PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Sedimentary Facies on the Rises and Slopes of Passive Continental Margins [and Discussion]

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Sedimentary facies on the rises and slopes of passive continental margins

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[Plate 1]

Joides drilling results provide new evidence concerning facies patterns on evolving passive margins that strengthens and extends hypotheses constructed from studies of morphology, seismic reflexion data and shallow samples on modern margins, and from field geologic studies of uplifted ancient margins. On the slopes and rise, gravity-controlled mechanisms – turbidity currents, debris flows, slides and the like – play the dominant role in sediment transport over the long term, but when clastic supplies are reduced, as for example during rapid transgressions, then oceanic sedimentation and the effects of thermohaline circulation become important.

Sedimentary facies models used as the basis of unravelling tectonic complexities of some deformed margins, for example in the Mesozoic Tethys, may be too simplistic in the light of available data from modern continental margins.

Introduction

A central aim of the Ipod Deep Sea Drilling programme is to confront models with new field facts, and I shall therefore attempt here to assess the impact of the drilling results on some of our ideas about sedimentary processes and facies on the continental slopes and rises of passive continental margins. Our models rest on many supports: (1) the patterns of deposition of modern sediments, as determined by piston and gravity cores; (2) the actual processes of transport, erosion, and sedimentation as inferred from current meters, nephelometers, bottom photographs and the like; (3) the internal geometry of the sedimentary accumulations as revealed by seismic studies; (4) the results of exploratory drilling for oil and gas in coastal regions and on continental shelves, which provide data on facies trends and subsidence rates that can be extrapolated farther seaward; and (5) the lithology and stratigraphy of now-lithified and uplifted sedimentary rocks that are supposed to have accumulated originally in these continental margin environments.

Pre-Ipod models of sedimentation on slopes and rises tended to stress continental influences such as upbuilding and outbuilding of terrigenous clastics; fluctuations of sediment supply rates governed by continental altitude and climate and modulated by transgression and regression; and sediment transport down the slope and rise by gravity controlled processes (see Kelling & Stanley 1976, for a review). More oceanic influences include transport of at least clay and silt in directions more or less parallel to the slope contours by deep boundary currents driven by the oceanic thermohaline circulation. The continental slope, except for regions with fairly rapid supply rates of terrigenous clastics, is regarded as a region where most sediments rest temporarily, while being transported down to the continental rise or even to abyssal plains beyond.

The models, of course, also recognize that passive margins subside. The subsidence most likely follows exponential curves similar in form to those characteristic of the main ocean basins, but with a large added isostatic component.

The IPOD results, which come chiefly from the Atlantic, and from margins with only a modest cover of sediments, mainly validate the essential features of the models, but at the same time they tend to place the features in a new perspective that emphasizes the importance of oceanographic as well as tectonic and climatic controls in determining the facies successions on continental slopes and rises.

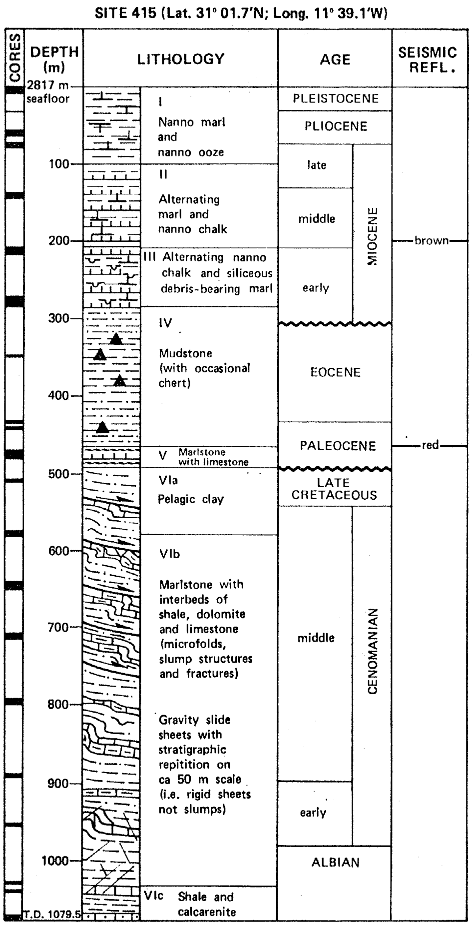

FIGURE 1. Graphic log of rocks drilled at Site 415 on Leg 50, on the continental rise off Morocco, showing slide sheets in Middle Cretaceous beds. Repetitions are documented on down-hole gamma-ray log.

GRAVITY-CONTROLLED SEDIMENTATION

If anything, the drilling results (Ewing *et al.* 1969; Peterson *et al.* 1970; Maxwell *et al.* 1970; Bader *et al.* 1970; Hollister *et al.* 1972; Laughton *et al.* 1972; Ryan *et al.* 1973; Hayes *et al.* 1972; Edgar *et al.* 1973; Barker *et al.* 1976; Talwani *et al.* 1976; Supko *et al.* 1977; Scientific Staff 1975 (*a*)–(*e*), 1976 (*a*)–(*c*), 1977 (*a*)–(*d*)) re-emphasize the dominance of gravity-controlled processes in sedimentation. In virtually all Atlantic-margin drill holes, a very large share of the terrigenous sediments actually cored shows evidence of transport by turbidity currents, debris flows, or other essentially down-slope mechanisms.

Disturbed beds – so-called slump structures – are especially common at drill sites located on the upper part of the continential rise. In some places the disturbance has proceeded to disruption of the bedding, and finally to the pebbly mudstone fabric. Modern debris flows have

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been identified (Embley 1976) on seismic profiler records and in piston cores on the continental rise in the same area off North Africa, where these features are found in the Miocene in a JOIDES drill hole. Profiler records off both western Europe and eastern North America (see, e.g., Stride *et al.* 1969; Schlee *et al.* 1976) commonly show features on the slope and upper rise suggesting slumped masses.

Drilling on the continental rise off Morocco on Leg 50 (Scientific Staff 1977*a*) showed a sequence of repetitions of middle Cenomanian beds some 200 m thick (figure 1), suggestive of gravitational slide sheets originating highei on the continental slope, and perhaps associated with Late Cretaceous uplift in the Atlas Mountains. Reflexion profiler records in this area show the slide mass as a discrete body, with complex internal reflexions, that spread out northward and seaward from the drill site where it was cored.

It is a curious feature of passive margins that profiler records so commonly show displaced slump masses along them, while similar features are rare along active margins. Perhaps the fate of such masses along active margins is rapid incorporation into the accreting wedges near the base of the slope, by which they thereby lose their original form.

My personal impression, gained from a study of cores from a few Atlantic sites and of colour photographs of cores from most sites, is that turbidites may be even more prevalent than one would gather from reading the descriptions in the *Initial Reports*, in *Geotimes*, and in the *Initial Core Descriptions*. Some of the turbidites are easy to recognize because they show the classic sequence of sedimentary structures formalized by Bouma (1962), and graded bedding is conspicuous (figure 2*a*). In some, the Bouma sequence may begin with the cross-stratified unit C (figure 2*b*) or even parallel-laminated silty unit D, making recognition less certain. Where burrowing is intense, the grading may be very difficult to recognize.

The fossils contained in the turbidites provide valuable clues to the transport paths of turbidity currents. Lower Cretaceous graded beds on the continental rise off Morocco, drilled on Leg 50, for example, commonly contain in their lower parts, redeposited benthonic fossils derived from shelf and upper slope environments, but only dwarfed deeper-water arenaceous foraminifers in their upper parts. Planktonic fossils – even very delicate forms such as calpionellids – are commonly redeposited in their proper settling velocity order in the turbidites. Some turbidites, indeed, may consist almost entirely of redeposited pelagic materials, and thus special care should be given to the vertical sequential properties of all cyclic-looking beds, even those without much terrigenous material. The redeposited fossils most commonly are the same age as the sediments enclosing them, suggesting continual stripping of the continental slope.

We are each of us victims of our own experiences, and there may indeed by a tendency for some shipboard sedimentologists to see more or fewer turbidites than others; my own experience on several cruises of Glomar Challenger suggests to me that geologists with extensive field experience in flysch terrains tend to label more beds in JOIDES cores as turbidites than do other sedimentologists.

Oceanographic effects

For geologists concerned with continental margins probably the most profound effect of JOIDES drilling on our thinking has been to help reorientate our point of view from the continent to the ocean side of the margin, that is, to permit us to see the importance of oceanic events and mechanisms – as well as continental tectonics and climate – as determinants in the accumulation of margin sediments.

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These oceanic effects are probably most sharply registered on the continental slope, which in many regions is shown by seismic profiler records to be a zone of low net accumulation rate, compared to the shelf and rise on either side. Slopes may commonly be too steep to permit permanent accumulation of thick sediments, and most terrigenous clastic sediments not trapped on the shelf may be bypassed to the rise, via submarine valleys and canyons. The very few JOIDES drill holes we have on continental slopes show a relatively condensed series of essentially pelagic to hemipelagic deposits, abbreviated by hiatuses. These record (where they have not been eroded away) the changing oceanographic conditions over the slope, such as fluctuations in carbonate solution levels, periods of intensified or expanded oxygen minima, times of increased fertility and fluctuations in the intensity of deep water currents. Even though hiatuses and slump deposits interrupt the record, I believe we would have a far better picture of near-continent oceanography, e.g. the history of upwelling, if we were to drill more holes on the slope, and fewer on the rise. Most of the JOIDES drilling on passive margins has been done on the continental rise, where sediments are thick and seismic reflectors numerous. Here the record tends to be dominated by resedimented materials derived from farther up slope, or perhaps from along slope.

Indeed, for more than a decade, evidence has accumulated showing that deep water currents driven by the oceanic thermohaline circulation have an important role in transporting sediment or even in eroding older sediments (Heezen *et al.* 1966). In the Western North Atlantic these boundary currents are held responsible for the construction and shaping of the Blake–Bahamas Outer Ridge, cored during Leg 11, and perhaps for much of the sedimentation on the continental rise. An important question for IPOD drilling in the Atlantic, therefore, is to assess the role of this mechanism of erosion and sediment transport in time and space. Seismic profiler data in the North Atlantic suggest that most sediment masses ascribable from their position and geometry to deposition by deep boundary currents are post-Eocene in age, and drilling is an attractive means for identifying other older sediments deposited in this way but not recognizable as such by external morphology or reflexion characteristics.

Cores taken on Blake–Bahamas Ridge during Leg 11 (Hollister *et al.* 1972) and by conventional piston coring showed laminated silts, commonly with cross-stratification. The problem in JOIDES drill cores is to discriminate, solely on the basis of lithology, these so-called 'contourites' from other types of beds, say distal turbidites. An example is the demonstration from the mineralogy of Eastern North American rise sediments of long-distance transport in a direction more or less parallel to the continental margin (Needham *et al.* 1969). Unhappily, the palaeogeology and palaeogeography of the adjacent continent is generally not sufficiently known to permit us to hazard such inferences. Bouma & Hollister (1973) suggested a purely lithological discriminator in the mineralogy of the small-scale cross laminae: in contourites, heavy minerals placer along laminae, while in turbidites clay minerals produce the dark streaks. My own limited study of thin sections of 'classical' turbidites (that is, those with good Bouma cycles) and with displaced shallow-water fossils in a deep-water setting (the Lower Cretaceous of Leg 50, Site 416, for example) shows that at least some turbidites also have heavy mineral streaks along the cross laminae (figure 3), and that while the criterion may have local usefulness, it may not be generally trustworthy.

One datum that would be useful in trying to assign silty laminae to a distal turbidite or to a contourite or even to another origin is the directional depositional fabric, which would show whether the depositing currents were aligned parallel to the regional slope contours. The

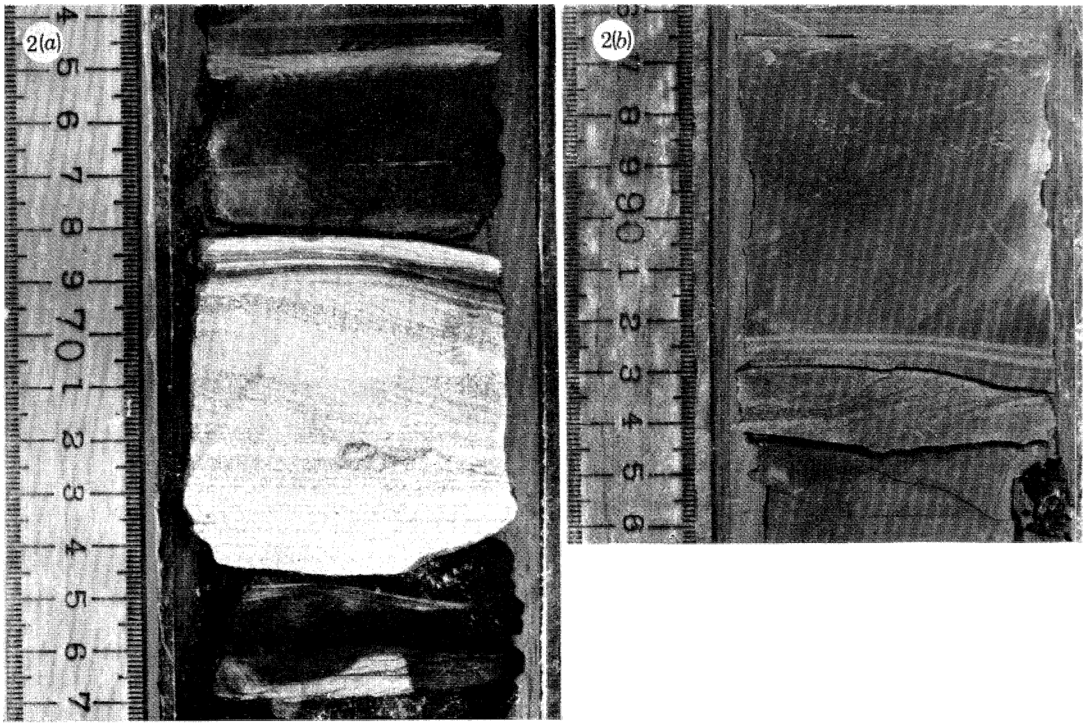

FIGURE 2. Turbidite beds, Lower Cretaceous, Leg 50, Site 416A, on continental rise off Morocco. Scale in centimetres. There are some 9000 turbidite beds in the Lower Cretaceous at this site. (*a*) Graded and cross-stratified layer of Valanginian age, beginning with parallel laminations at the base. (*b*) Graded and cross-stratified layer of Hauterivian age, beginning with cross laminae at the base.

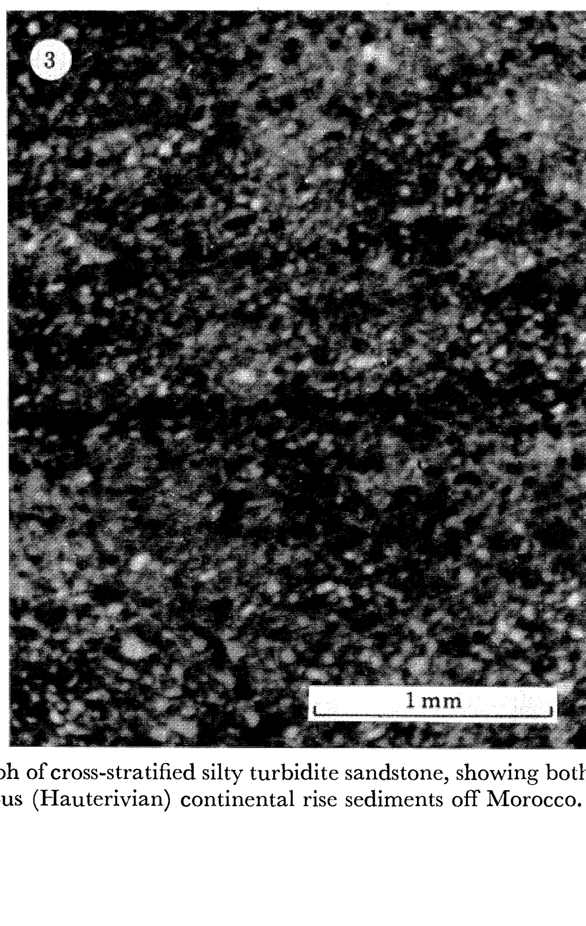

FIGURE 3. Photomicrograph of cross-stratified silty turbidite sandstone, showing both heavy mineral-rich laminae. Lower Cretaceous (Hauterivian) continental rise sediments off Morocco. Leg 50, Site 416A.

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JOIDES cores would have to be oriented from their remnant magnetization, and then the fabric described, perhaps most readily from the anisotropy of the magnetic susceptibility. The proper recognition of sediments deposited by deep thermohaline currents is not a trivial question, for it bears on the most fundamental aspects of oceanic circulation. We must be as cautious in proposing such currents as we are, say, in proposing that a given pebbly mudstone is a tillite.

A comparison of JOIDES drill results around the Atlantic shows that hiatuses interrupt the record at certain stratigraphic levels at virtually all sites, for example at the Eocene–Oligocene boundary, where commonly at least a part of the lower Oligocene – and in some places practically the whole series – is missing. There appears to be a relation between position of the drill sites and the length of this hiatus: sites on the continental rise are most affected; further seaward and further up the slope the effects are less severe, and on Atlantic oceanic plateaus and aseismic ridges there is virtually no hiatus. This arrangement suggests thermohaline currents focused along the base of the continental slope.

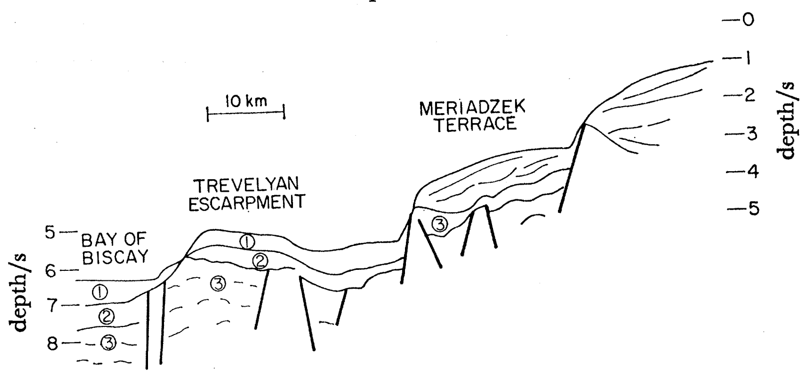

FIGURE 4. Schematic profile showing structure of the Armorican margin. 1, Quaternary and post-Eocene Tertiary; 2, Lower Tertiary and Upper Cretaceous; 3, Lower Cretaceous. From Montadert *et al.* (1974).

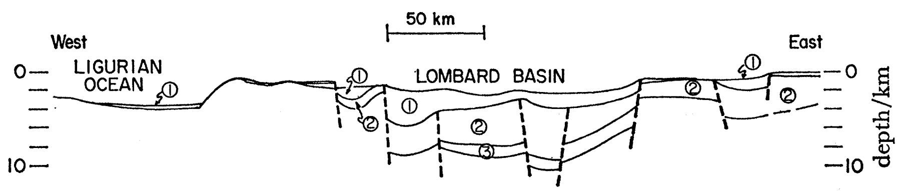

FIGURE 5. Schematic reconstruction showing structure of the northwest margin of the Apulian plate, in the southern Alps, Italy, at the close of the Jurassic Period. 1, Middle and Upper Jurassic; 2, Triassic; 3, Permian. From Winterer & Bosellini (in preparation).

When clastic supply rates are reduced by inshore trapping or by low continental erosion rates, pelagic sediments accumulate on the continental rise, but these are commonly deposited in water too deep to record fluctuations in carbonate dissolution levels. On the other hand, they do commonly record anoxic conditions, either at the drill site or, via redeposited sediments, at shallower depths. The much discussed Mid-Cretaceous anoxic conditions are strongly registered in continental rise sediments in the Atlantic off Southern and Central Africa, but are scarcely noticeable off Morocco. The organic matter in the sediments, where determined, tends to be dominated by the debris of higher terrestrial plants, but at some sites, a marine planktonic origin for the organic matter has been reported (Berger & von Rad 1972), rekindling the debate as to whether anoxic conditions extended down into the oceanic bottom waters, or rather were confined to a zone higher up within the water column. In this debate, as suggested by Schlanger & Jenkyns (1976), the possibility of down-slope re-deposition of organic debris, even planktonic organic debris, from the continental slope should not be ignored. Rapidly accumulating organic-rich planktonic material on a slope starved of terrigenous clastics might be unstable or be easily eroded and transported by even weak gravity currents. The reworked delicate planktonic fossils in turbidites attest to this process. The depth range of the Cretaceous anoxic conditions, at least in the North Atlantic, should probably be regarded as a question that is still open.

Morphology

The original morphology of a continental margin, to judge by modern examples of young margins and the deep structure of older margins as revealed by seismic surveys, can be very complex. The present Armorican Margin, north of the Bay of Biscay, is probably fairly representative. One sees a complex staircase, now partly smoothed over by sediments (figure 4). The steps, or terraces, are not continuous laterally, nor are all the elements arranged rigidly parallel to the general trend of the margin (Montadert *et al.* 1974). Similar structures, at least in cross-section, can be seen in slightly deformed margins now uplifted into mountains, for example in the Southern Alps in Italy, where the palaeogeography of a late Jurassic margin can be worked out in some detail (figure 5).

Structural geologists working in much more deformed passive margins – in parts of the Alps, for example – have traditionally had to assume very simple facies models as parts of simple morphological models that they then crumple and telescope. The resulting structural complexities are in some places incredibly intricate, and it is becoming increasingly clear that the original sedimentary facies models can probably be made more realistic by giving more attention to the palaeogeographic clues in the sediments themselves, sometimes with the result of simplifying the structural geometry and tectonic history.

Conclusions

Sedimentation on a mature continental slope and rise is a result of a shifting balance between dominance by terrigenous clastic sediments controlled by more or less local tectonics and climate, and dominance by oceanic effects, which can be local, regional or even global. The oceanic effects, commonly synchronous over very large regions, give rise to 'privileged times' when certain lithological facies on continental margins are particularly widespread, even in widely contrasting tectonic settings, or on different continents. The Oxfordian black clays and cherts, the late Jurassic red nodular limestones, the Tithonian calpionellid limestones, the Mid-Cretaceous black shales, and the Danian chalks are witness to these pervasive effects, which are probably the very root of the natural subdivisions of the stratigraphic column.

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Discussion

W. O. Sayre and E. A. Hailwood (*Oceanography Department, University of Southampton, Southampton SO9 5NH, U.K.*). Dr Winterer called for work to be done in the study of anisotropy of magnetic susceptibility of D.S.D.P. sediments. Work in this field has been in progress at Southampton for several years, and includes study of samples recovered from D.S.D.P. Legs 39, 40, 41, 47, 47a and 48b in the eastern Atlantic. Some preliminary results have recently been published (Sayre & Hailwood 1977; Hailwood 1979), and indicate that the method of study is capable of giving useful information on directions of sediment transport and palaeo-circulation trends, provided reasonable care is taken in the selection of undisturbed material, having a significant terrigenous component. At Southampton the anisotropy of magnetic susceptibility is measured by means of a low field torsion magnetometer, and orientation of the inferred direction of grain alignment is achieved from measurements of the stable magnetic remanence.

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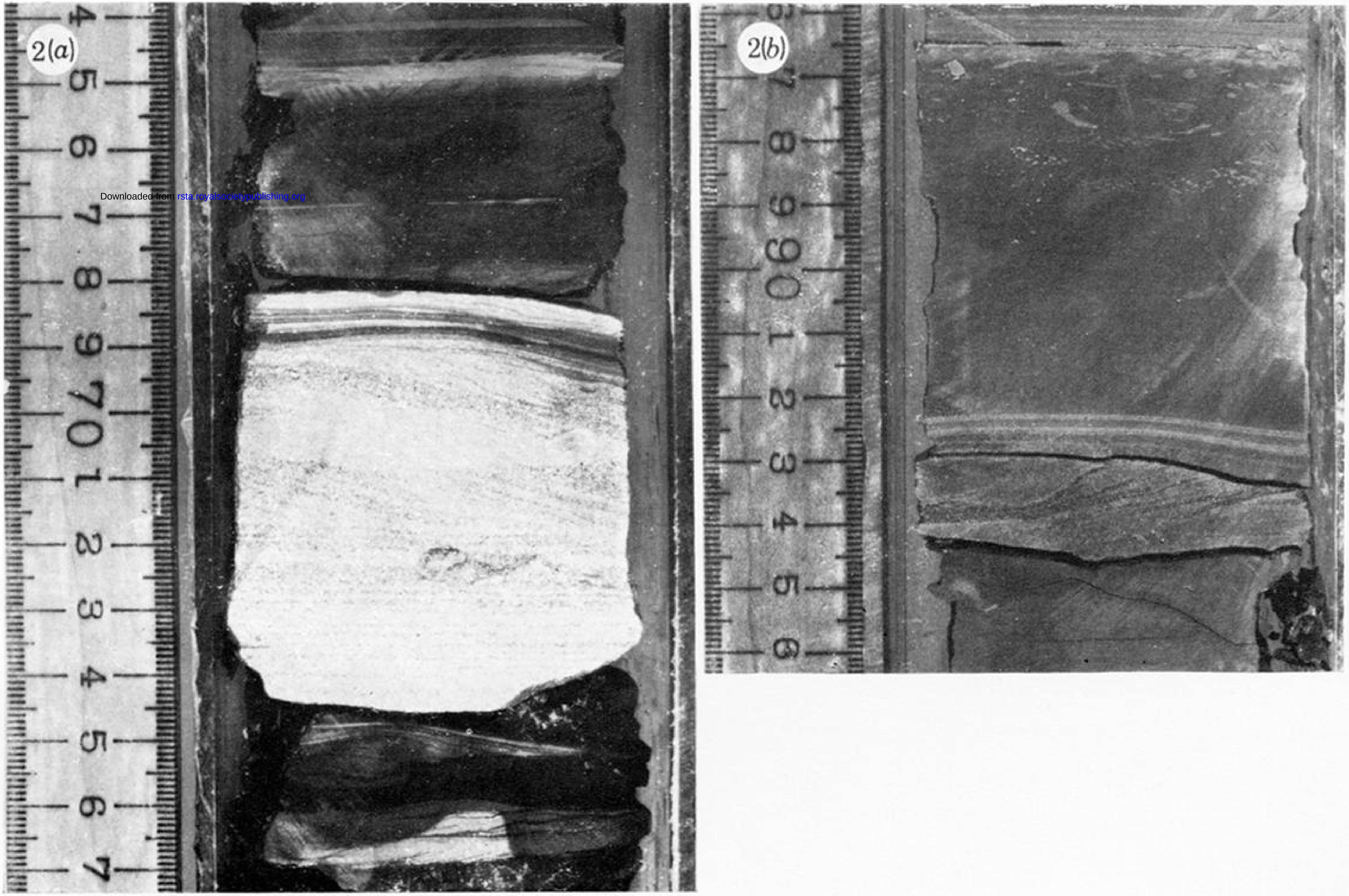

FIGURE 2. Turbidite beds, Lower Cretaceous, Leg 50, Site 416A, on continental rise off Morocco. Scale in centimetres. There are some 9000 turbidite beds in the Lower Cretaceous at this site. (*a*) Graded and cross-stratified layer of Valanginian age, beginning with parallel laminations at the base. (*b*) Graded and cross-stratified layer of Hauterivian age, beginning with cross laminae at the base.

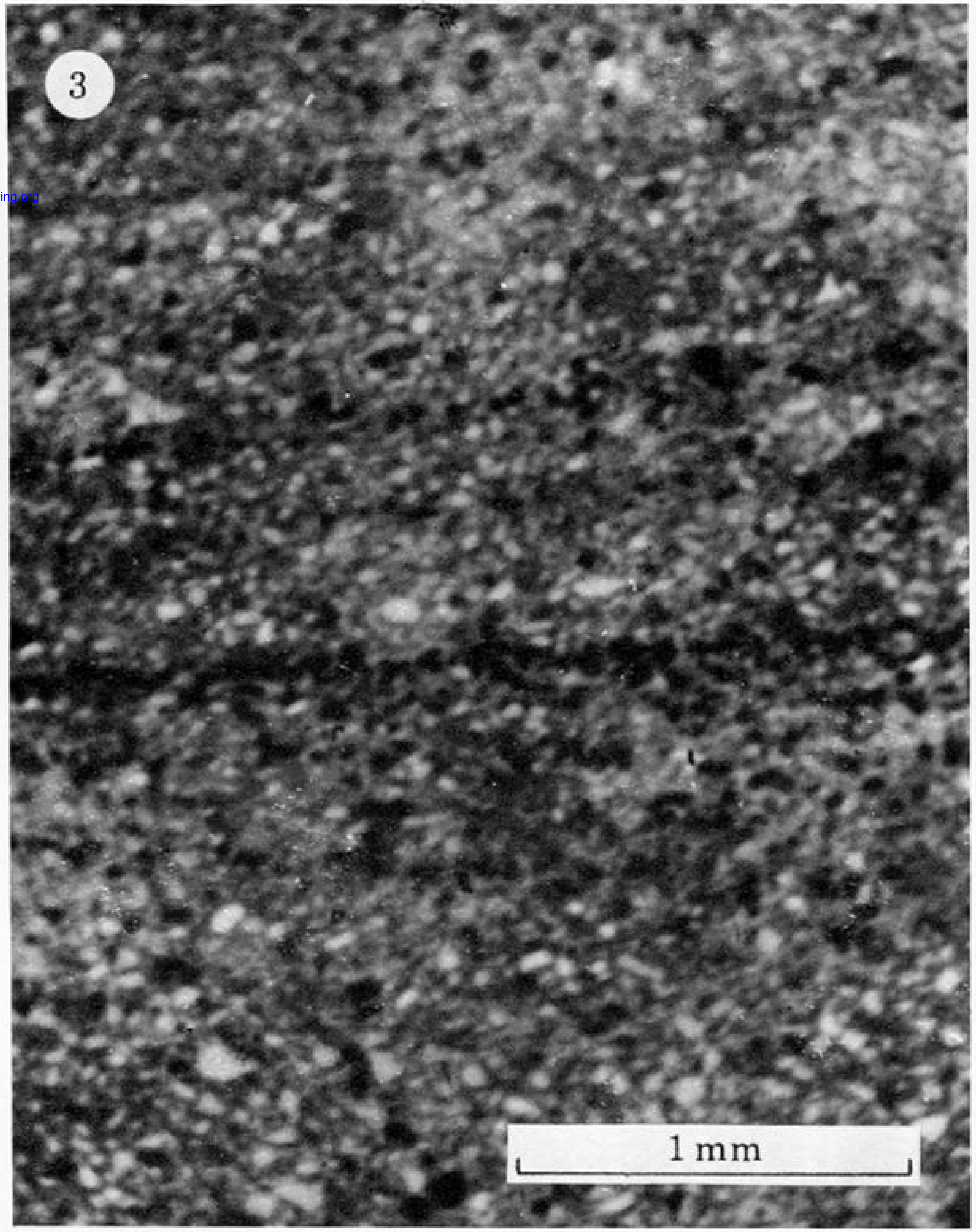

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FIGURE 3. Photomicrograph of cross-stratified silty turbidite sandstone, showing both heavy mineral-rich laminae. Lower Cretaceous (Hauterivian) continental rise sediments off Morocco. Leg 50, Site 416A.