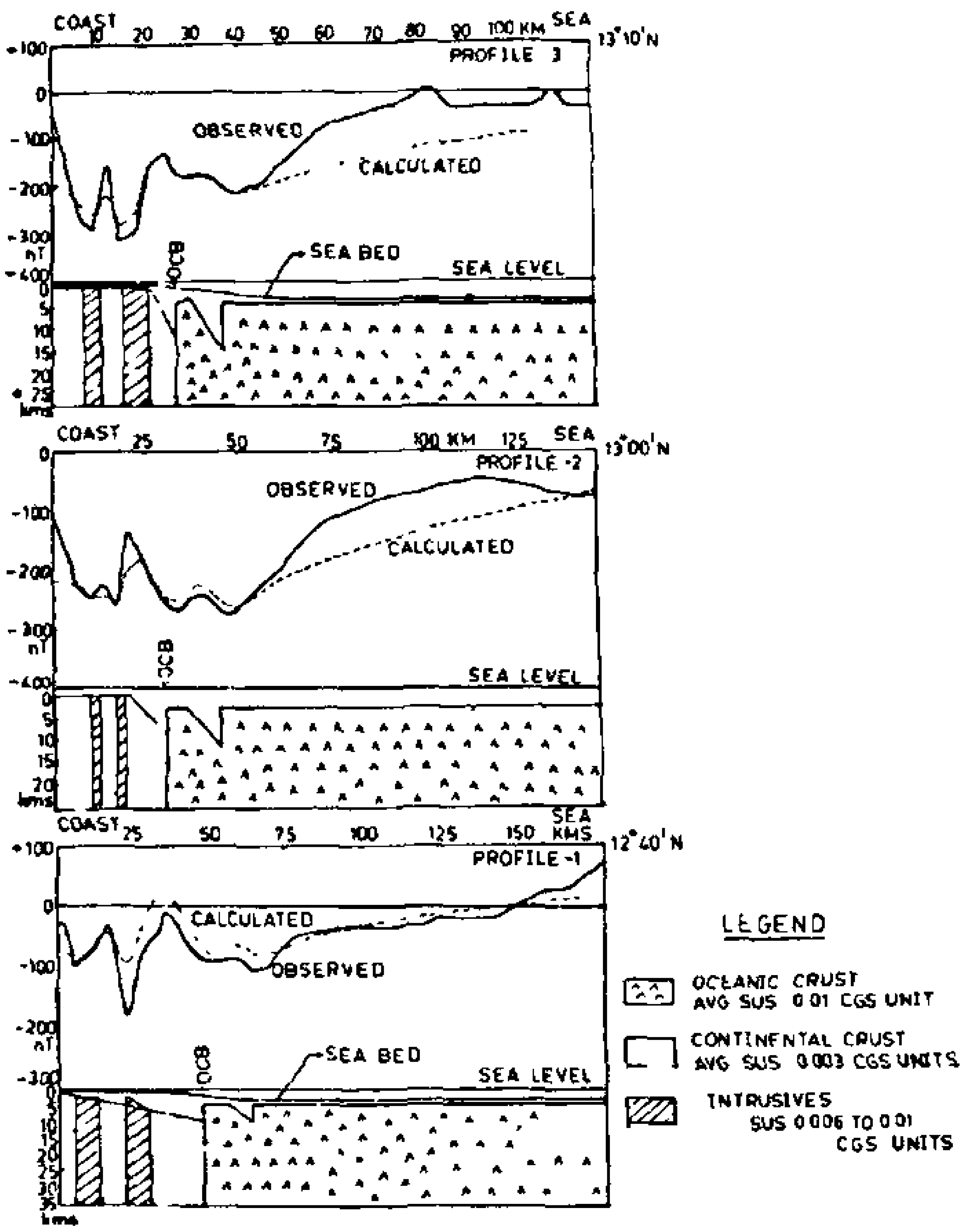

Figure 4b. Model derived for OCB off ECMI from magnetic sections off Madras (13° N)

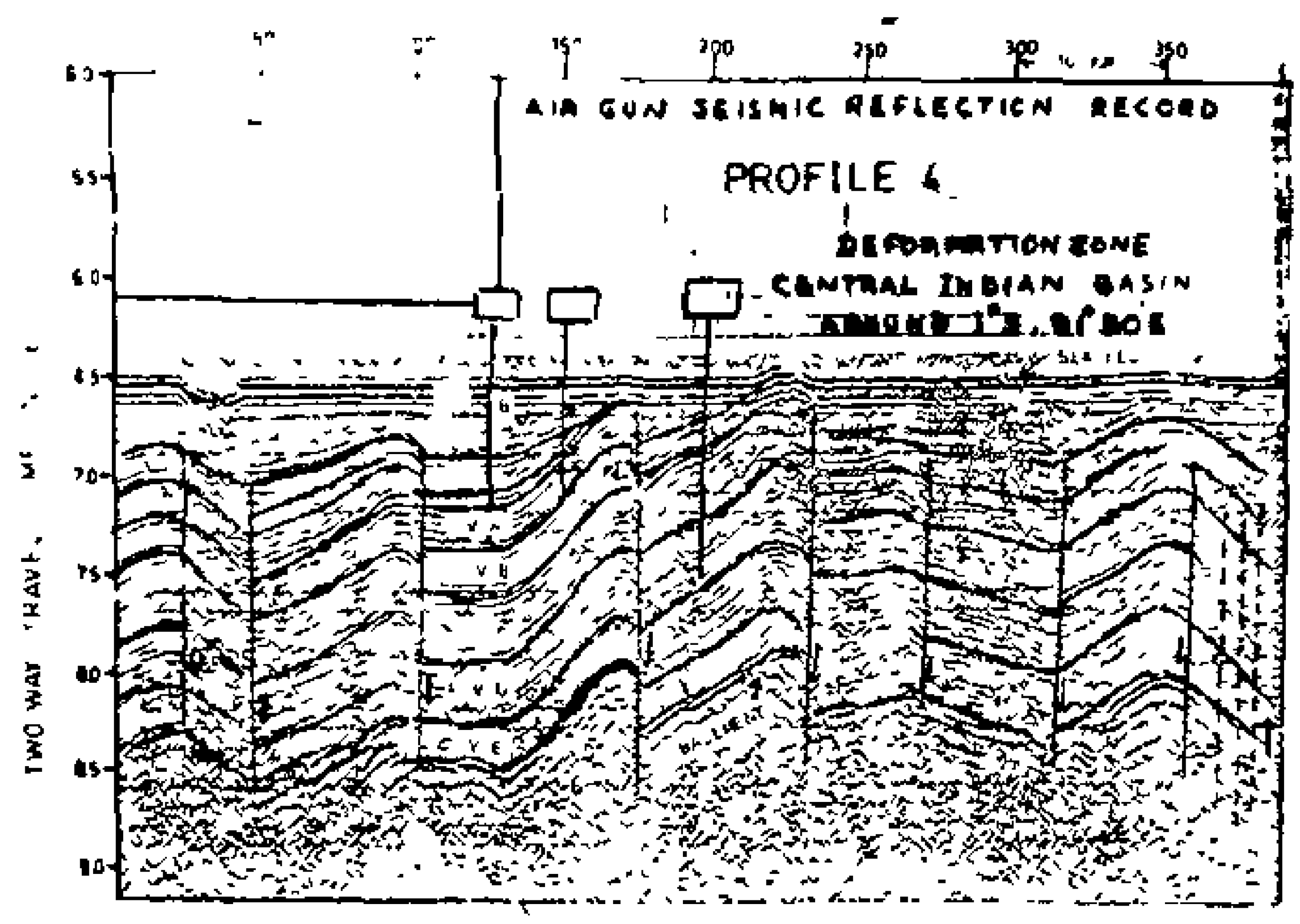

Figure 5. Seismic record over a deformed oceanic crust in Central Indian Ocean Basin.

structions (geodynamics) but also in the offshore exploration of the continental margins. The ocean-continent boundary (OCB) of many passive margins has been found to be an ideal target for hydrocarbon exploration.

Crustal deformation

A peculiar phenomenon is found to take place in the equatorial region of the Central Indian Ocean Basin (CIOB) since late Miocene (7 millions years) where the oceanic crust including the basement and sediments is presently under a major compressional stress, resulting in deformed oceanic crust in the form of huge anticlinal and synclinal blocks (Figure 5). According to the theory of Plate Tectonics, such a deformation should generally occur at plate boundaries where either new oceanic crust is generated or an older crust is subducted. These areas are known as divergent or spreading centres and oceanic trenches or convergent margins. The intra-plate deformation observed in the equatorial region of CIOB is therefore peculiar and is a consequence of two mutually opposing forces[9]; one is the spreading across SEIR which is pushing the Indian plate northwards and the other the resistance offered by the Asian plate at the northern end. The imbalance due to the two mutually opposing forces resulted in the compression of the oceanic crust in the equatorial region. If this process continues, scientists believe that a new subduction zone might develop in the equatorial region of CIOB.

Seismic reflection data collected on board the Russian vessel *Prof. R. V. Shtokman* in 1989 under an International collaborative programme between CSIR, India (NIO and NGRI) and the Institute of Oceanology, Moscow have been analysed at this Regional Centre.

The analysis revealed some new observations on the stratigraphy and tectonics of the deformation zone. The major axis of compression on the oceanic crust has been confirmed to be in a NW-SE direction. Sediments in this area are mostly fan turbidites that have been deposited from the apex of the Bengal Fan (after the collision of Indian and Asian plates). A significant observation is that the age of these fan turbidites in this area is of Oligocene period (24 million years). This is much older than the hitherto assumed early Miocene age (17 million years). Seismic records also indicate pre-fan (or pelagic) sediments below the fan turbidites that might have been derived from ECMI before the Indian plate collided with Asian plate. These studies further suggested that the intra-plate deformation observed in the equatorial region is a combined effect of the differential spreading across the three midoceanic ridges, the SEIR, SWIR and CIR.

Marine archaeology

The Regional Centre of NIO, in collaboration with the Archaeology group of NIO, Goa is also involved in the marine archaeological studies off east coast of India starting from the Tamil Nadu coast. Geophysical investigations with echosounder, magnetic and side scan sonar (an acoustic method that gives the scanned images of the sea floor) were carried out off Tranquebar and Poompuhar; the latter is known as Kaveripatnam where the river Cauveri joins the Bay of Bengal. Poompuhar was a major port city that enjoyed flourishing trade during the regime of Chola kings in early centuries.

Based on geophysical studies and diving, a ship wreck was located for the first time off Poompuhar at about 19 m water depth[10]. This ship was carrying lead ingots which were found to be of the late 18th century and seven of these ingots were recovered. In addition several man-made structures were also identified. Plans are underway to extend such studies to other ancient port cities of Andhra and Orissa coasts.

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