Lithology, Stratigraphy and Geochemistry of Sediments

SEDIMENTARY GEOLOGY OF THE DEFORMATION ZONE


Central Indian Ocean Basin sedimentation history

The basin sediments can be characterised into four main facies zones: northern, central, southern and the Afanasy Nikitin Seamount. The northern facies zone sediments are hemipelagic terrigenous muds, silts and silty clay, with little (up to 30%) CaCO$_3$ content. They have grey and greenish colours, layered structure, relatively high C$_{org}$ content (sometimes up to 1.5%), abundant authigenic pyrite. Plagioclase, illite and quartz dominate in fractions 2-20 and terrigenous smectite, quartz and illite - in fractions less than 2 (according to XRD data). A large part of this zone is occupied by the Bengal Fan sediments with clear turbidite sequence, sands in erosion trenches, muds on levees, and so on. The source of these sediments is the denudation of Sri Lanka, Indian Peninsula and the Himalayas. The geographic set up and high productivity in the vicinity explains enormous high sedimentation rates (up to some hundreds m/my) and bulk mass accumulation rates (up to some dozens g/cm$^2$/ky). They diminish southward. The boundary between northern and central facies zones has irregular character: it is more northerly in the western part of the basin, and more southerly - in the eastern part, following the Bengal Fan contour.

The central facies zone sediments consist mainly of noncarbonate
siliceous oozes: radiolarian-diatom and more rare-diatom-radiolarian, diatom, radiolarian, clayed siliceous and radiolarian mud. In general, these sediments have different shadows of yellow and brown colour, abundant burrows, moderate $C_{\text{org}}$ content. Cu- and Ni-rich Mn nodules are very common. Smectite, barite and Mn micronodules are the most common. Authigenic minerals are quartz, illite, feldspars, kaolinite, palygorskite. The sediments mark the south tropics divergent zone with enhanced (for pelagic environment) productivity. As these sediments have accumulated below Carbonate Compensation Depth (CCD), sedimentation rates and bulk mass accumulation rates are not very high: about 3-5 m/my and 0.5-1.0 g/cm²/ky, respectively. The boundary between central and southern facies zones is roughly parallel to equator and is situated near 4°S.

The southern facies zone sediments are represented mainly by noncarbonate pelagic clays (generally, miopelagic clays and rare-eupelagic clays) of brown colour and structureless. Cu- and Ni-poor Mn nodules are common. Clays have very low $C_{\text{org}}$ content (no more than 0.4-0.5%), abundant authigenic smectite, quite often - phyllipsite and Mn micronodules. Among detrital minerals potassium feldspars, plagioclases, quartz, illite, kaolinite and palygorskite (a little) are the most common. Sedimentation rates and bulk mass accumulation rates are minimal in comparison with other facies zones. The same is true about primary production values.

The sediments from these zones have higher CaCO$_3$ content at the boundary regions with different ridges surrounding the basin. Sometimes one can find carbonate turbidites in these regions. Near the boundary of the southern facies zone with the triple junction area, relatively small field of the metalliferous carbonate sediments occur.

The Afanasy Nikitin Seamount facies zone is situated above CCD and consists typical variety of pelagic carbonate oozes distributed according to the bathymetric control (downward): foraminiferal sands, foraminiferal-nannoplankton oozes, nannoplankton oozes, marly nannoplankton oozes. They have pink, yellowish, greyish and white colors. The remains of siliceous micro-organisms are rare. CaCO$_3$ content decreases downward. $C_{\text{org}}$ percentage is almost equal to the pelagic clays sedimentation rates and bulk mass accumulation rates are about twice higher than in the central facies zone. The mineral composition of abiogenic matter resembles one from the surrounding sediments below CCD. In general, recent sediments from the Ninetyeast Ridge and the South-East Indian Ridge are similar with these sediments but the former have more carbonate turbidites. Chagos-Laccadive Ridge sediments consist of shallow-water pure carbonates which are composed from the remains of corals, mollusks, echinodermata, bryozoa, algae, and so on. Pelagic carbonates are also observed in the deep depressions of this ridge.

The facies zones described above are the surficial expression of the formation zones with the same names. Cross-sections of the formation zones
revealing their complicated history which depend on tectonic processes, changes in the CCD level, paleoproductivity, paleotemperatures and paleocirculation, terrigenous matter supply and many other reasons. The same is true about the position of boundaries between the formation zones.

We know that the following typical sequence of the sedimentary formations exists in the deep sea basins (upward): basal metalliferous formation, pelagic carbonate (siliceous-carbonate) formations and pelagic clays (siliceous oozes).

Most of the northern zone of CIB is occupied by the Bengal Fan. According to seismostratigraphy, Bengal Fan cross-section consists of two parts: the lower (pelagic) and the upper (turbidite). We propose that the northern part of this zone during the early stage consisted of hemipelagic muds with rare layers of limestone, and the southern part consisted of pelagic sediments: metalliferous carbonates, pelagic clays. Studies of Banerji (1981, 1984) indicate early Oligocene or early/late Oligocene time for the initiation of sedimentation in the Bengal Fan. During this stage the following chain of events and geological processes have taken place: variations in the tectonic uplift of the Himalayas, proximal/distal turbidites ratio, coarse/fine detrital sediment and position of Bengal Fan boundary. The main features of the recent fan structure were formed during middle-late Miocene. Tectonic pulses during middle part of Pliocene and the Quaternary/Pliocene played very important role. The sedimentation rates in Holocene were sharply diminished compared to those in Pleistocene.

For the Central Bengal Fan we can propose the following stages: late Cretaceous carbonate formation, Paleocene-Miocene pelagic clays, with episodes of biogenic silica accumulation in the middle-late Eocene and uppermost Miocene; late Miocene miopelagic which have changed to eupelagic of the late Miocene, Pliocene-Quaternary siliceous formations.

In the south, traditional sequence of sedimentary formations: metalliferous, carbonate and pelagic clays are present. Study of the Afanasy Nikitin Seamount will provide more details of it.

**Sedimentary history of the Afanasy Nikitin Seamount**

During cruise 20 of the Russian research vessel "Akademik Mstislav Keldysh (1990)" a detailed geological and geophysical study of the Afanasy Nikitin Seamount (3° S, 82°30' E), was carried out to understand geological history of the Seamount and its relation with the deformation (Sborschchikov et al. 1996 *in press*). Submersibles were used for direct geological observations and for sampling of both volcanic and sedimentary rocks. The latter revealed reconstruction of the sedimentation history and paleo-environments during late Cretaceous (75 to 80 Ma) to Recent.

Sedimentary rocks above the volcanic basement are represented by zeolitic clays or zeolitites, pelagic nanno-foraminiferal ooze or limestone,
edaphogenous basaltic breccia and conglomerate. The oldest upper Cretaceous sediments dated by nannofossils were found both in chalk inclusions within the basalts and as reworked species in Quaternary sediments. Therefore, the age of Afanasy Nikitin Seamount volcano is late Cretaceous and it was adjacent to the spreading center. This conclusion is consistent with the paleomagnetic studies of the oceanic crust beneath the Afanasy Nikitin Seamount, which is 75-80 Ma old (anomaly 32).

The upper Cretaceous nannofossil limestones observed on the lower slope of the Seamount are represented by nanno-chalk inclusions in basalts and by redeposited upper Cretaceous nannofossils (Zygolithus crux, Z. dubius, Z. diplogrammus, Z. ribulus, Zugodiscus amphibons, Discolithina cf. numerosa, Micula staurophora, Defiandrius infectus, Cretarchabius sp; the determinations by V.V. Mukhina) in Quaternary pelagic nanno-foraminiferal oozes (4000-4400 m water depth) and have been deposited just before or simultaneously with the earliest volcanic eruptions, building up the massive pedestal of the seamount. The sedimentation probably took place on the slope of the Cretaceous mid-ocean ridge far south of the present location of the Afanasy Nikitin Seamount.

On the upper slope of the seamount, outcrops of clastic rocks - hyaloclastites, breccias and conglomerates of alkaline basaltic and trachytic composition were observed and sampled. Some samples contain well-rounded pebbles and gravel of different volcanic rocks, including red "oxidized" varieties, possibly indicative of subaerial weathering. The conglomerates are cemented by crystalline calcite with relicts of both planktonic and benthic foraminifera, as well as poorly preserved nannofossils. We found similar gravelstone piece with calcareous cement, in nucleus of a manganese nodule which contained Paleocene nannofossil assemblage. The Paleocene nannofossils were also identified in a thin fissure filling in a palagonitized hyaloclastite fragment. The nannofossil assemblage is rather poor, the most typical species are Discoster multiradiatus, Radiodiscoaster nobilis and a few others (determined by V.V. Mukhina).

The rounded pebbles in conglomerate are an evidence for subaerial weathering and high vesicularity of alkaline basalt fragments in the hyaloclastites are indicative of volcanic island and near-shore environments in the latest Cretaceous to Paleocene time.

However, presence of Paleocene nannofossils in cracks and hyaloclastite crusts in the basalt fragments from the upper slope (2232 m depth) is an evidence either for submarine eruptions on island slopes or for rapid subsidence already in Paleocene.

Soft, non-lithified, light yellowish grey pelagic nannofossil ooze, obtained by submersible from the lower slope (4400 m water depth), is composed of well preserved early Eocene assemblage of Discoasters, determined by V.V. Mukhina: Discoster lodonensis, D. barbadensis, D. Kuepperi, Marthasterites robustus, M. tribachiatus, Coccolithus eopelagicus.
Foraminifers and siliceous microfossils are absent. The depositional environment can be interpreted as moderately deep and well above CCD water depths, but likely below foraminiferal lysocline. Absence of siliceous fossils, commonly abundant in Eocene pelagic sediments, is indicative of low biological productivity facies belt. This is consistent with the northward plate movement through the southern subtropical anticyclonal gyre during Eocene inferred from plate tectonic reconstructions (Benerji, 1981; Schlich, 1982).

Upper Eocene sediments were collected by submersibles MIR from an outcrop on the upper slope adjacent to the Seamount crest edge at 1620 m waterdepth. They consists of fragments of hard, well lithified limestone, possibly representing submarine hardground. The limestone is composed of planktonic foraminiferal tests and their fragments, cemented by microcrystalline calcite. The rock contains abundant well-rounded and semi-rounded gravel of basalts with some plagioclase sand. Nannofossils occur as minor admixture and are moderately preserved. V.V.Mukhina determined the following late Eocene assemblage: Discoaster barbadensis, D. tani, D. derlandrei, Coccolithus eopelagicus, Chiasmolitus grandis, Sphenolithus moriformis and others.

The limestones have been deposited in a high-energy environment (active bottom currents) on the seamount upper slope, the gravel being derived possibly from Paleocene coastal deposits, which perhaps cropped out at the crest edge.

The limestone slabs are extensively burrowed. Empty burrows are covered by manganese-oxide films. The burrows are rather old and limestones have been exposed to bottom waters for a long time.

Spectacular outcrops of snow-white Oligocene foraminiferal-nannofossil ooze were observed from submersible MIR on the upper seamount slope as large “piles” overlying conglomerates and basalts. The steep scarp-like outcrops of rather soft calcareous ooze are possibly created either by slumping or by faulting, both indicating post-Oligocene tectonic activity. The ooze is composed of 10-20% nannofossils, 10-20% foraminifers and their fragments, the rest is unidentified micritic matrix, perhaps broken and/or recrystallized nannofossils. The Oligocene age was determined by V.V.Mukhina based on the following nannofossil assemblage: Coccolithus eopelagicus, Discoaster woodrangi, D.saipanensis, D. derlandrei, Helicospontosphaera sp., Chiasmolitus, Sphenolithus moriformis.

Miocene sediments were recovered on the seamount crest. They crop out at 1620 m water depth, and are represented by white, slightly lithified foramin-nanno chalk. The chalk is composed of foraminifers (5-10%) and their fragments (20-30%) of nannofossils (15-20%) and of micritic matrix (about 40%). Carbonate content is as high as 90-95%. The samples are flat slabs, perhaps a kind of hardground, formed during long exposure. Nannofossils, determined by V.V.Mukhina, indicate late Miocene age: Discoater
_neochamatus, D. quinqueranus, D. variabilis, D. browetifo, Coccolithus pelagicus, Cyclococcolithina machintire._

Pliocene sediments were found as redeposited lumps of nanofossils ooze in Quaternary sediments from lower slope (3700-4400 m). The Pliocene age is indicated by the nanofossil assemblage: _Discoaster broweri, D. pentaradiatus, D. surculus, D. asymtricus, D. challenger, D. Variabilis, Ceratolithus rugosus._

Neogene nanofossil ooze was deposited on the seamount crest and upper slopes during periods of relatively low current energy, which have been interrupted by erosion and hardground formation.

The Quaternary sediment cover on the seamount is intermittent as numerous vast outcrops of volcanic rocks, alternate with sediment-covered gentle slopes and subhorizontal terraces. The pelagic sediments are represented by diatom and radiolarian bearing pelagic clay with manganese nodules at the base of seamount slope and on the adjacent abyssal plain below CCD (about 4800 m). At depths from 4800 m to 4500 m calcareous pelagic clay and marly ooze were found, containing foraminifers, nanofossils, diatoms and radiolarians. Manganese nodules also occur within this depth range. The upper slope is intermittently covered by nanno-foraminiferal ooze or foraminiferal sand reworked by bottom currents.

So, the history of sedimentation on the Afanasy Nikitin Seamount was controlled: 1) by migration of the site from high latitudes through subtropical regions to the recent position within the equatorial facies belt with its high biological productivity and biogenic siliceous sediments; 2) by progressive sinking of the volcanic edifice, which has emerged above sea level as volcanic island in late Cretaceous, and eroded in Paleocene and then gradually subsiding flat-topped seamount. The seamount was faulted during late Neogene or Quaternary, when it was affected by intraplate deformations. No evidence for late reactivation of volcanism or hydrothermal activity was found by the detailed study.

**Sedimentation in the deformation zone**

The seismic stratigraphy (Chapter 7) and by ODP Leg 116 drilling (Cochran, Stow et al. 1990) results of the intraplate deformations revealed mainly the Neogene distal turbidites of the Bengal Fan and less thick (if at all) Quaternary sediments, represented by pelagic and hemipelagic sediments. The abyssal hills created by the deformations are built up of folded and faulted Neogene turbidites which are well demonstrated on the seismic records as a strongly stratified sequence which is unconformably overlain by a transparent seismic layer, interpreted as Quaternary pelagic blanket.

The Neogene sequence of distal turbidites drilled in Leg 116 (Cochran, Stow et al. 1990) is 1.5-2 km thick. The drilling at sites 717-719 (about 1°S, 80°E) recovered alternate fine and coarse turbidite units with silt layers at
the base. The most complete section recovered at Site 717 drilled in a syncline, recovered the turbidites beginning with upper Miocene. The section comprises of three distinct and lithologically different parts overlain by a thin layer of hemipelagic clay and marly ooze. The lowermost upper Miocene silt turbidites are at least 250 m thick. The mean sedimentation rate for this unit is estimated as 75 m/my. The unit correlates well with corresponding lithostratigraphic units recovered by holes 718 and 719, drilled on anticline structures without significant decrease in thickness. This was interpreted (Cochran, 1990) as a strong evidence for dating the onset of deformation in uppermost Miocene (about 7.5 Ma).

The next lithostratigraphic units are uppermost Miocene and Pliocene (to lowermost Pleistocene) finer grained mud turbidites, differing from the strata below by predominance of mud and clay members in the turbiditic sequences, and by presence of biogenic carbonate mud turbidites. The mud turbidites show sharp decrease in thickness from the syncline hole 717 to the anticline hole 719, both due to thinning of the correlated individual turbidite beds and pinching out of the turbidite sequences.

The thinning of some turbidite beds and complete pinching out of others was interpreted as an effect of the intraplate deformation on sedimentation. They suggested that progressive uplift of the tilted blocks (for example as at the sites 717 to 719) effected the southward movement of the fan turbidites. This resulted in the energetic overflowing off the high, while the weak ones veered off.

The upper coarser silty turbidites (100-150 m thick) accumulated very rapidly (350 m/my.) during the Pleistocene. The thinning of the unit from the "syncline" site 717 to the "anticline" site 719 is apparent, but the amplitude seems to be less, indicating gradual uplift.

The uppermost pelagic/hemipelagic Holocene and uppermost Pleistocene unit is only 2-5 m thick, being composed of calcareous foram-nannoclay. So the stratigraphic volume of the non-deformed pelagic blanket, at least in this region, is much less, than thought before.

In two cruises of the Russian research vessels "Dmitry Mendeleev" (Cruise 31) and "Professor Shtokman" (cruise 22) we studied the distribution and composition of youngest sediments on abyssal hills created by the intraplate deformation.

The deformation rises (hills) are at present up to several hundred meters above the Bengal Fan abyssal plain. The plain is covered by fairly horizontal Holocene to uppermost Pleistocene distal turbidites and hemipelagites. Gravity cores taken on the abyssal plain recovered micaceous radiolarian-bearing hemipelagic clay with rare turbidite interbeds composed either of terrigenous micaceous silt or of foraminiferal sand and ooze (Fig. 10.1).

The cores obtained from uplifted deformation blocks are represented by light brownish gray pelagic calcareous nanno-foram ooze or marly ooze. The carbonate content decreases with depth due to CaCO₃ dissolution,
Fig. 10.1. Lithological profile throughout the rise at polygon M31-V, the Central Indian Basin. hatchings with plus - siliceous micrite ooze; hatches with fencing - siliceous Foraminifera-coccolithic ooze; hatchings with continuous lines - red deep-sea clay (RDC); hatchings with discontinuous lines - terrigenous light brownish-yellow clay (pelagic silt); hatchings with dot and with dot and dash - clay silt-terrigenous siltstone (turbidite); hatchings with dash and dash and continuous lines - terrigenous light yellowish-brown (pelagic silt); hatchings with wavy lines - Miocene clays; hatchings with oblique lines - solid red peels glasses hydrothermal substance containing up to 20% of Fe; hatchings with triangles - admixture of disintegrated Foraminifers (1-5%); hatchings with closed ovals - polymetallic nodules within PR columns and BG samples; hatchings with open ovals - suggested areas of polymetallic nodules; dash lines with CCCD - depth CCCD in Holocene; hatchings with arrow - supply of terrigenous turbidite material.
demonstrating common facies changes of pelagic sedimentation (Murdmaa, 1987). According to dating by radiolarians, diatoms and nannofossils, the age of basal sediments in the most short cores is late Quaternary (0.4-0.6 Ma, maximum to 0.8 Ma). In several cores only youngest (less then 0.1 Ma) sediments were recovered.

Pelagic sediments are characterized by extensive burrowing. Their predominant brownish colour is indicative of oxidation. Only lowermost strata show colour change to light gray, possibly due to weak early diagenetic reduction. Sediments contain very rare silt-size terrigenous minerals, predominantly flakes of mica. In several cores we found interbeds enriched in colorless vitric ash, likely derived from the Sunda Island Arc volcanoes. Pumice-like structure, acidic composition and mineralogy of the ash similar to the island-arc tephra are widespread in the Western North Indian Ocean (Svalnov, 1983; Murdmaa, 1987). The tephra is supposed to be transported by wind (as airmole) or by surface currents (as floating pumice) from the Sunda Island. The land-derived origin of the tephra is confirmed by occurrence of fresh-water diatoms Aulacosira in one of the ash layers.

Both transportation mechanisms carry the ash particles to sea surface. Their setting is similar to that of pelagic sedimentation, which does not depend on local bottom topography. However, on the abyssal plain rapid deposition from turbidity currents exceeds the slow “background” pelagic sedimentation, including deposition of vitric ash particles, and thus the latter are diluted by terrigenous sediments. Indeed, we have not found any ash in the cores from abyssal plain. On the abyssal hills the slow pelagic sedimentation, allows relative “passive” concentration of ash. Other indicators of slow pelagic sedimentation, such as manganese micronodules and benthic foraminifers, are also present in the pelagic cap on the deformation hills.

Thus we distinguished the specific facies on the deformation hill tops, different from those on the adjacent abyssal plain, where near-bottom transport of sediments by turbidity currents and nepheloid “clouds” strongly prevail over the “background” pelagic sedimentation. These two different facies can be easily discriminated even in separate samples, using lithological, mineralogical and micropaleontological criteria. Such facies patterns can thus be used in order to date the onset of deformation blocks, where the turbidites were primarily deposited prior to the deformation. If one finds late Miocene turbidites exposed along scarps of the hills, the age of deformation is dated as post-Miocene. The first appearance of pelagic facies on its top gives the upper age limit of the deformation.

We recovered, for example, small fragments of semi-lithified laminated micaceous clay intercalated with nannofossil marl by dredging from a scarp at the base of deformation rise. The sediments apparently belong to turbidites, and show the mineral composition similar to the Bengal Fan deposits. Nannofossils in these rocks are dominated by Discoaster variabilis, D.
*braarudii* and *D. druggii* indicating middle Miocene age. So the middle Miocene turbidites, primarily deposited on the abyssal plain, are among the deposits, incorporated into deformation block. The Pleistocene pelagic carbonate facies on the hill top indicate that the structure was already well above abyssal plain at that time.

**CHEMICAL AND BITUMINOLOGICAL STUDIES OF ORGANIC MATTER IN BOTTOM SEDIMENTS**

The Central Indian Basin is characterized by unusual structural and geophysical features (high recent seismicity, high heat flow, volcanism, deformations of sediments and basement) which supports its tectonic activity. Active tectonic zones usually have been connected with the gases emanated from the earth's interior, followed by uplifting of matter and energy. In addition, tectonic processes also are associated with fluids because deformation and faults occur in structures saturated by gases and fluids. Following these facts it can be assumed, that the organic matter in such areas consists of deep origin components, differing from biogenic matters. Indicators of such processes are bituminoidal matters, enriched by hydrocarbons and especially polycyclic aromatic hydrocarbons (PAH), which practically do not originate from normal temperature-pressure conditions.

In this study we have included data collected during three cruises of research vessels of the SIO, RAS: the 25th cruise of the R/V Dmitry Mendeleev (1980), the 31st cruise of the R/V Akademik Kurchatov (1981) and 20th cruise of the R/V Akademik Mstislav Keldysh (1989). The areas studied cover deformation zone from 3°04' N to 9°00' S and from 78°57' E to 87°07' E (Fig. 10.2).

Most samples were taken along 80° E Fracture Zone, where the fracture zone was discovered from magnetic investigations. Some stations (3385, 2098, 2099) lie near to boundaries of intensely deformed crustal blocks. On lithologic data, the bottom sediments in the northern part of area consist of siliceous clay and terrigenous pelagic oozees (Eh = +400 to +500 mV). In the southern part of the area brown clays were found (Emelyanov and Kruglikova, 1990).

The main purpose of this work was to study the displacement of carbonate matter, the structure and properties of bituminoids and hydrocarbons in bottom sediments for finding sources of organic matter (OM). Earlier, limited study of the organic matter in sediments from Central Indian Basin intraplate deformation has been carried out.

The method of OM study was the same as has been developed for study of metalliferrous sediments of Indian and Pacific Ocean (Alekseeva and Teplitskaya, 1981) and consists of bituminological and physico-chemical analysis.