22. MESOZOIC SEDIMENTATION ON THE EASTERN FALKLAND PLATEAU

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INTRODUCTION

Mesozoic sediments were encountered in two borings on the Falkland Plateau, Hole 327A and Site 330, both of which are situated in water depths on the order of 2500 meters on the southern flank of the slightly elevated eastern end of the plateau (Figure 1). At Hole 327A, calcareous ooze of Late Cretaceous (Maestrichtian) age was first encountered at a subbottom depth of 90 meters and the hole was terminated in carbonaceous claystones of Early Cretaceous (Neocomian-Aptian) age at a subbottom depth of 470 meters. At Site 330, calcareous (nanno) clay of Albian age was first cored at a subbottom depth of 129 meters and thereafter Mesozoic sediments ranging back to at least Upper Jurassic (Oxfordian) were drilled to a total depth of 550 meters. Below these a probable old soil profile and underlying basement rocks of granulitic gneiss and granite pegmatite were encountered. The Mesozoic sequences penetrated at these two sites suggest a depositional history as follows:

1) subaerial (paralic ?) sedimentation resulting in infill and aggradation of local bedrock basins;

2) Middle (?) to Upper Jurassic marine transgression followed by accumulation of predominantly terrigenous silts and clays in an open-shelf environment;

3) euxinic conditions and deposition of dark carbonaceous claystones which began in Upper Jurassic and persisted until near the end of the Lower Cretaceous (late Aptian);

4) open marine deposition of pelagic carbonate oozes and zeolitic clays through the remainder of the Mesozoic and most of the Tertiary.

The following discussion summarizes the characteristics of the Jurassic and Lower Cretaceous sediments encountered at these two sites and their interpretation in terms of depositional environments and geologic events. Detailed lithologic descriptions of the sedimentary column at these sites are presented in other chapters, this volume.

MIDDLE (?) TO UPPER JURASSIC SUBAERIAL SEDIMENTATION

The oldest sediments penetrated on the Falkland Plateau comprise a 2.7-meter section of silty sandstone and sandy siltstone first encountered at a subbottom depth of 547 meters at Site 330. Interbedded in this section are several thin (<3 cm) layers of lignite and a 30-cm bed of greenish-gray montmorillonitic claystone (Figure 2). Age of these sediments is uncertain because no faunal remains are present; however, pollen analysis from the immediately overlying sediments indicates Middle (?) to Upper Jurassic (Oxfordian).

Most of the sediments in this section fall in the textural categories of sandy silt, sand-silt-clay, and silty sand (Figure 3). The sands are predominately fine to medium in size, but are poorly sorted and range from very fine to very coarse. These varied textural types are arranged in curdely graded beds the order of 0.8 to 1.0 meters in thickness which are suggestive of cyclic sedimentation (Figure 2). Yellowish-brown silty sand or sand-silt-clay occurs at the base of each cycle and grades upward to drab-colored (olive-gray) clayey silt associated with lignite near the top. Convolute bedding and lithologic mottling are common in the finer sediments (Figure 4). Fragmental plant remains, lignite clasts, and angular granules of quartz and K-feldspar occur throughout the section, but are particularly concentrated in the coarser beds. Overall, the section coarsens upward, with sandy silt more common near the base and silty sand more common near the top.

The brown (oxidized) color, absence of marine fossils, and occurrence of lignite indicate these sediments were deposited in a subaerial swampy environment. The textural variability implies marked fluctuations in current conditions with attendant reworking of previously deposited sediments. Taken together, the evidence is suggestive of flood-plain conditions with episodic overwash from a nearby channel providing the coarse materials and reworking. The drab silt beds and lignite are due to temporal lakes left in the waning stages of flood overflow and to gradual reestablishment of marshes on the flood plain surface. Sequences similar to this have been reported in overbank sediments of streams having unimpeded flood plains and from flood basins and deltas of leveed streams where the coarse deposits and fining-upward cycles are related to crevasse splays (Allen, 1965; Casshyap, 1975). The close vertical proximity of marine sediments in the section plus the occurrence of a few marine palynomorphs make the deltaic interpretation a tempting one.

Textural and mineralogic evidence imply derivation of these sediments from a local terrain composed of gneissic rocks similar to those encountered in the bottom of the hole. The sands are subarkosic in composition with typical quartz/feldspar ratios of 4 to 8 and with K-feldspar predominant over plagioclase (Figure 5, Table 1). The nonopaque heavy mineral suite consists almost exclusively of garnet, tourmaline, and zircon, precisely those minerals which are most common in the underlying gneiss. The poor sorting of these sands, coupled with their coarseness and generally angular nature imply a relatively short transport history. The presence of very angular granules of quartz and K-feldspar, in many cases "floating" in a matrix of finer sand or silt, suggests the possibility of an adjacent

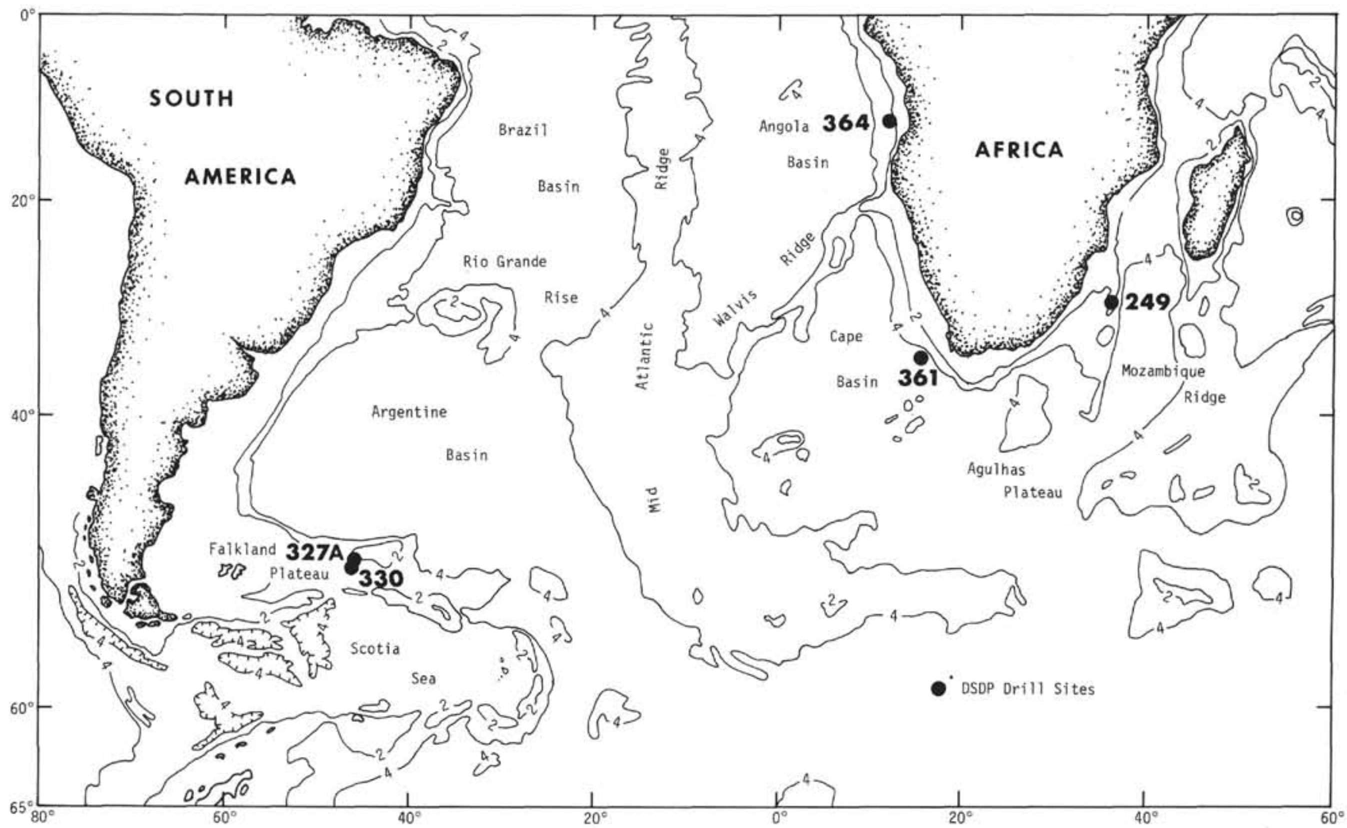

Figure 1. *Location map showing Leg 36 drilling sites on the Falkland Plateau and sites around southern Africa where Lower Cretaceous carbonaceous sediments were encountered on other legs. Bathymetry from Chase, 1975. Contours in km.*

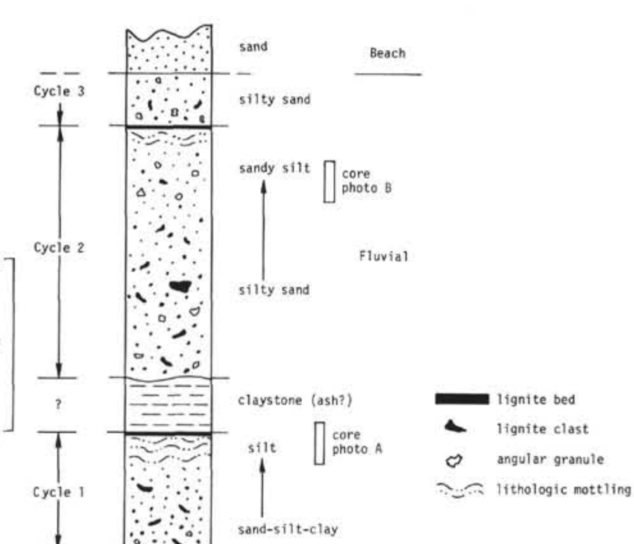

Figure 2. *Generalized lithologic section of basal subaerial deposits, lower Site 330, 547-550.5 meter. See Figure 4 (for indicated core photos).*

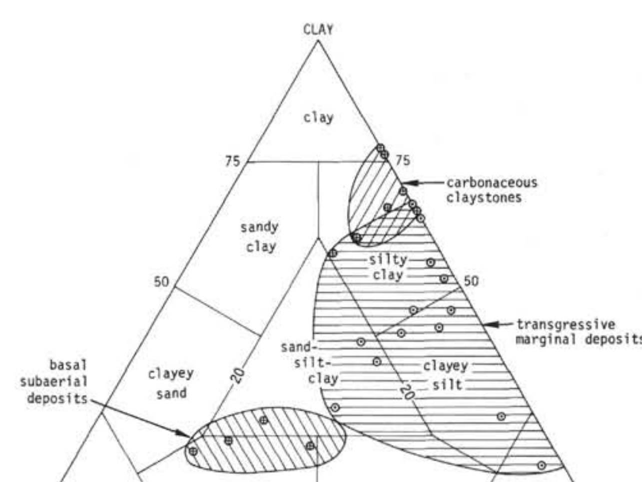

Figure 3. *Textural classification of Jurassic-Lower Cretaceous sediments, Site 330, Falkland Plateau.*

bedrock high in the immediate vicinity which occasionally shed coarse material onto the flood plain through processes of mass wasting.

Separating the silts and sands of the above section from the underlying granulitic gneiss is a 0.5-meter section of soft clayey sand (Figure 2). This unit is very poorly sorted and grades from bluish-white at the base to yellowish-brown near the top. The sand fraction isolated from this section contains about 67% quartz and 30% K-feldspar, both of which are very angular

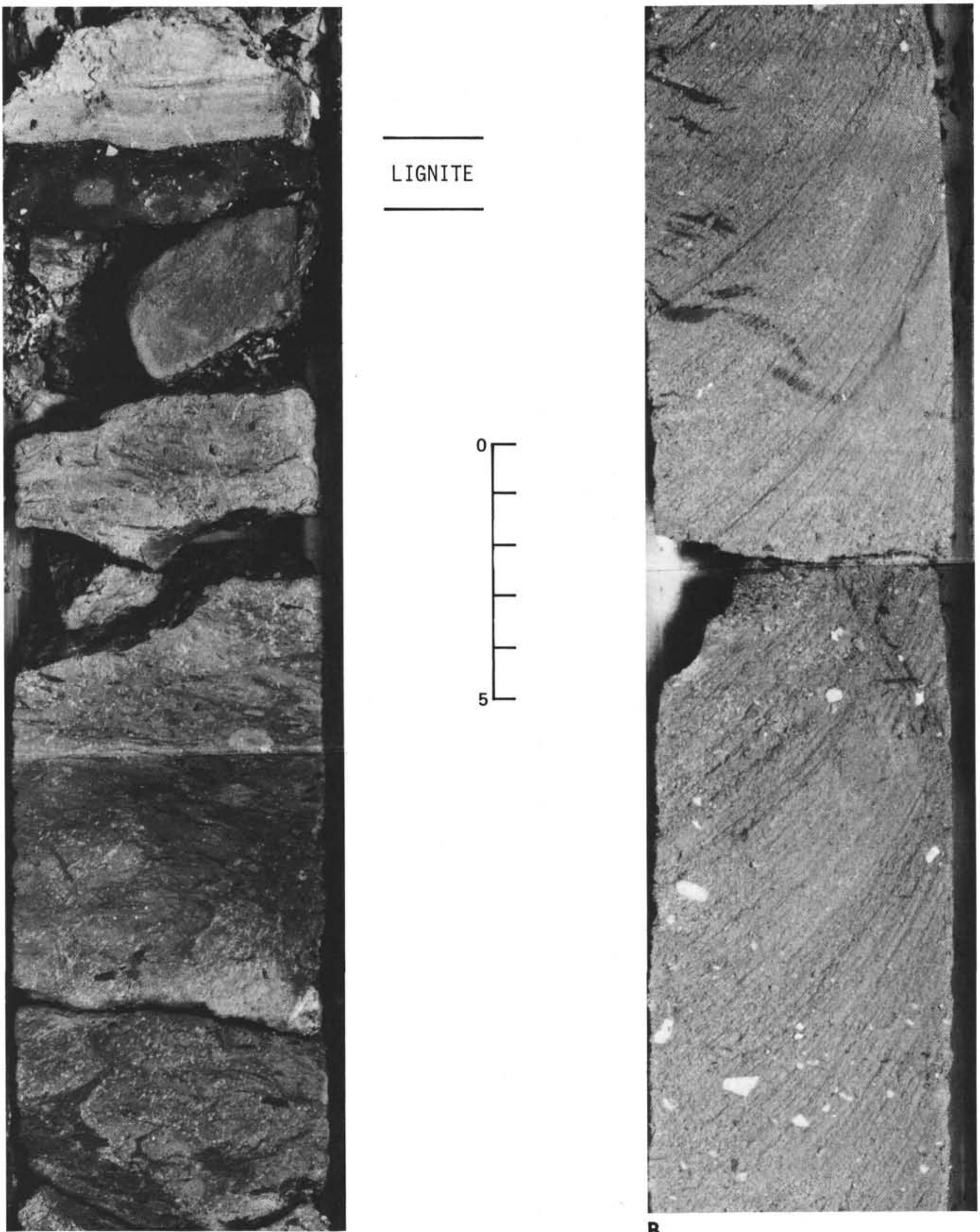

Figure 4. *Representative cores from basal subaerial sediments, lower Site 330. (A) Sample 330-15-2, 60-64 cm, mottled silstone and lignite from upper part of "cycle"; (B) Sample 330-15-1, 64-87 cm, sandstone with angular quartz and feldspar granules and lignite clasts from middle part of cycle. See Figure 2 for location in the section. Scale in cm.*

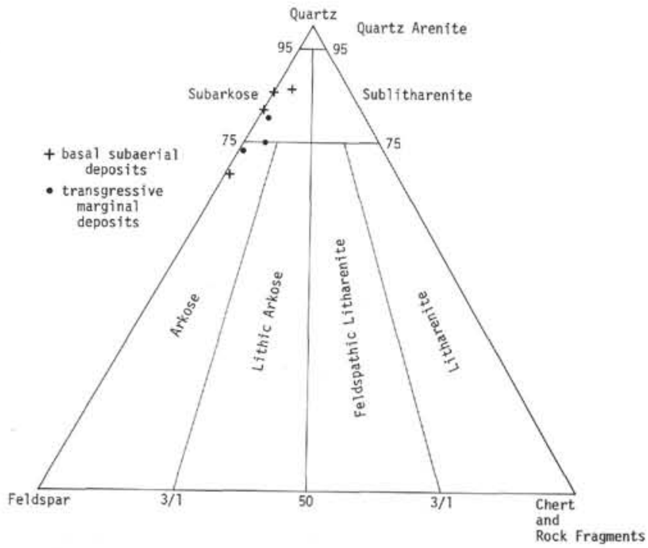

Figure 5. *Light mineral composition of sand fraction (0.062-2 mm) from Middle (?) -Upper Jurassic sediments, Site 330. Classification after Folk, 1974.*

and very poorly sorted; the nonopaque heavy mineral fraction is composed solely of angular grains of yellowish-brown tourmaline (Table 1). Kaolinite makes up greater than 80% of the clay fraction ($<2\ \mu m$). This unusual mineralogy coupled with the softness and lack of obvious sedimentary texture suggest this section represents part of an old soil profile which developed on the gneissic basement prior to burial. This is underlain by highly calcitized gneiss (calcrete), presumably also part of an old soil profile, and is capped by a 3-cm layer of lignite which may either be a remnant of an old A-horizon or related to the overlying alluvial fill.

The overall impression of the Middle (?) to Upper Jurassic sedimentary conditions on the Falkland Plateau gained from this section is that of an irregular basement topography being gradually buried by debris shed from the fairly immediate surroundings. Isolated hills remained protruding above flood plains of probably restricted extent and occasionally shed very coarse material onto the flood plain surface. The common occurrence of kaolinite in the sediments, the low content of plagioclase compared to the underlying gneiss, and the abundance of fragmental plant remains plus lignite all argue for substantial rainfall and chemical weathering. On the other hand, the calcrete developed on the gneissic basement implies conditions of low to moderate rainfall. Thus, the possibility exists that the calcrete formed under earlier, more arid conditions and that a significant time gap, marked by a change to a more humid climatic regime, may separate the calcitized gneiss from the overlying kaolinite-rich soil zone.

MIDDLE (?) TO UPPER JURASSIC MARINE TRANSGRESSION

A clean, olive-gray sandstone of unknown thickness occurs at the top of the basal sandy section penetrated at Site 330. This sand is medium in size, well sorted, and composed principally of subangular to subrounded quartz (87%). Compositionally, the sand is very similar to that in the underlying sediments (Figure 5, Table 1) with the exception of the notable lack of organic detritus. The well-sorted nature of this sand indicates a high energy environment of deposition, and the size and mineralogy are consistent with what would be expected by extensive reworking of the underlying sediments. Furthermore, it occurs between definite marine sediments above and subaerial sediments below. Accordingly, this sand is interpreted to represent part of an ancient beach deposit and to mark the inception of a Middle (?) to Late Jurassic marine transgression across this part of the Falkland Plateau.

The beach sand at Site 330 is overlain by a section of marine silts and clays (marginal deposits) estimated to be about 115 meters thick. These occur at subbottom depths of 425 to 540 meters. The marine origin of this sequence is indicated by the occurrence of Belemnite rostra, occasional layers of pelecypod remains, and thin interbedded limestones. A few coccoliths and benthonic foraminifera (chiefly agglutinated types) are found scattered through the section. None of the faunal remains are of much use in age dating. However, pollen analysis indicates that most of the section is Upper Jurassic (Oxfordian) in age with possible Middle Jurassic near the base.

The dominant sediment types in this section are clayey silts and silty clays (Figure 3). These occur interstratified through the section in 10 to 50 cm beds. However, silt beds predominate in the lower section whereas clays become pervasive in the upper section. Beds of clean silt and sand-silt-clay, the order of 10-20 cm thick, occur throughout but are particularly common in the lower half of the section. These coarser beds typically have a mottled structure which probably reflects extensive bioturbation whereas lamination on a scale of 1 to 3 cm is characteristic of most of the silty clay layers (Figure 6).

Petrographic examination of the sand fraction and X-ray analysis of the silt fraction show these sediments to be similar mineralogically to the underlying sands (Figure 5, Table 1). Typical quartz-feldspar ratios are on the order of 2 to 4 with K-feldspar clearly prevalent over plagioclase. The heavy mineral suite is dominated by authigenic pyrite; however, garnet, tourmaline, and zircon prevail in the nonopaque fraction. Persistent heavy minerals noted here which were not seen in the coarser underlying sediments include apatite, pyroxene, epidote, rutile, and cassiterite. This difference plus the somewhat higher plagioclase content of these sediments probably are due in part to sorting; however, they also may indicate a more diversified provenance as the site became more remote from the source area. Other characteristics of these sediments which imply increasing distance from the source area or, at least, waning terrigenous supply, include: (1) the upward fining in texture from predominantly silt with a significant sand admixture to predominantly clay; (2) decreasing content of kaolinite and corresponding increase in illite in the clay and fine silt fraction; (3) a progressive change from mainly land-derived (structured) organic detritus in the

TABLE 1
Petrographic Analyses of Sand Fraction from Middle(?)-Upper Jurassic Terrigenous Sediments, Site 330

Sample (Interval in cm)	Percent (by number) of Nonopaque Heavy Mineral Fraction S.G. > 2.9								Lithology and Lithofacies
	Garnet	Tourmaline	Zircon	Apatite	Pyroxene	Other[a]	Altered	Opaque[b]	
13-4, 73	47	19	7	7	3	12	5	75	Sand-silt-clay; marginal deposits
13-4, 80	62	17	6	2	1	5	7	64	Sandstone; marginal deposits
15-1, 10	79	16	3	–	–	–	2	41	Sandstone; transgressive beach
15-1, 30	81	9	9	–	–	1	–	8	Silty sandstone; subaerial deposits
15-2, 26	60	31	5	–	1	1	2	47	Silty sandstone; subaerial deposits
15, CC	–	100	–	–	–	–	–	13	Clayey sand; soil (?)
Mean ($\bar{X}$)	66	18	6	2	1	3	4	47	Excludes Sample 15, CC

Sample (Interval in cm)	Percent (by number) of Light Fraction					Quartz/Feldspar	Lithology and Lithofacies
	Quartz	K-feldspar	Plagioclase	Rock Fragment	Other		
12-3, 89	72.5	18	8	1	0.5	2.8	Sand-silt-clay; marginal deposits
13-4, 73	75	16	5	4	–	3.6	
13-4, 80	80	15	3	2	–	4.4	
15-1, 10	87	9	1	3	–	8.2	See
15-1, 30	86	11	3	–	–	6.1	above
15-2, 26	82	6	12	–	–	4.5	
15, CC	68	30	0.5	1	0.5	2.2	
Mean ($\bar{X}$)	78	15	5	2	tr	4.5	

Note: Heavy minerals (S.G. > 2.9) in very fine-fine sand fraction (0.062-0.25 mm). Light minerals in total sand fraction (0.062-2 mm). Determinations on grain mounts etched with HFl and stained with sodium cobalt-nitrate. Mica not counted.

[a]Principally epidote, rutile, cassiterite.

[b]Core 13 – mainly pyrite; Core 15 – mainly magnetite, ilmenite (?), leucoxene.

lower section to a mixed organic fraction containing both land-derived and marine (sapropelic) material in the upper section; (4) an upward increase in the frequency of limestone interbeds in the section.

Little definitive evidence upon which to base an interpretation of depositional environment exists in this sequence. The subtle alternation of textural types into thin beds indicates an environment of moderate but fluctuating currents and terrigenous sediment supply. The occurrence of occasional sandstones, common evidence of extensive bioturbation, and presence of thin layers of fragmented pelecypod shells (assuming they were benthonic types) imply periods of reworking and the probability of reasonably well-aerated bottom conditions. The preponderance of silt and clay, generally laminated and containing an abundance of land-derived detritus, imply that sediment supply, though apparently quite variable, was substantial and may indicate the presence of a river mouth situated in the general vicinity. Finally, interpretation of the seismic reflection record suggests that the Upper Jurassic sediments at this site were deposited on a low gradient surface in close proximity to a much steeper basin slope to the southwest (Barker, this volume). The geometry is suggestive of a continental margin though probably the adjacent basin floor was of less than oceanic depth. All lines of evidence seem consistent with the interpretation of a continental shelf as the depositional environment for this sequence.

The origin of the thin, olive-gray limestones intercalated in this section remain an enigma which is discussed in more detail below. In this part of the column, most of the limestones are partially to completely recrystallized into sparry or microsparry calcite, often containing a significant admixture of terrigenous silt and sand. Several samples examined in thin section from the middle part of the section (Core 13, Site 330), however, contain recognizable allochems of gastropods, pelecypods, echinoid spines, and possible coral along with about 10%-15% of angular, medium to coarse quartz and feldspar. Assuming these sediments have not been redeposited, their presence implies the persistence of local (?) bedrock shoals on which reefs were developed. Notably, seismic reflection records in-

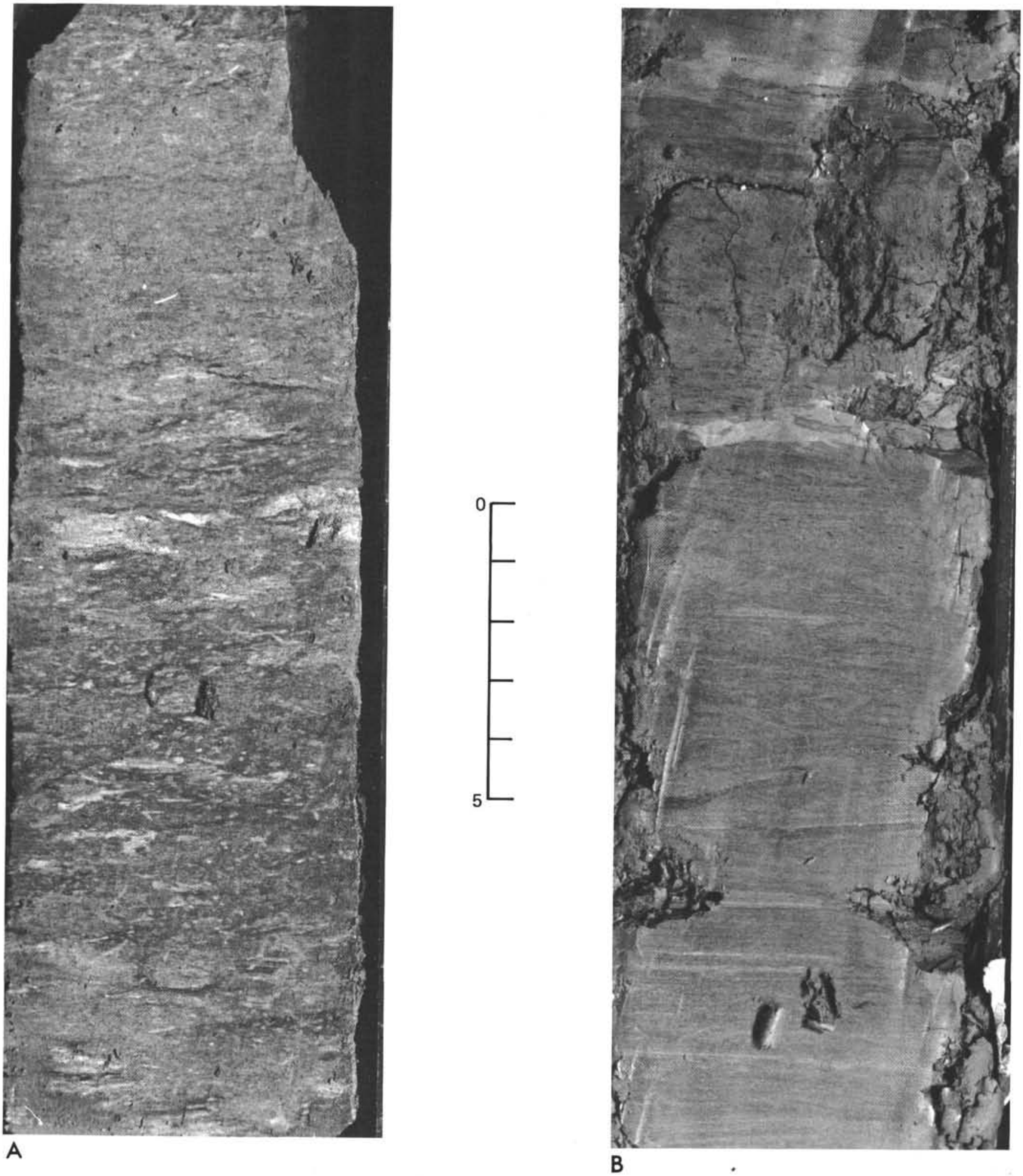

Figure 6. *Representative cores from Upper Jurassic marginal deposits, Site 330. (A) Sample 14-2, 50-70 cm, bioturbated clayey silt; (B) Sample 12-5, 29-49 cm, laminated to bedded silty clay. Scale in cm.*

dicate that Site 330 is situated over a protuberance in the underlying bedrock. Whereas this basement hill appears to have been buried at this locality by Late Jurassic time, similar features to either side of the line of section may not have been. Thus, the possibility of shelf-edge reef development is raised, and this, in turn, raises the possibility of conditions conducive to the formation of lime mud. Hence, limestones in the section

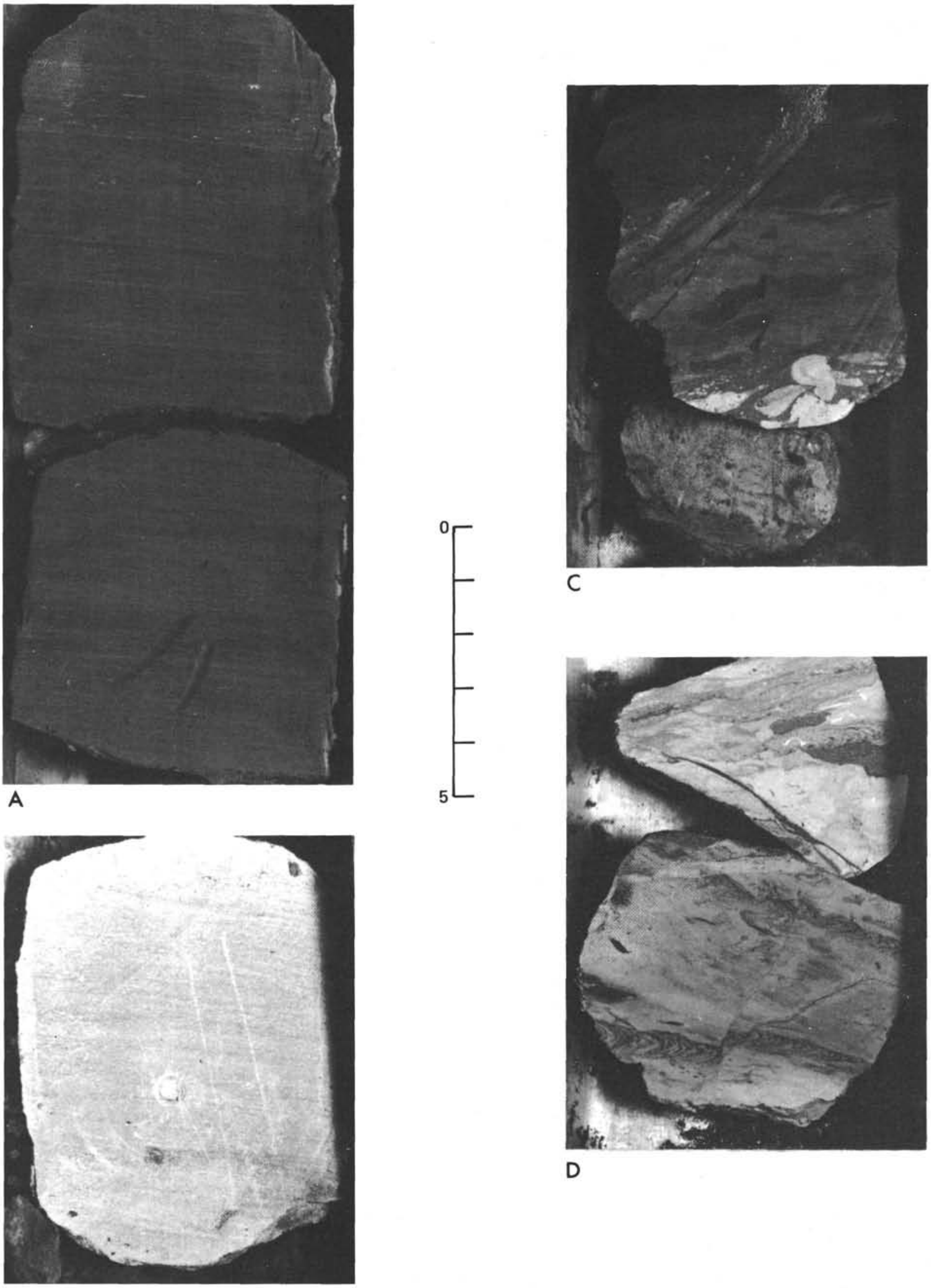

Figure 7. *Representative cores from Lower Cretaceous carbonaceous claystones, Hole 327A. (A) Sample 26-1, 130-144 cm, laminated sapropelic claystone; (B) Sample 26-2, 0-7 cm, laminated micritic limestone; (C) Sample 22-2, 60-70 cm, bioturbated carbonaceous claystone; (D) Sample 22-2, 23-32 cm, bioturbated micritic limestone. Scale in cm.*

which lack evidence of coarser debris and generation by reworking may represent either recrystallized coccolith ooze as suggested for the overlying section (see below), or recrystallized lime mud of some other origin.

UPPER JURASSIC-LOWER CRETACEOUS EUXINIC CONDITIONS

Beginning in Upper Jurassic (Oxfordian) time and lasting into the Lower Cretaceous (Aptian), euxinic conditions prevailed on the eastern Falkland Plateau as evidenced by the accumulation of olive-black carbonaceous claystones. These rocks are typically well laminated, contain an average of 3%-4% organic carbon, and are characterized by a very restricted benthonic fauna composed mainly of thin-shelled pelecypods and a few agglutinated foraminifera (Figure 7). Such sediments were encountered at subbottom depths of about 200 to 425 meters at Site 330, and from 325 meters to the bottom of the hole at 470 meters at Hole 327A (Figure 8). At Site 330, a jump from probable Oxfordian-Kimmeridgian to Neocomian-Aptian sediments over the unsampled depth interval between 275 and 300 meters indicates a period of either very slow sedimentation rates or a significant hiatus.

Clay and slightly silty clay are the principal textural types occurring in this part of the section (Figure 3), thus continuing the trend of decreasing particle size witnessed in the underlying units. The clay fraction is dominated by illite and montmorillonite with a noticeable and perhaps significant trend of decreasing illite/montmorillonite ratio upward in the section (Figure 8). The persistent though small (10%-25%) silt fraction is composed principally of quartz, K-feldspar, and mica along with probable biogenous remains. Coarse fractions (>62 μm) examined from the claystones consist almost exclusively of carbonized plant remains, *Inoceramus* prisms, and other pelecypod shell fragments. Only a trace of terrigenous sand is present, this being most conspicuous near the base.

The most obvious variations in composition and character of the claystone section relate to type and abundance of organic carbon, percentage of limestone interbeds, and the $CaCO_3$ content. These are summarized graphically in Figure 8. In compiling these plots, the entire section at Hole 327A has been shifted downward by 50 meters from its actual position relative to Site 330, as suggested by age correlation between the sites based on pollen and nannoflora.

Organic carbon content shows a gradual increase from 1% to 2% in the underlying terrigenous silts and clays (marginal deposits) to a value of about 4.5% in the Upper Jurassic carbonaceous claystones. Maximum values of nearly 6% are found in the early Aptian claystones at both sites and the organic content drops off to less than 1% in the overlying Albian sediments. Most of the organic carbon is yellowish-brown, sapropelic (amorphous) material of probable planktonic origin; however, a significant admixture of structured kerogen (land-derived) occurs in the lower 100 meters of the claystone section and reappears again near the top, in the late Aptian (Komer and Littlejohn, this volume).

The quantity of calcium carbonate in the claystones and the percentage of limestone interbedded in the section vary in a fashion much as the organic content. Both components increase upward in the section and peaks in their abundance in late Oxfordian and early Aptian correspond broadly to more subtle peaks in the organic carbon content. The obvious exception to this correspondence is in the early Albian where organic content drops abruptly while $CaCO_3$ continues to increase. Investigation of smear slides shows that variations in the carbonate content of the claystones relate primarily to the quantity of nannofossils present; thus the fluctuations shown in Figure 8 are thought to reflect mainly changes in the balance between terrigenous and biogenous supply. The nature of the limestones examined from this part of the section supports this view. Typically these contain the order of 20%-40% allochems, principally Radiolaria, which in most cases have been replaced with sparry-microsparry calcite or authigenic silica. The allochems are set in a matrix composed of mixed clay and micrite or microspar which is laminated on a millimeter scale much as the encasing claystones (Figure 7). Traces of nannofossils are present in many of the Cretaceous limestones where micrite prevails in the matrix, but absent in the Jurassic limestones where microspar dominates due presumably to recrystallization. Thus, most of the limestones appear to have originated as clayey, radiolarian-rich, nanno oozes, and they are interpreted to represent intervals of increased biogenous input relative to terrigenous rather than episodic bottom aeration or redeposition of lime mud generated elsewhere.

Available evidence indicates that fluctuations in abundance of organic carbon, calcium carbonate, and limestone interbeds in the sapropelic claystones reflect variations in the relationship between terrigenous input and plankton productivity combined with changing conditions of bottom aeration. Accordingly, one may propose a steady decline in terrigenous input during the Upper Jurassic which was accompanied by the development of poorly oxygenated (euxinic) bottom conditions. Productivity may have increased during this same interval in response to decreased water turbidity and onset of more open-marine surface conditions. This was still apparently a marginal marine environment, however, as indicated by rather high sedimentation rates of the predominantly terrigenous clays, the order of 20-25 m/m.y. Very similar conditions prevailed during late Neocomian-early Aptian time, but in late Aptian terrigenous supply apparently increased again. This is evidenced by the low $CaCO_3$ content of the claystones, the decline in abundance of limestone, and the reappearance of land-derived kerogen. As discussed below, other changes are apparent in this part of the section which imply somewhat improved bottom circulation and presumably herald the onset of more typical pelagic sedimentation conditions which have prevailed here since early Albian time.

Considerable interest from the tectonic viewpoint centers on the interval between Oxfordian-Kimmeridgian and earliest Aptian, the time during which rifting between Africa and South America is thought to have occurred (Larson and Ladd, 1973). This 35-40 m.y. interval is represented in the uncored section between Cores 4 and 5 at Site 330 and probably

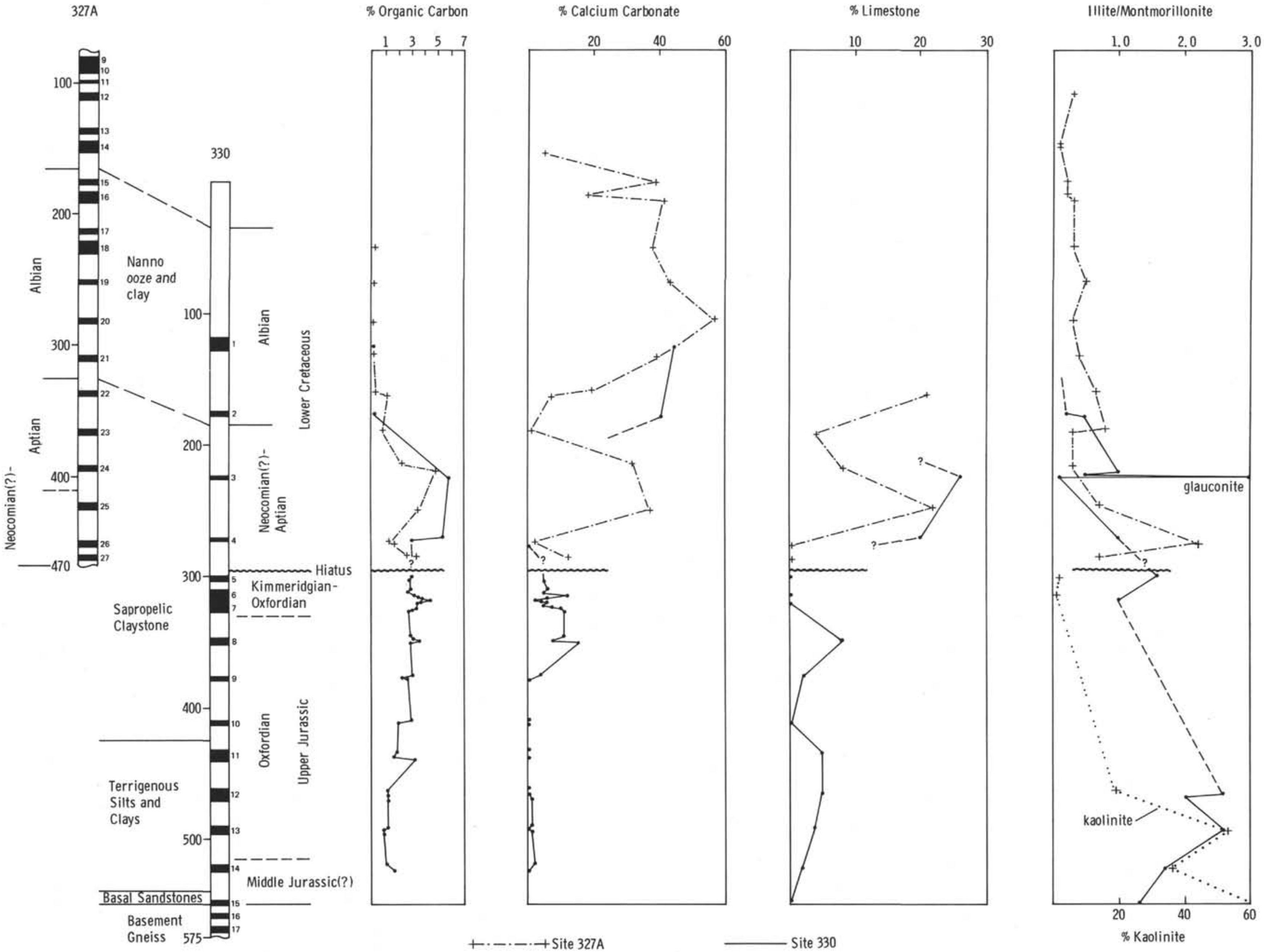

Figure 8. *Graph showing compositional variations in the Jurassic-Lower Cretaceous sediments of Holes 327A and 330. For data on organic carbon, calcium carbonate and clay mineralogy, see Appendix. Limestone values represent aggregate thickness of limestones as percentage of recovered core length. Clay mineral values are for combined <2 μm and 2-20 μm fractions.*

lies a short distance below the bottom core of Hole 327A (Figure 8). The lowermost cores of Hole 327A (Neocomian-early Aptian) and youngest Jurassic cores of Site 330 (Oxfordian-Kimmeridgian) are all characterized by well-laminated sapropelic claystones with moderate to high organic contents, relatively low $CaCO_3$, and a virtual absence of limestone. Those limestones that do occur (Core 5, Site 330) consist mainly of coarse fibrous calcite which appears to have grown by replacement in preexisting claystone. No allochems are present.

Using the reasoning outlined above, one might argue that terrigenous supply increased in Oxfordian-Kimmeridgian time and was likewise relatively high in Neocomian-early Aptian, thus accounting for the low $CaCO_3$ and absence of limestone. This would imply a pronounced hiatus due to nondeposition or erosion somewhere in the interval to account for the thin section. Such would allow for a proposal of uplift and erosion at or near the site in synchroneity with the separation of Africa and South America. The presence of reworked Jurassic palynomorphs in the Neocomian-Aptian claystones appears to support this view. It seems rather fortuitous however, that virtually identical, euxinic environments would precede and follow such an event. An alternative argument, supported by the apparent continuity of sedimentation conditions across this time interval, is that this area was part of an extremely starved basin in Late Jurassic, one to which both terrigenous and biogenous supply continued, but at a very slow rate. Age considerations allow a maximum sedimentation rate during the interval of about 1-2 m/m.y. Development of an intervening sediment trap during the rifting process might account for low terrigenous supply. This possibility is discussed in the subsequent section concerning tectonic events. Low biogenous supply would most likely reflect some change of surface water conditions which the planktonic coccolithophores could not tolerate. Substantial fresh water inflow with consequent reduced salinity of the surface waters in this restricted basin is one obvious possibility. Salinity change is offered as the explanation for a somewhat similar change from coccolith ooze to sapropelic clay in Holocene sediments of the Western Black Sea (Ross and Degens, 1974; Bukry, 1974). Supporting evidence for this possibility on the Falkland Plateau is provided by the occurrence of the coccolithophore, *Braarudosphaera*, including a braarudosphaerid limestone (Core 3, Site 330), in early Aptian cores at both sites (see discussion by Wise and Wind, this volume). Bukry (1974) points out that concentrations of this coccolith, both modern and ancient forms, are most common in coastal waters of low salinity. In the Black Sea, they are particularly common in sediments marking the transition from earlier less saline conditions to those of the present with surface salinities the order of $17^0/_{00}$-$18^0/_{00}$.

LOWER CRETACEOUS (ALBIAN) OPEN MARINE SEDIMENTATION

By early to middle Albian time, conditions of open marine (pelagic) sedimentation prevailed on the eastern Falkland Plateau. This is evidenced by the occurrence of light brown, yellowish-gray, and pink nannofossil clay, ooze, and chalk which were encountered at sub-bottom depths between about 120 and 200 meters at Site 330, and 155 and 323 meters at Hole 327A. Fragmented pelecypod remains (including *Inoceramus*), in some cases reworked into thin coquina layers, evidence for moderate to intense bioturbation, and a well-diversified benthonic foraminiferal fauna are found throughout this section. The organic carbon content is consistently well below 1% (Figure 8). Clearly, well-oxygenated bottom conditions were established at these sites by early-mid Albian time. Furthermore, the appearance of a significant planktonic foram assemblage, which becomes more profuse upward in the section, and concomitant decrease in the clay mineral content relative to biogenous constituents, reflect the onset of more normal marine conditions which probably relate to increased distance from the terrigenous source. Possible additional evidence of the waning influence of continental runoff is the shift to predominance of montmorillonite over illite among the clay minerals and the common occurrence of clinoptilolite. The persistence of braarudosphaerids, however, may indicate continued conditions of somewhat lower than normal salinity.

Reoxygenation of the bottom waters here could have resulted from any one of a number of causes. A few obvious possibilities include: (1) subsidence below an oxygen minimum zone; (2) relative lowering of the boundary between well-oxygenated surface water and poorly oxygenated deeper water; (3) improved bottom circulation and elimination of euxinic conditions in the entire basin. The actual cause is unknown, although (3) appears most likely as discussed below in conjunction with tectonic events. Whatever the reason, initial stages of this reoxygenation apparently began in late Aptian time. In the uppermost part of the carbonaceous unit at Hole 327A, many of the claystones and virtually all of the limestone interlayers show evidence of bioturbation (Figure 7). Even the occasional undisturbed claystone sections are characterized by thin bedding (occasionally graded) with apparent textural variations rather than the paper-thin lamination of the sapropelic claystones beneath. This argues for increased current activity and possibly some redeposition. By this point in time, then, the eastern Falkland Plateau appears to have been just that, a submerged plateau or bank elevated above the sea floor to the north and south, and relatively isolated from the influence of continental runoff from Africa. The breach between this part of South America and Africa apparently was complete by early-middle Albian time.

RELATION OF SEDIMENTATION TO TECTONIC EVENTS

Reconstruction of Gonwanaland and closing of the South Atlantic based on the tenets of sea-floor spreading and plate tectonics imply that the southern tip of Africa fit into the southwestern extremity of the Argentine Basin and that the Falkland Plateau was situated along the southeast coast of Africa, extending from Agulhas Bank to about the vicinity of Durban (Figure 9; Dingle and Scrutton, 1974). The finding on

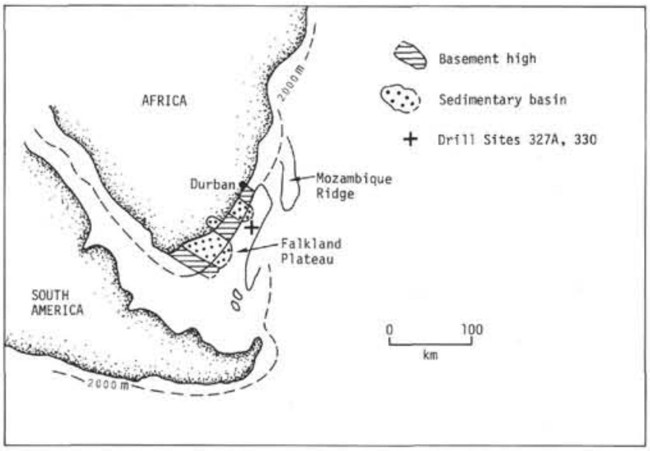

Figure 9. *Relationship of Falkland Plateau to South Africa in mid-late Jurassic, prior to breakup of western Gondwanaland. Modified from Dingle and Scrutton, 1974.*

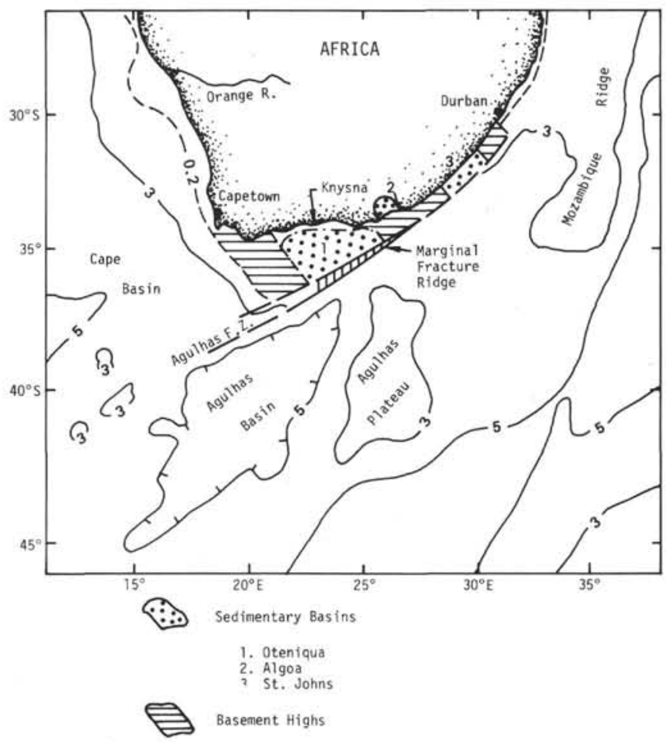

Figure 10. *Bathymetric map around southern Africa showing structural elements of the South African continental margin. Contours in km. Compiled from Scrutton (1973); Dingle and Scrutton (1974).*

the Falkland Plateau of continental basement rocks which may well correlate with Precambrian metamorphic rocks cropping out along the southeast coast of Africa in the vicinity of Durban offers support for such a reconstruction (Tarney, this volume). As discussed below, the comparison of Mesozoic stratigraphy on the plateau with that of southeast Africa provides additional supporting evidence, and the tectonic events involved in the formation of the southeast African continental margin offer clues to the interpretation of the sedimentary record on the Falkland Plateau.

According to Dingle and Scrutton (1974), the last major tectonic event to affect the southeast coast of Africa prior to the breakup of Gondwanaland was a late phase of the Cape Orogeny which occurred in late Paleozoic-early Mesozoic time, on the order of 200-235 m.y.B.P. This resulted in the formation of northwest-southeast trending faulted folds (Cape Fold Belt) and intervening basins (Figure 10) in the area of the present coast and adjacent continental margin, and initiated a cycle of erosion and intermontane basin filling. Seismic evidence indicates that these sedimentary basins are truncated on their southeastern margins along the line of the Agulhas Fracture Zone (Dingle, 1973; Francheteau and Le Pichon, 1972), hence presumably they formerly extended onto the Falkland Plateau (Figure 9; Dingle and Scrutton, 1974). The Mesozoic stratigraphy in these basins is not well known; however, the initial phase of sedimentation, perhaps beginning as early as late Triassic and lasting at least into Middle to Late Jurassic, was characterized by accumulation of nonmarine conglomerates and sandstones. These sediments, described from outcrops around the Algoa Basin (Figure 10) as detrital fans and assigned to the Enon Formation (Dingle, 1973), were shed into the steep intermontane basins of the Cape Fold Belt and their accumulation resulted in basin coalescence and burial of "the rugged early Mesozoic landscape." The basal sandy sediments encountered at Site 330 are consistent with this interpretation based on their lithologic characteristics. Furthermore, seismic reflection evidence indicates that these sediments represent but a wedge edge of a much thicker sequence (>500 m) which has "filled" a low in the basement topography immediately northeast of the site (see Barker, this volume).

The earliest evidence for marine transgression found in Mesozoic sediments along the southeast coast of Africa is the occurrence of Upper Jurassic shallow marine clays at Knysna (Figure 10) and in the Algoa Basin. These mark temporary marine incursions, and in the Algoa Basin they pass vertically and laterally into paralic sediments of the Kirkwood Formation. Full marine conditions were established by Neocomian time with deposition of shallow marine sediments of the Sundays River Formation (Dingle, 1973). Both of these formations are diachronous and become younger toward the north. The earliest marine sediments at Site 330 are Middle (?) to Late Jurassic in age, and these are followed upward by a sequence of silts and clays, the lithologic and faunal characteristics of which imply deposition on a fairly shallow shelf that became progressively further removed from the source area. Taken together, the sequences indicate a marine transgression from southeast to northwest across the Falkland Plateau in Middle (?) to Late Jurassic time. Scrutton (1973) proposed that eastern Gondwanaland (Antarctica, India, Australia) separated from western Gondwanaland (Africa, South America) along the southern margin of the Falkland Plateau in Middle Jurassic time. This implies that the basement slope south of Site 330 represents part of a rifted continental margin and that the aforementioned transgression across the eastern Falkland Plateau and onto southeast Africa reflects the extension of a narrow arm of the

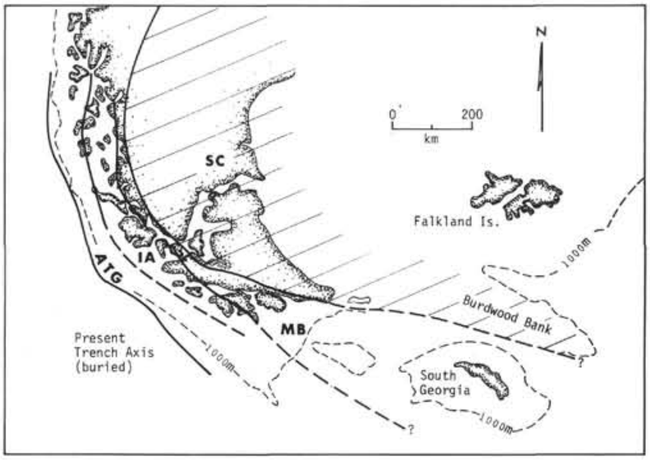

Figure 11. *Diagram showing main tectonic elements of southernmost South America in Early Cretaceous time. ATG - arc-trench gap; IA - island arc; MB - marginal basin; SC - stable continent. Adapted from Dalziel et al., 1975.*

proto-Indian Ocean, the earlier history of which is documented in eastern Africa and Madagascar (Kent, 1974). According to this supposition, the eastern Falkland Plateau was part of the gradually subsiding southeast African continental margin during Late Jurassic time, and the terrigenous silts and clays of this age at Site 330 represent marginal deposits which, for the most part, were supplied from the northwest, that is, the African land mass.

Working from the South American side, a rather different picture of the situation evolves. Based on their mapping in Patagonia and Tierra del Fuego, Dalziel et al. (1974a) have proposed the existence of a marginal basin in southernmost South America which opened in Late Jurassic and persisted at least through Aptian times (Figure 11). This basin separated the stable continental block (southeastern South America-southern Africa) from an andesitic volcanic arc on the Pacific side, the roots of which are marked by the Patagonian batholithic belt of southern Chile. Their reconstruction shows this marginal basin widening to the southeast, and they propose that the volcanic arc continued into the Antarctic Peninsula. Recent work by Suarez (1976) substantiates this proposal and also divulges evidence for the existence of a Late Jurassic-Early Cretaceous back arc (marginal) basin along the east side of the Antarctic Peninsula. Just how the subduction activity involved in opening this basin relates to rifting along East Africa is not clear; however, the proposal implies that the Falkland Plateau was not part of a true continental margin, but rather a shelf area flanked by less than oceanic depths of a marginal basin (Dalziel et al., this volume). The early marine facies at Site 330 seem equally consistent with this hypothesis. Furthermore, one must speculate that Late Jurassic shallow marine sediments found in the Magallanes Basin (Natland and Gonzalez, 1974) reflect a continuation of this same shelf seaway into southern Argentina and Chile.

The specific cause for the onset of euxinic conditions and deposition of sapropelic claystones on the eastern Falkland Plateau is unknown; however, the age of these sediments, Upper Jurassic (Oxfordian) through Aptian, indicates they are related in some way to the initial fragmentation of Gondwanaland and opening of the South Atlantic. The fact that similar sediments of about this same age are widespread in the South Atlantic supports this view (Figure 1). Dark carbonaceous shales have been reported, for example, from the Magallanes Basin of southern South America (Natland and Gonzalez, 1974; Dalziel et al., 1974b) where they are Upper Jurassic (Kimmeridgian) to Early Cretaceous (Aptian) in age; from the Cape and Angola basins (Bolli, Ryan, et al., 1975) where respectively they are lower Aptian and upper Aptian to Coniacian; and from the Mozambique Ridge (Simpson, Schlich, et al., 1972) where they are Neocomian-Aptian in age. Available evidence suggests a progression in age of the South Atlantic euxinic facies from oldest at the south to younger further north; this also argues for association with the opening of the South Atlantic.

One possible circumstance which might have caused the stagnation and onset of euxinic conditions in these basins is the combination of density stratification in the water column and restricted deep water circulation due to the existence of relatively shallow bathymetric ridges or sills. Many Quaternary examples of sapropelic mud deposition apparently are (or were) caused by such a situation, for example, in the Adriatic (van Straaten, 1972), the eastern Mediterranean (Ryan, 1972), and the Black Sea (Ross and Degens, 1974). In the South Atlantic region, density stratification might have been the product of runoff from South America and Africa into the initial semiisolated basins; this was perhaps enhanced by warming of the surface waters. The Falkland Plateau could well have provided the restricting sill for the Cape Basin in Early Cretaceous time much as the Walvis Ridge did for the Angola Basin (Bolli, Ryan, et al., 1975), since the eastern end of the plateau is not thought to have cleared the tip of Africa until Albian (Dingle and Scrutton, 1974). What feature, then, restricted circulation in the earlier basin situated south of the Falkland Plateau? The Agulhas Plateau (Figure 10), thought by Scrutton (1973) to represent an abandoned segment of the early Mid-Atlantic Ridge, is one possibility, however several factors argue against this. First and most obvious is the depth. The crest of the Agulhas Plateau is presently at depths of about 2500-3000 meters. Whereas the feature may have subsided since initial formation, it is doubtful that the crest was ever shallow enough to restrict circulation in the 200-500 meter depth range, the estimated depositional depth of the euxinic facies on the Falkland Plateau and in the Magallanes Basin. Second is the age. The oldest rocks thus far dredged from Agulhas Plateau are Coniacian (Scrutton, 1973). While the oceanic basement rocks of the plateau are likely to be older, still one must question whether in fact the feature even existed prior to the spreading episode which separated Africa from South America, an episode which apparently postdates inception of euxinic conditions. Finally, supposition of the Agulhas Plateau as the restricting feature for areas to the west would still necessitate looking for an additional restriction to the northeast to account for the Early Cretaceous euxinic sediments on the Mozambique Ridge.

A second, and seemingly more likely, possibility is a shallow restriction in the Late Jurassic seaway between East Africa and East Antarctica. A tempting prospect here is the vicinity of Mozambique where many authors (e.g., Dietz and Sproll, 1970; Smith and Hallam, 1970) place the Princess Martha coast of Antarctica in Gondwana reconstructions. The euxinic sediments of the Mozambique Ridge (Site 249) would thus have originated in the same restricted basin as those to the west. Possible support for this contention is the evidence of widespread basalt extrusion in Mozambique and Madagascar beginning in Neocomian-Aptian time and lasting to Albian-Coniacian (Kent, 1974; Vallier, 1974). This may reflect the complete breakthrough of this seaway and the beginning of subsidence to oceanic depths. Recent investigation quoted by Kent suggests seismic continuity between the Early Cretaceous (?) basaltic basement drilled at Site 249 on the Mozambique Ridge and continental basalt extrusions in Mozambique; this argues for possible shallow water origin of the former as suggested by Vallier (1974).

Another aspect of the euxinic sediments on the Falkland Plateau which deserves further inquiry regards their very fine grained nature and, particularly, any reason for possible conditions of very low terrigenous supply and slow sedimentation rates near the Jurassic-Cretaceous boundary as suggested above. These are in marked contrast to euxinic sediments in the Cape Basin, for example, which occur interbedded with rapidly deposited coarse terrigenous material (mudstones and sandstones) presumably supplied largely by the ancestral Orange River drainage (Bolli, Ryan, et al., 1975).

Southeast Africa and the Falkland Plateau are thought to have separated by strike-slip motion along what are now the Agulhas and Falkland fracture zones (Francheteau and Le Pichon, 1972; Scrutton, 1973). Estimates of the time of inception of this event and rates of subsequent spreading motion involved in the initial opening of the southernmost Atlantic vary considerably. Larson and Ladd (1973) estimate initial opening to have occurred in the Neocomian (125-130 m.y.B.P.) based on their interpretation of magnetic lineations in the Cape Basin. Recently, however, these anomalies were reinterpreted by Emery et al. (1975) to indicate initial opening in the Middle to Late Jurassic (165 m.y.B.P.). In view of the uncertainty, it does not seem unreasonable to suppose that initial fragmentation, prior to the actual spreading and separation of Africa and South America, commenced in the Upper Jurassic. Then, using the spreading history of Larson and Ladd (1973) and assuming the eastern end of the Falkland Plateau originally lay near Durban, the area of the drill sites would have been situated about adjacent to Agulhas Bank in middle to late Aptian, and would have become progressively further removed from continental influence during Albian time as the eastern tip of the plateau cleared the corner of Africa. It is of some interest to review the stratigraphic record at Site 330 and Hole 327A in this light.

In Late Jurassic time, the sedimentary environment at Site 330 changed from one dominated by terrigenous silts and clays with occasional coarser beds to one characterized by accumulation of very fine grained carbonaceous claystones. The change was gradual and probably reflects a combination of reduced relief in the source area, increased remoteness of the depositional site due to the transgression, and slow subsidence of the African margin into deeper, poorly oxygenated waters of the marginal basin to the south. The rather high sedimentation rates (20-25 m/m.y.) and the persistent admixture of terrestrial palynomorphs in these early claystones indicate that sediment supply from land remained substantial during this time. Beginning in the Oxfordian-Kimmeridgian (Core 7, Site 330) and lasting into the late Neocomian-early Aptian, the possibility of exceptionally low terrigenous supply was suggested above to account for the very thin (or missing) section. The reason for this change may well relate to the development of an intervening sediment trap along the Agulhas-Falkland transform fault zone. Perhaps enlightening in this regard is the observation by Scrutton and du Plessis (1973) of a basement ridge running beneath and parallel to the slope northeast from Agulhas Bank (Figure 10). The crest of this "marginal fracture ridge," the origin of which they relate to strike-slip faulting, is now at a depth of about 2000 meters, but data from Dingle (1973) imply the possibility of at least 1500 meters of marginal subsidence since Early Cretaceous time. The ridge, then, could have isolated the plateau sites from significant terrigenous input in Late Jurassic-Early Cretaceous time and thus account for very slow sedimentation rates. Indeed Dingle states: "If Scrutton and du Plessis's (1973) dating of the formation of the Agulhas marginal fracture ridge is correct (Late Jurassic-Early Cretaceous) then the late Uitenhage group sediments were dammed behind a high ridge—earlier representatives of the group were deposited before southern Africa separated from the Falkland Plateau." The early representatives of the Uitenhage Group probably correspond to the terrigenous silts and clays (marginal deposits) and underlying subaerial sands of lower Site 330, as discussed above. Furthermore, uplift of such a ridge could provide a situation which allowed reworking of Late Jurassic sediments as indicated by the palynology of the early Aptian claystones. Going one step further, one must suspect that increased terrigenous supply in middle-late Aptian, as suggested by the lithology and palynology of the uppermost carbonaceous claystone section, may relate to movement of the site into the proximity of Agulhas Bank where the marginal fracture ridge disappears and where southerly transport of sediment from rivers emptying along the African west coast became a distinct possibility.

In Albian time, influx of terrigenous sediment tapered off significantly and pelagic conditions with well-oxygenated bottom waters became established at the

Falkland Plateau sites. This change is roughly synchronous with the disappearance of euxinic sediments in the Cape Basin (Site 361) and on the Mozambique Ridge (Site 249). Also at about this time, the tip of the Falkland Plateau was clearing Africa and volcanism, probably accompanied by subsidence, was occurring around Mozambique and Madagascar. Thus, the change in conditions apparently reflects the tectonic removal of the restrictive sills which separated these basins and the onset of free exchange of deep and shallow water masses. Available ages, though tenuous, suggest that reoxygenation progressed from deep water (Cape Basin) to shallow (Falkland Plateau) with Hole 327A, the shallowest plateau site, being last. This implies that termination of the euxinic conditions involved inflow of denser Indian Ocean water along the bottom accompanied by surface removal of basin waters. The apparent early Aptian to late Albian hiatus at Site 249 on the Mozambique Ridge (Simpson, Schlich, et al., 1974) may be a manifestation of this process.

One final comment concerning the occurrence of Mesozoic euxinic facies in the Atlantic seems appropriate. Euxinic sedimentation was apparently widespread in the North Atlantic as well as the South Atlantic in Late Jurassic-Early Cretaceous time (Saunders et al., 1973). To explain this by analogy to modern euxinic environments such as the Black Sea necessitates a great deal of speculation regarding possible restrictive sills and tectonic movements to initiate and terminate the euxinic conditions. This may give one reason to question the analogy, and to wonder about possible alternative interpretations. One possibility is the lack of very cold waters at high latitudes in the Mesozoic Atlantic so that bottom circulation was generally more sluggish than at present. A second is the development of an oxygen minimum layer in the water column and accumulation of at least some of the organic-rich sediments in the limited depth range where this layer intersected the bottom. The fact that carbonaceous sediments of both the Falkland Plateau and Magallenes Basin were deposited in depths well above the adjacent basin floor makes this a tempting interpretation. Still, the association of euxinic facies with initial fragmentation of Gondwanaland, and the apparent correspondence in time between barrier removal and disappearance of restricted conditions seems more than fortuitous. This is particularly true in the South Atlantic where the start and stop of euxinic sedimentation is not everywhere synchronous, but appears to have progressed northward as the new basin opened.

ACKNOWLEDGMENTS

I extend thanks to appropriate personnel at Humboldt State University and the Deep Sea Drilling Project who made possible my participation on Leg 36. Appreciation is extended to T.L. Thompson and others at the Amoco Production Co. Research Laboratory who arranged for and carried out analyses of organic carbon and palynomorphs. I.W.D. Dalziel, D.H. Elliot, and C.C. von der Borch read earlier versions of this paper and made many helpful suggestions for which I am grateful. Finally, I wish to acknowledge the constructive criticism of J.R. Curray who reviewed the final manuscript.

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