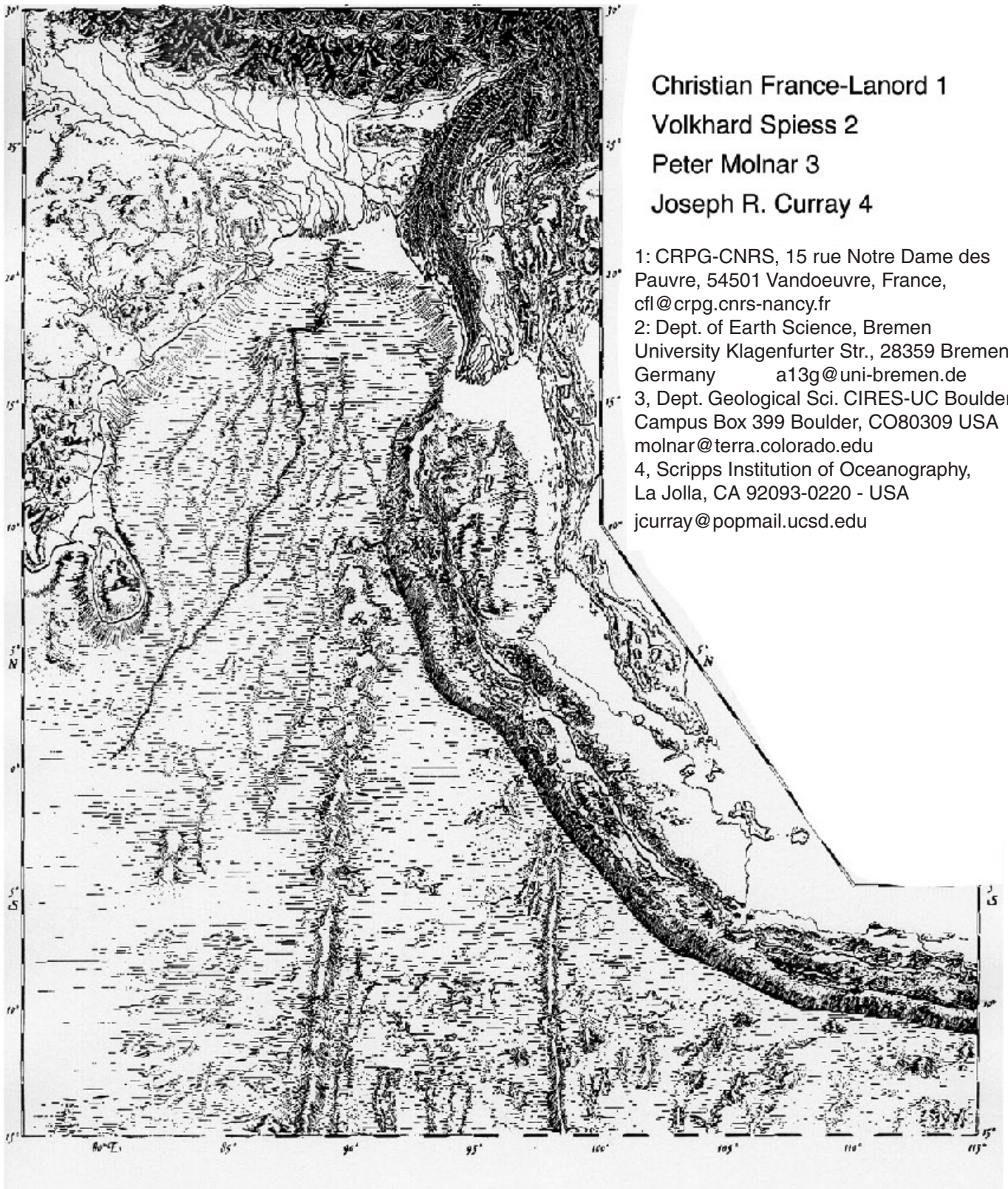# Summary on the Bengal Fan
An introduction to a drilling proposal
March 2000

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Physiographic Diagram of the
North Eastern Indian Ocean and Adjacent Land Areas
JANUARY 1982   Drawn by jo p griffith
Data from Franz J. Emmel and Joseph R. Curray

A summary on the Bengal Fan March 2000

I - The Bengal Fan and its Seismic Framework
II - The growth of the Tibetan Plateau and the Himalaya
III - The development of the Asian Monsoon

I - THE BENGAL FAN AND ITS SEISMIC FRAMEWORK

The Bengal Fan covers the floor of all of the Bay of Bengal (Fig. 1), from the continental margins of India and Bangladesh to the filled Sunda Trench off Myanmar and the Andaman Islands, and along the west side of the Ninetyeast Ridge. It spills out south of the Bay of Bengal at its distal end to about 7˚S. Another lobe of the fan, called the Nicobar Fan, lies east of the Ninetyeast Ridge, but its primary source of turbidites from the head of the Bay of Bengal apparently was cut off during the Pleistocene by convergence between the northern end of the Ninetyeast Ridge and the Sunda Trench. The northeastern edges of the fans have been subducted, and some of the Tertiary turbidites cropping out in the Indo-Burman Ranges of Myanmar, the Andaman and Nicobar Islands, and in the outerarc ridge off Sumatra have been interpreted as old Bengal and Nicobar Fan sediments.

The Bengal and Nicobar Fans were delineated and named by Curray and Moore [1], who also noted two reflecting horizons that pass into unconformities over the exposed and buried hills of folded sediments in the southern part of the fan and over the Ninetyeast Ridge. They concluded that these two horizons are regional and used them to subdivide the sedimentary section into three parts in the Bay of Bengal. The ages of these unconformities were tentatively determined to be uppermost Miocene and upper Paleocene to middle Eocene by DSDP Leg 22 [2,3], at Sites 218 and 217, respectively (Fig. 1). They interpreted the older unconformity as dating the India-Asia collision, with the pre-Eocene sedimentary unit consisting of pelagic sediment and terrigenous material derived from India before the collision. Hence, the upper two sedimentary units define the Bengal Fan *sensu stricto*. They associated the upper Miocene unconformity with intraplate deformation, probably correlated with a plate edge event. These tentative age assignments were confirmed and refined by later drilling by ODP Legs 116 and 121 [4-6], although the interpretation and significance of the older unconformity and the time of initiation of Bengal Fan deposition and progradation remain very controversial.
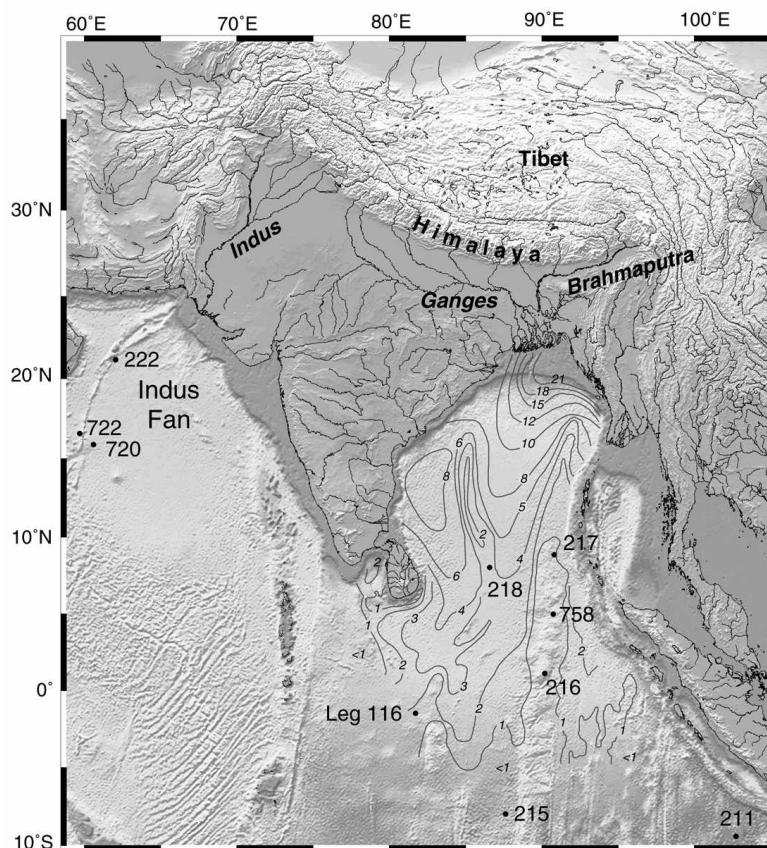

Fig. 1 – Map of the Himalayan erosion system showing the position of the different DSDP and ODP Sites documenting the Bengal and Indus fans or the monsoon history. Isopachs (in km) of the Bengal Fan are simplified from [7]. They represent the total sedimentary and metasedimentary rocks above the oceanic second layer, as interpreted from seismic reflection and refraction data.

The Miocene unconformity was drilled and sampled in the fan, but the older unconformity was drilled and sampled only on the Ninetyeast Ridge. Correlation of the latter reflecting horizon off the ridge into the fan section is possible along some seismic lines e.g.[8-10] but not along all. Where it is clear, the horizon in the fan section is a major reflector and usually a refracting horizon as well. DSDP sites from Leg 22 have sampled what we correlate as that horizon. Site 215, Leg 22, showed a hiatus from early Eocene to late Miocene. Site 211, located at the eastern distal edge of the Nicobar Fan showed a hiatus from some time after the Maastrichtian until Pliocene. The overlying younger sections have been interpreted as distal fan.

An Eocene initiation of Bengal Fan deposition is also suggested by the geology of Bangladesh, the Indo-Burman Ranges of India and Myanmar, and the Andaman-Nicobar Ridge. Hydrocarbon exploration on and offshore from southeastern Bangladesh e.g.[11] shows total sediment thicknesses calculated from gravity to be greater than 20 km, apparently with the Eocene and Oligocene Disang Series of deep water shales and turbidites overlying oceanic crust. These are in turn overlain by Neogene prograding deposits of the Bengal Delta, of the Ganges, Brahmaputra (Jamuna), Meghna, and their ancestral rivers. Some of this rock has been mildly metamorphosed and uplifted into the accretionary prism in the Indo-Burman Ranges, with some sparsely fossiliferous flysch units correlated with the Disang Series e.g.[12,13]. Similar turbidites, the Andaman Flysch or Port Blair Formation, are found in the Andaman and Nicobar Islands, again usually assigned Eocene and Oligocene ages e.g.[14,15] and interpreted to represent parts of the early Bengal Fan, some of which have been incorporated into the Sunda Arc accretionary complex.

Analyses of seismic refraction and reflection profiles by Moore et al. [2]; and Curray et al. [16] suggested a total sedimentary section of over 16 km beneath the Bangladesh shelf. More recently, however, reinterpretation of the data [17,7] suggests that the unit beneath the 16 km boundary is high density, high velocity metasediment rather than oceanic layer 2, and that the total metamorphosed plus unmetamorphosed sedimentary section exceeds 22 km (Fig. 1). Extrapolation of temperature and pressure conditions to these depths suggests greenschist facies, bottoming in amphibolite facies. Extrapolation of the horizon interpreted to be the Paleocene-Eocene unconformity to the 16 km boundary divides the section into a pre-Eocene, pre-collision metasedimentary section, overlain by Post-Paleocene fan sediments and sedimentary rocks.

Two ridges affect the distribution of sediments in the Bay of Bengal, the 85° E Ridge and the Ninetyeast Ridge e.g.[1,18,9,19]. Both have been interpreted as traces of hot spots e.g.[20,4]. The 85°E Ridge was in place before most sediment was deposited.

The initiation of deposition and progradation of the Bengal Fan followed the collision of India with Asia and the formation of a large proto-Bay of Bengal. Continued convergence of the Indian and Australian plates with the southeast Asian plate reduced the size of the Bay and focused the source of turbidites into the present Bengal Basin, Bangladesh shelf, and the Swatch-of-no-Ground.

Fans grow by progradation and the first sediments are deposited at the mouth of a canyon and at the base of the slope, in this case the continental slope. With time the fan progrades farther from the original base of the slope. Our limited information suggests that the Bengal Fan has prograded as shown in Figure 2. The oldest rocks interpreted as Bengal Fan in the Indo-Burman Ranges are early Eocene; the oldest such turbidites in the Andaman and Nicobar Islands are middle Eocene. DSDP Sites 215 and 211 revealed upper Miocene and Pliocene turbidites, respectively. DSDP 218 did not reach the base of the fan; nor did the ODP Leg 116 sites. The interpretation that the Eocene unconformity marks the base of the fan suggests that it may represent a hiatus of variable duration (Fig. 2).
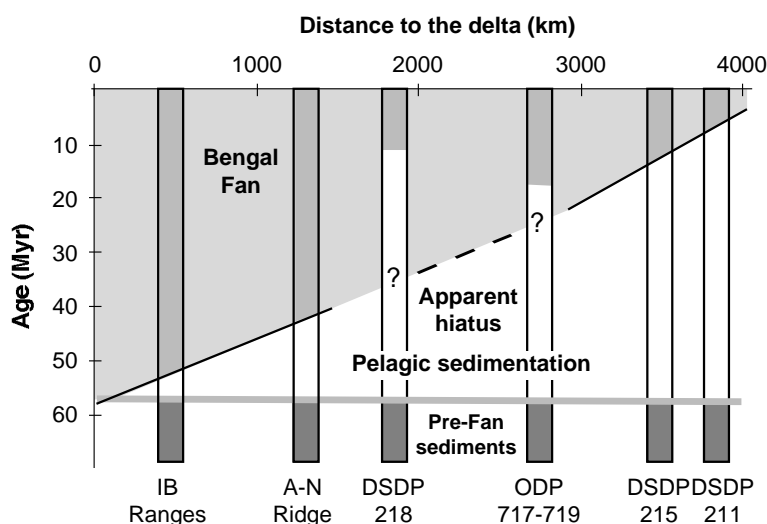

Figure 2 - Estimated age span of Bengal Fan sedimentation versus distance from the present apex or source of the fan, showing that age span of the apparent hiatus was short near the source and long in the lower and distal fan. This plot is obviously oversimplified, because the distance from the fan apex changed through time with convergence of the Indian and Eurasian plates, and with progradation of the delta in Bangladesh. The shaded area at each site indicate the known age span of fan sedimentation..

Depositional processes in a sediment fan often reveal a high degree of complexity and lateral, vertical and temporal variability e.g.Amazon Fan_[21], which limits the continuity of the sedimentary records and stratigraphic resolution. To perform drilling in the Bengal Fan this problem has to be investigated, and drilling strategy as well as positioning of drill sites needs to be adjusted. From analyses of digital echosounder records and sediment cores [22-24] it became evident that sediment accumulation in the Bengal Fan is restricted to the currently active channel with a lateral extent of no more than 20-100 km. Maximum sedimentation rates are found on the flanks of the channel-levee system and on internal terraces. Piston coring to the base revealed an age of ~12,800 years and youngest sediment ages of 9700 years [23,25] (Fig. 3). This means that ~100 meters of sediment accumulated within ~3000 years, corresponding to average sedimentation rates of >30 m/ka in this locality. Presumably this material was deposited in a channel, which rapidly became buried when it was abandoned and a new main channel formed. This leaves a sedimentary record of variable time resolution. Because the lifetime of channels and levees is limited, frequent lateral jumps associated with a buildup of a new levees must occur, burying the old system at some distance. Moreover, intervals of non-deposition to low sedimentation rates of unknown length must be expected [23]. At greater distance from the active channel only background sedimentation of eventual turbiditic activity at much lower, 'normal' rates can be expected.

From the large scale features discussed above, however, it is clear that on a scale of some 100 ka accumulation rates are similar, resulting in an overall uniform thickness of seismic units. This observation has been confirmed by very high-resolution multichannel seismic surveys carried out recently in the vicinity of the active channel between 8°N and 17°N [24]. To understand the findings in drill sites targeted at greater depth and longer time scales, we propose to carry out a detailed study of a recent channel levee system, which also has recorded the Holocene history of sediment flux into the Bengal Fan at a very high resolution.
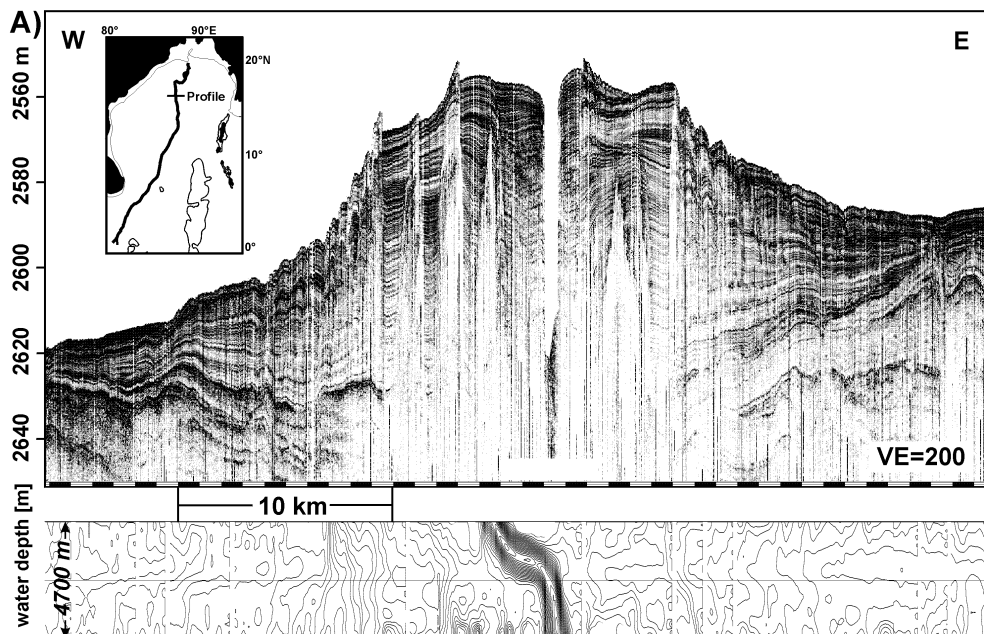

Fig.3 - Segmented channel levee system from the Bengal Fan at 16°50'N. From Hübscher et al.[23].

II - THE GROWTH OF THE TIBETAN PLATEAU AND THE HIMALAYA

Both the Tibetan Plateau and the Himalaya result from India's collision and penetration into Eurasia. Virtually all of the rock exposed in the Himalaya either was attached to the Indian subcontinent when it separated from Gondwana, or it was deposited on India's northern margin as India drifted north. Most of the Tibetan rock was part of the Eurasian landmass in Mesozoic time when India departed from Antarctica. Moreover, much of Tibet lay below sea-level in Cretaceous time, for marine limestone covers parts of southern and western Tibet e.g.[26-28]. Although an Andean margin of high terrain and thick crust may have bounded southern Eurasia in late Cretaceous time, before collision e.g.[29,30], most of Tibet and all of what is now the Himalaya were low, below sea level or near it, before collision.

One can separate the tectonic and topographic history of Tibet and Himalaya into four periods, each of which is likely to have left a record in the Bay of Bengal. (1) Before collision, there seems to have been little relief, and as far as the Bay of Bengal is concerned, sediment from whatever relief did exist in southern Eurasia is likely to have been blocked by a trench south of the Andean margin and by the Indian subcontinent farther south. Thus, the date of the collision marks the beginning of mountain building within the Himalaya and a new provenance of sediment deposited in the Bay of Bengal. (2) Evidence, from Tibet itself, of growth of high terrain is sparse until ~20 Ma. Some sediment apparently derived from growing relief in the Himalaya has been mapped, but most such sediment remains in the Bay of Bengal or has been underthrust beneath the Himalaya. Many believe that the Himalaya did not emerge and erode significantly until ~20 Ma, which is also when intrusion of anatectic granite, initiation of north-south extension and normal faulting on the northern edge of the Himalaya, and rapid exhumation in southern Tibet occurred. Leg 116 sediments have provided the first direct evidence that Himalaya was already a major mountain range undergoing rapid exhumation 15-18 Ma ago. (3) An important development began at ~7-8 Ma. East-west extension on normal faults within Tibet seems to have begun near 8 Ma, when folding south of the Bay of Bengal also began. Moreover, evidence from the both the northwestern Himalaya and from the Arabian Sea suggests that the Asian monsoon strengthened, if not began, at that time. (4) Finally, rapid cooling of rock exposed in the Himalaya and the suggestion of a change in erosion rate since approximately 2-3 Ma is thought by some to mark a final tectonic burst, but by others to reflect the change toward cooler global climates associated with increased glaciation and erosion.

Date of collision. Collision surely did not occur at the same time at all points along the northern edge of India. Deposition of middle Eocene terrigenous sediment on early-middle Eocene marine nummulitic limestone in the northwestern Himalaya suggests that initial contact occurred between 50 and 55 Ma[31-36]. Farther east, in the Everest area, however, Rowley [37] has inferred from shallow-facies deposition that at ~46 Ma e.g.[38] that area had not yet been flexed down, and therefore that collision there should be somewhat younger than farther northwest. Because sediment from the northwestern Himalaya is unlikely to reach the Bay of Bengal, sampling of early Cenozoic sediment in the Bay might help constrain the extent to which the timing of collision was diachronous. More importantly, the development of sediment in the Bay of Bengal from 60 Ma to 20 Ma could provide the only record of how the Himalaya grew in that period.

Events near ~20 Ma. Constraints on tectonic events between ~55 Ma and ~25 Ma are few. Abundant evidence for early to mid-Cenozoic metamorphism e.g.[39-42] apparently indicate burial beneath the southern edge of Eurasia e.g.[43]. Sparse late Paleogene sediment apparently derived from the Himalaya e.g.[44,45], however, provide little record of the early history of the Himalaya, except for the suggestion of flexure of the Indian plate as early as 33 Ma [46]. Much of the sediment deposited near, and clearly derived from, the Himalaya appear to date since latest Oligocene time e.g.[47-50], which might suggest that elevated terrain was modest before that time. Ironically, the evidence most suggestive of high terrain in the Himalaya before ~20 Ma comes from ODP samples. Galy et al. [51] showed that Rb/Sr cooling ages (25-30 Ma) of biotite in sediment deposited in the Bay of Bengal at ~18-19 Ma indicated an interval (6-10 Myr) between cooling below 350°C and deposition, identical to that for sediment deposited since ~1 Ma. They inferred that at ~30 Ma erosion rates, and therefore presumably relief, must have been comparable to those at present.

With regard to the tectonic development of the Himalaya, we are aware of no useful constraint on when slip began on its major thrust fault, the Main Central thrust, for which a minimum of ~100 km [52], and perhaps many hundreds of kilometers, of slip have occurred. Deformation of crystals within the zone demonstrate that the fault was active at ~20 Ma [53]. At approximately the same time, Himalayan crust, apparently above the Main Central Thrust, melted and intruded the rock above e.g.[54-58]. Moreover, normal faulting occurred along the northern slopes of the Himalaya simultaneously with underthrusting on the sub-parallel Main Central Thrust [59-64,58,65]. Hypotheses of what triggered what among thrust and normal faulting and anatectic melting span the gamut from (a) frictional heating on the Main Central Thrust dropping the shear stress on it to allow normal faulting in the hanging wall, to (b) normal faulting responding to crustal thickening and increased potential energy and then decompression melting occurring as pressure dropped isothermally, to (c) melting causing weakening of the crust that allows initiation of slip on either or both faults [66-69]. Dating appears to be insufficient to determine which precedes the others.

How does this simultaneity of events in the Himalaya relate to an ODP proposal? Approximately concurrently with these tectonic events, rapid cooling of crystals within granite along the southern margin of Tibet at ~18 Ma implies rapid denudation [70,71]. Although normal faulting may have denuded not only the

northern Himalaya, but also parts of southern Tibet, the widely repeated opinion has been that this cooling records erosional denudation due to uplift of the Plateau [70-72]. Clearly, the discovery of a change in deposition rate, particularly of material obviously derived from Tibet, in the Bay of Bengal at ~18 Ma would support the contention that erosion accelerated at that time. Amano and Taira [73], in fact, suggested that deposition in the Bay of Bengal did increase at ~17 Ma in response to increased uplift, but sampling of sediment is too sparse to make this case strongly. Obviously, an absence of a change in deposition rate at ~18 Ma would not prove that uplift and resulting increased erosion did not occur at that time, but whatever one observes at that time is likely to bear on, if not constrain, the processes that occurred near ~20 Ma.

Suggested initiation of east-west extension and uplift of the Tibetan Plateau at ~7-8 Ma. Fault plane solutions of earthquakes, active faults seen on satellite imagery, and detailed field work in selected parts of Tibet demonstrate that east-west extension, largely by normal faulting on north-south planes, but also by conjugate strike-slip faulting on northeast or northwest trending planes, dominate the active tectonics of the Tibetan plateau e.g.[74-78]. Thus, a change in style of deformation must have occurred, for the plateau could not have been built by such deformation. Accordingly, the date when that change took place must mark an important change in the balance of forces that built and maintain the plateau. England and Houseman [79] showed that among the plausible processes that could have caused a change from north-south shortening to east-west extension across the entire plateau, an uplift of the plateau, presumably due to convective processes beneath it, appears most likely. Thus, dating the normal faulting is thought (by many, but not all) to date an uplift of Tibet of ~1-2 km (not the full ~5-km height) e.g.[72,80]. Moreover, several additional arguments have been used to buttress this contention of an abrupt ~8-Ma rise of Tibet. Because of the apparent significance of the 7-8-Ma date in the tectonic evolution of the Himalaya-Tibet region, in the sediment recorded by DSDP Leg 22 and ODP Leg 116, and in the evolution of the Asian Monsoon, we discuss more than just the observations made on Tibet.

Determining when east-west extension of the plateau began, let alone if and when it rose abruptly, requires dating the onset of extension at many different parts of the plateau, for there is no guarantee that one locality should be representative of the whole of the plateau. Only one normal fault system within the plateau, however, has been dated convincingly; Pan and Kidd [81] and Harrison et al. [72,64] showed that normal faulting in the Nyainqentanghla region became active at ~ 8 Ma. Harrison et al. argued that two other normal faults also date from approximately the same time. Coleman and Hodges[82] dated small tension gashes that they relate to extension of the Thakhola graben at 14 Ma. We do not share Coleman and Hodges's conviction that their 14-Ma date is related to uplift of the plateau. Such extension, however, characterizes the active deformation of many island arcs above the downgoing slabs of lithosphere [83,84] and therefore may not reflect the same processes that have occurred within the plateau.)

If the uplift of the plateau occurred in response to convective removal of mantle lithosphere, as some have contended [85,79,72,80], then the initiation of basaltic volcanism should define the approximate date when uplift began. Both isotopic and rare-earth compositions of basalt from northern Tibet imply that mantle lithosphere [86-88], and most dates of such basalt from *within* the plateau are younger than 10 Ma, with the oldest ~13 Ma [86]. Chung et al. [89], however, argued that uplift of Tibet began yet earlier, from 40 Ma given by their oldest date in a study of potassium-enriched volcanic rock from Tibet and its surroundings. Because this volcanic rock was erupted within pre-Cenozoic belts ("terranes") that extend into Tibet, they treated it as representative on the entire Plateau. Many of their samples come from southwestern China, however, and not from the Tibetan Plateau. Without meaning to impugn the quality of their work, we contend that these dates place no useful constraint on the timing of Tibetan uplift.

Clearly, neither the dating of normal faulting, nor that of basaltic volcanism in Tibet is adequate to demonstrate that Tibet rose ~1-2 km at ~8 Ma, and the principal reason that this idea is taken seriously by more than a handful of advocates derives from other, seemingly relevant phenomena having also occurred at 7-8 Ma e.g.[72,80]. Discussed further below is a suggestion that the Asian monsoon strengthened at ~8 Ma, which is relevant here because a higher plateau is thought to induce a stronger monsoon. More direct as constraints on the tectonic development of Tibet, however, are changes in the style of deformation both north and south of Tibet, including that just south of the Bay of Bengal.

Folding south of India, once thought to be intra-plate deformation within the Indian Plate [90-93], has been dated at 7-8 Ma using the onlap of sediment drilled by DSDP Site 218 and Leg 116 [2,4,5]. Refined analysis of magnetic anomalies in the Indian Ocean has shown that this deformation occurs sufficiently rapidly that it makes sense to treat it as a ~1000-km wide plate boundary between the Indian and Australian plates [94-96]. Moreover, further refinements indicate that although relative movement of the Indian and

Australian plates must have begun before 8 Ma [97], the rate and direction between them changed at ~8 Ma to give rise to the observed folding [98].

Although the constraints are weaker, deformation north of Tibet also seems to have accelerated in the last ~10 Ma, both in the Tien Shan, the prominent range north of Tibet and the Tarim Basin, and in the Gobi Altay, the region farther east and northeast of the Tarim Basin [99,100].

The logic that ties a 1-2 km uplift of Tibet to the increase in deformation both north and south of plateau presumes that a higher plateau implies a higher pressure at any depth below it, and hence a greater horizontal compressive force per unit length applied by the plateau to it surroundings than before. An estimate of the horizontal compressive force per unit length needed to fold lithosphere south of Tibet matches that applied by a plateau at Tibet's current elevation, but not one at an elevation of only 3.5-4 km, especially if it were underlain by a heavy lithospheric root [80,101]. Although not a unique explanation, an increase in the mean elevation of Tibet, like increased pressure in a higher water tower, should augment the horizontal compressive force per unit length sufficiently to induce, or accelerate, deformation both north and south of Tibet.

A rapid ~1-2 km uplift of Tibet at 7-8 Ma might not be recorded by sediment in the Bay of Bengal. The absence of a change in the isotopic composition of sediment younger since at least ~17 Ma, sampled from drill holes of ODP Leg 116, suggests that the same Himalayan source of material was eroded throughout this period [102,51]. The change in grain size of sediment at ~7 Ma from coarser to finer material [103,102] is not what one might expect in a more energetic environment associated with uplifted terrain. Similarly, rates of deposition during the period between ~7 and ~1 Ma were lower than before or after (Figure 3) [102]. Reviewers might question whether another ODP hole has a chance of revealing useful information about Tibetan uplift, but note that the holes on Leg 116 were drilled at the southern edge of the Bengal fan in basins that formed between folds beginning at ~7-8 Ma. Thus, the change toward lower sedimentation rates results at least in part from sea-floor topography due to that folding. Moreover, clearly the results from one area need not be representative of the entire fan.

Accelerated cooling of rock and erosion in the Himalaya at 2-3 Ma. Throughout the earth, rugged mountain ranges have been described as "juvenile," with the suggestion that recent uplift is responsible for the relief. Among tectonic phases of the Himalaya that he considered important, Gansser [104] referred to the last 2-3 Ma as the "morphotectonic phase," which gave rise to the present relief. He assumed that rapid Quaternary uplift had induced the rapid erosion needed to create the present relief. From cooling ages of only 1.5-2.4 Ma based on fission tracks in samples from the central Himalaya, Sorkhabi et al. [105] also argued that recent uplift had induced rapid erosion and cooling. A plot of ages vs. elevation of the sources with an assumed geotherm yields a rate of denudation of 2.5 mm/yr, much higher than the average of ~1 mm/yr 20 Ma e.g.[106,107,105]. Sorkhabi et al. [105] pointed out that such an inferred erosion rate is subject to large errors due to topographic perturbations to the temperature structure, but their young fission-track ages require rapid erosion. In addition, Galy[108] (p. 367) has inferred that average erosion rates of the Himalayan regions drained by the Ganga and Brahmaputra are 1.8 ± 0.6 and 2.8 ± 1.1 mm/yr, respectively, also significantly higher than the average since 20 Ma. Rea et al. [109] inferred an uplift of the northeastern part of the Tibetan Plateau at ~3.6 Ma from increased aeolian sediment deposition in the North Pacific at that time. Loess deposition on the Loess Plateau of eastern China accelerated at 2.5-3 Ma by 4-5 times [110]. Finally, reconstitution of mass accumulation in the Bengal Fan and the flood plain show a sharp accelaration since 2-3 Ma [111].

Recent rapid erosion has traditionally been used to infer late Cenozoic uplift of mountain ranges throughout the world, not just the Himalaya. Climate change, however, offers a global phenomenon that can account for the evidence used to infer recent uplift, if erosion rates changed in response to climate change [112]. Glaciers, which surely became widespread at 2-3 Ma, seem to erode more rapidly than rivers [113], though one can imagine other hydrologic changes associated with climate change and leading to increased erosion. Glaciation is widespread in the Himalaya, and the isotopic content of clay minerals in Himalayan rivers supports the contention that glaciers are an important erosive agent there [108]. Moreover, there is little reason, except the rapid late Cenozoic erosion itself, to suppose that tectonic processes changed at 2-3 Ma. Thus, the Himalaya offer an excellent place to study the erosional response to climate change, and hence to test the idea that climate change accelerated erosion rates; the Bay of Bengal is the place to look at the erosional record. Both grain sizes (Fig. 2) and sedimentation rates (Fig. 3) in holes from ODP Leg 116 show increases at ~1 Ma, consistent with such a change, when allowance is made for inaccuracies in dates

III - THE DEVELOPMENT OF THE ASIAN MONSOON

Two periods have been suggested for the onset, or marked strengthening of the monsoon, Early Miocene and 7-8 Ma, but the evidence for both must be considered suggestive at best. Moreover, none of that evidence comes from the Bay of Bengal.

Early Miocene onset of the monsoon. Using reconstructions of both India's position with respect to Eurasia and the evolving distribution of shallow seas as boundary conditions, Ramstein et al. [115] and Fluteau et al. [116] calculated climates using a General Circulation Model. In their calculations, the most important boundary condition was the disappearance during Early Miocene of a shallow sea (Para-Tethys) that occupied a large area west Tibet, of which the Caspian and Aral Seas are the last remnants. A small uplift of only 1-2 km of Tibet, discussed above, had little effect in their simulations.
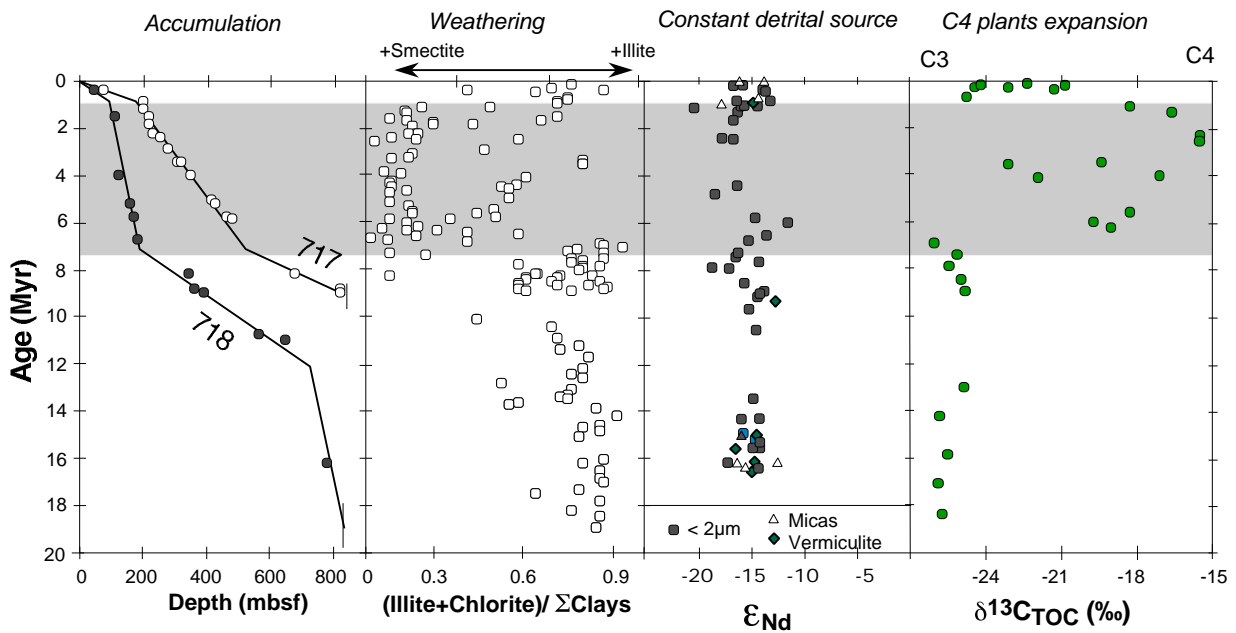

Fig. 4 - Accumulation rate[5], clay mineralogy[102], Nd isotopic data[103], and total organic carbon isotopic composition from ODP Leg 166 Holes 717C and Ages recalculated using time scale of Cande and Kent[104]. Low sedimentation rates (A), smectite-kaolinite (SK) clays (B) and organic carbon derived from C4 plants (D) characterize the interval from 7.4 to 0.9 Ma. The Nd isotopic composition (C) remain stable at all periods indicating the stability of the eroded source of material. The biostratigraphic constraints on sediment accumulation are uncertain for the early Miocene. The apparent increase in sedimentation rate near 12 Ma could be an artifact of poor biostratigraphic control prior to that time.

7-8-Ma onset, or marked strengthening, of the monsoon. Quade et al. [117] showed that both carbon and oxygen isotopes in pedogenic carbonate sediments in northern Pakistan changed abruptly between 6 and 8 Ma (Fig. 4); from those changes they suggested that the monsoon strengthened at that time. Subsequent measurements from both Pakistan [118-120], Nepal [121,119], and the Bengal Fan [122] (Fig 4) confirm the regional importance of the C4 plant expansion, but their significance has come under doubt. First, the C4 grass expansion appears to be a consequence of a global evolutionary development of plants driven by falling PCO_2 of the atmosphere [123,124]. Thus, the change in ^{13}C near 6-7 Ma need not indicate a local climate change.and would be a response to global change. Evidence for change in the level of atmospheric CO2 is however debated[125]. The drop in ^{18}O at 7-8 Ma does seem to indicate some kind of climate change, but the type of change remains controversial, for such a change might, among a number of possibilities, reflect a change in temperature in northern Pakistan or a change in the isotopic composition of the water evaporated and brought to that area. In contrast to Quade et al.[117], Stern et al. [120] suggested

that the sense of the ^{18}O change is opposite to what a stronger monsoon implies, and inferred either a change in the source of the precipitation or increased aridity of the region.

Perhaps the evidence most suggestive of a strengthening of the monsoon at ~7-8 Ma comes from marine micro-organisms in the northwestern Indian Ocean and, in particular, from the abrupt increase in the fraction of *Globigerina Bulloides* in cores obtained in holes drilled on ODP Leg 117 from the Arabian Sea. *G. Bulloides* apparently evolved between 14 and 15 Ma. It thrives in cold nutrient-rich water that upwells during both the summer and winter monsoons. In fact, the majority of *G. Bulloides* live at high latitudes. Before ~8 Ma, *G. Bulloides* accounted for <10% of the micro-organisms in the cores sampled by Kroon et al. [126] and Prell et al. [127], but afterward, it has accounted for many tens of percent (Fig. 5). *G. Bulloides* is widely recognized as an indicator of the monsoon [128,129]; systematic measurements using sediment traps demonstrate that it virtually disappears between the monsoon seasons, and that it is significantly more abundant during the summer than the winter monsoon e.g.[130,131]. It, like many organisms, thrives in the cold water that upwells during the monsoons e.g.[132].

The argument that the increase in the fraction of *G. Bulloides* at ~8 Ma marks a marked strengthening of the monsoon contains some weaknesses that make it still impeachable. The change toward a greater percentage of *G. Bulloides* might result as much from the extinction of other micro-organisms comparably sensitive to upwelling as from *Bulloides's* penchant for upwelled nutrients, as Kroon et al. [126] suggested for the low percentages of *G. Bulloides* at ~ 5 Ma. Nevertheless, Prell et al. [127] noted qualitative increases in the abundance of two species of radiolaria [133] suggestive of a strengthening of the monsoonal winds that cause the upwelling. In addition, Rea [134] reported increased terrigenous sedimentation at ~8 Ma, if from only sparsely sampled cores, and Baldauf et al. [135] reported an increase in siliceous sedimentation in the Arabian Sea, which presumably reflects an increase in upwelling of nutrient-rich water. Yet, a four-to-five-fold increase in deposition rates in the North Pacific, also at ~8 Ma, appears to be due to increased biogenic silica deposition [109], which is not easily assigned a monsoonal cause.

Sampling from the Bay of Bengal on Leg 116 indicates changes at ~7-8 Ma, but their significance for a stronger monsoon is obscure, if not simply inconsistent with such a change in climate. As discussed above, grain sizes changed from coarser to finer at ~7 Ma. Moreover, the clay mineralogy changed from largely illite and chlorite to predominantly smectite and kaolinite at the same time, suggesting greater weathering and longer durations in saturated environments between ~7 and 1 Ma than before or after [114,136,102]. Moreover, at the same time, the ratio of ^{87}Sr/^{86}Sr in pedogenic clay minerals in sediment of the Bengal fan increased which has been interpreted to imply decreasing erosional fluxes [137]. Sediment deposited in the foreland basin in Nepal and Pakistan show the same trend in Sr isotopic composition of pedogenic carbonate [138].

These various observations pose a puzzle to the interpretation of a strengthening of the monsoon at ~7-8 Ma. The decreased grain sizes, the shift in clay mineralogy, and the increase in ^{87}Sr/^{86}Sr ratios suggest a less energetic erosive agent after ~7 Ma, including both decreased runoff and a more equable climate associated with long-term sediment storage. Weathering of sediment stored en route to the Bay of Bengal altered clay minerals. Derry and France-Lanord [137], in fact, inferred that the increased ratio of ^{87}Sr/^{86}Sr recorded by marine sediment resulted from decreases in the supply of Sr and in erosion rates during the period between ~7 and 1 Ma. Such a climate is not what one might expect from a transition to an enhanced monsoon, with its seasonally stormy climate with heavy rain fall and energetic erosion [137,139]. In support of a more equable climate, France-Lanord and Derry[122,140,139,141] called attention to increases in both organic carbon burial and an increase in ^{13}C in organic carbon deposited in the Bengal fan near 7 Ma. The increased values of ^{13}C suggest greater deposition of organic carbon from C4 grasses (Fig. 4), which presumably grew in the Ganga basin, not in the Himalaya

Finally, using magneto-stratigraphy to date loess deposits, Sun Donghai et al [110] showed that aeolian deposition on the loess plateau of eastern China began at ~8 Ma. This result suggests a substantial cooling of the source area of these deposits or a strengthening of winds that transports the material, either of which implicates Tibetan uplift. In addition, Rea et al. [109] noted a pulse in aeolian deposition in the North Pacific at ~8 Ma, though such deposition decreased before returning to its current high level at ~3.6 Ma. Rea et al. [109] offered no explanation for this pulse of about 1 Myr duration and clearly were puzzled by it.

The summary given here emphasizes three facts. (1) Climate change(s) of some kind in southern Asia and the neighboring Indian Ocean occurred at ~7-8 Ma. (2) The nature of the change(s) is not clear, but evidence from the western Himalaya and Arabian Sea are consistent with a strengthening of the monsoon at that time. (3) Evidence from the Bay of Bengal, however, seems inconsistent with a strengthening of the

monsoon, or if it is consistent, its relationship is not clear. Part of the difference between the observations in the eastern and western parts of this area could stem from the signatures of the monsoon being different in these areas. In the west, a seasonal change in winds, the process that gave the monsoon its name, seems implicated by the observations assigned a monsoonal cause, but in the east, heavy rains characterize the monsoon, and their geologic record is likely to be different from that of changing winds. The need to understand better how variations in the Asian monsoon are recorded motivates discussion of the next aspect to be considered.

The Late Quaternary development of the Asian monsoon. To use sediment in the Bay of Bengal to understand how a change in the Himalaya and Tibet may have effected a strengthening of the monsoon, we must understand how that sedimentary record depends on the strength of the monsoon. Considerable work has been carried out in the Arabian Sea using the concentration of *G. Bulloides* and oxygen isotopes, as well as using wind-blown pollen and dust deposited both on land and off shore e.g.[142-148]. Variations in ratios of $^{18}O/^{16}O$ in planktonic foraminifera, in abundance of *G. Bulloides*, and in pollen transported to sites on Africa and Arabia adjacent to the Arabian Sea show weaker summer monsoons during the last glacial period, than after it. Moreover, the strong coherence at frequencies associated with precession and obliquity imply that solar forcing is dominant, if monsoon strength lags such forcing [143,146,148]. Coherence with ice volume is weaker. These patterns all imply varying strengths of the steady monsoonal winds that blow, via Ekman transport, the surface water away and allow cooler, nutrient-rich water to upwelle.g.[132].

In the Bay of Bengal, manifestations of a stronger monsoon are less likely to derive from the action of winds, and more from precipitation. In particular, the heavy summer rains over the Bay of Bengal and its drainage basin, lead to much lower salinity of surface waters there than in the Arabian Sea, where evaporation is high [149]. This difference, however, reverses in autumn and winter, when surface currents carry the low-salinity water of the Bay of Bengal into the Arabian Sea. In particular, Duplessy [149] showed that during the last glacial maximum (~18 ka), the ratio of $^{18}O/^{16}O$ in the planktonic foraminifera *G. Ruber*, was significantly higher than at present, presumably because less rain water, with its low $^{18}O/^{16}O$, both drained off the land and fell on the bay at that time. Moreover, the gradient in $^{18}O/^{16}O$ across the Bay of Bengal was low during the last glacial maximum; but during Holocene time, it was quite steep, decreasing northeastward across the Bay of Bengal toward the fresh water source of the Ganga and Brahmaputra Rivers.

The considerably greater amount of paleoceanographic work related to the monsoon carried out in the Arabian Sea than in the Bay of Bengal might seem an argument to work in the former, not latter region. Yet, we anticipate that the Bay of Bengal will turn up surprises that might allow it to offer better clues of what controls the strength of the monsoon than the Arabian Sea. For instance, recent studies of both sapropels on land [150] and of marine sediment rich or poor in organic carbon [151] not only suggest a strong correlation of millennial-scale climatic variability with that observed in ice cores but also implicate variations in precipitation, largely in the northwestern Indian Ocean. Because of the greater variability of precipitation over the Bay of Bengal than over the Arabian Sea, we might find stronger and clearer signals in Late Quaternary sediment in the Bay. In addition, just as the work of Schubert et al [152] has recently revealed several new indicators of paleo-productivity and other changes in surface water of the Arabian Sea, we expect that similar developments will allow new insights into the evolving monsoon record from the Bay of Bengal.

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