Deep-sea phosphorite of Tertiary age
from Annan Seamount, eastern equatorial Atlantic

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Abstract—Phosphatized bioclastic limestones of Early Tertiary age have been dredged from the crest of a seamount in the equatorial Atlantic near 9°N, 21°W. The samples were recovered from water depths of 700 to 970 m but clearly were deposited in a high-energy reefal environment, thus indicating significant Tertiary subsidence. The vertical movement is believed to reflect reactivation of an old structural line, the Guinée Fracture Zone, which may have had important effects on the transfer of bottom waters of polar origin between the Sierra Leone and Gambia basins. Examination of foraminiferal limestone coating the shallow water material suggests that deep-water conditions were established on the seamount by Middle Miocene time. All phosphatized samples are covered with a layer of ferromanganese oxides which, from textural and faunal evidence, is Palaeocene or Eocene in age and of shallow water origin.

Pervasive phosphatization of the bioclastic limestones appears to have been accomplished before the end of the Eocene while the crest of the seamount was near sea level, because Upper Eocene limestone of shallow water facies is unaffected by such radical diagenesis. Phosphatization probably was associated with vigorous upwelling near the seamount and has been taken to an unusually advanced stage, resulting in a phosphorite of high economic grade. P_2O_5 contents are in the range of 37 to 41%. The purity of the phosphorites may be related to the intensity of upwelling during the Early Tertiary, but other factors such as the paucity of terrigenous detritus, frequent reworking of the sedimentary capping of the seamount, and a high primary porosity of the limestones may have been important in their formation. The Early Tertiary period of phosphorite deposition on the seamount and in northwest Africa ended before the close of Eocene time in both areas, while shallow water conditions prevailed. It is argued that the cessation of phosphorite formation reflects major changes in the surface circulation of the Atlantic during the Eocene.

INTRODUCTION

DURING A 1975 research cruise of R.R.S. *Shackleton*, sedimentary rocks were dredged from the crestal region of a seamount on the northern margin of the Sierra Leone Rise (Fig. 1), the sampling being part of a general programme designed to investigate the crustal structure and history of sedimentation in the eastern equatorial Atlantic. The seamount, which we have named Annan in this paper (Figs 1 and 2), lies some 600 km off the West African coast and is one of several on the line of the Guinée fracture zone, a major transverse feature that constitutes the southern boundary of the Guinée Plateau (KRAUSE, 1964; EGLOFF, 1972; EMERY, UCHUPI, PHILLIPS, BOWIN and MASCLE, 1975). The dredged samples have proved to be of interest because the majority are Lower Tertiary phosphatized limestones, which have been formed in much shallower water depths than those presently found on the seamount. They provide clear evidence for appreciable subsidence in this area during Tertiary time.

The sampling location (Sta. S-1225) is indicated on the bathymetric map in Fig. 2. As the

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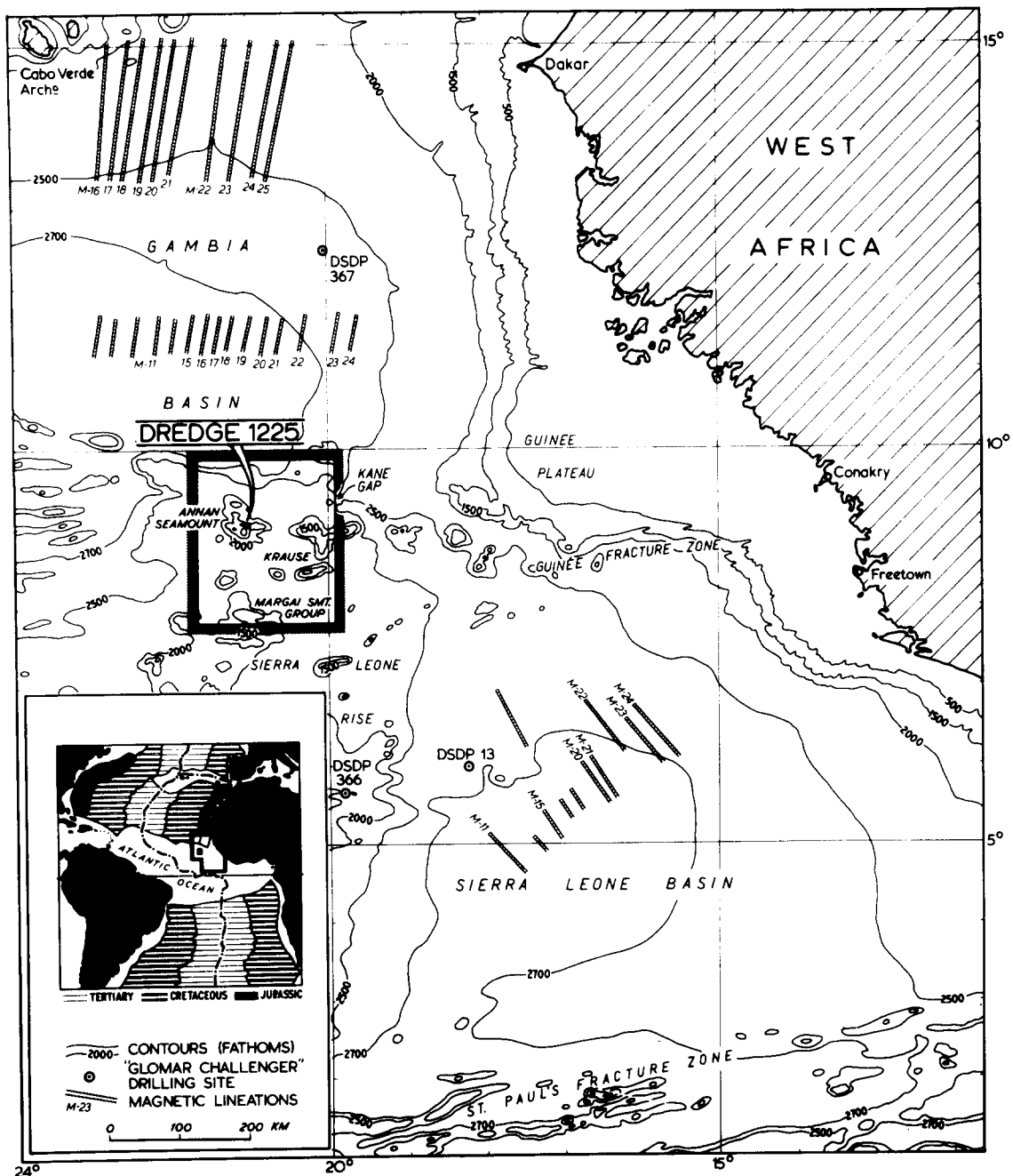* Department of Geology, University College London, Gower Street, London WC1E 6BT, U.K.

Fig. 1. Location of Annan Seamount and dredge Sta. S-1225. Regional bathymetry taken from maps by Jones and Stuart (1979). 500 fathoms = 914 m. Positions of magnetic lineations are derived from Hayes and Rabinowitz (1975) and Jones and Mgbatogu (1977); anomalies are numbered according to the time scale of Larson and Hilde (1975). M-11, 126×10^6 y BP (Valanginian); M-24, 151×10^6 y BP (Oxfordian). Ages of oldest sediments samples at Glomar Challenger drill sites are: 13, Senonian (acoustic basement not reached; Maxwell et al., 1970). 366, Maestrichtian (acoustic basement not penetrated; Lancelot et al., 1977a). 367, Oxfordian to Kimmeridgian (acoustic basement penetrated; Lancelot et al., 1977b).
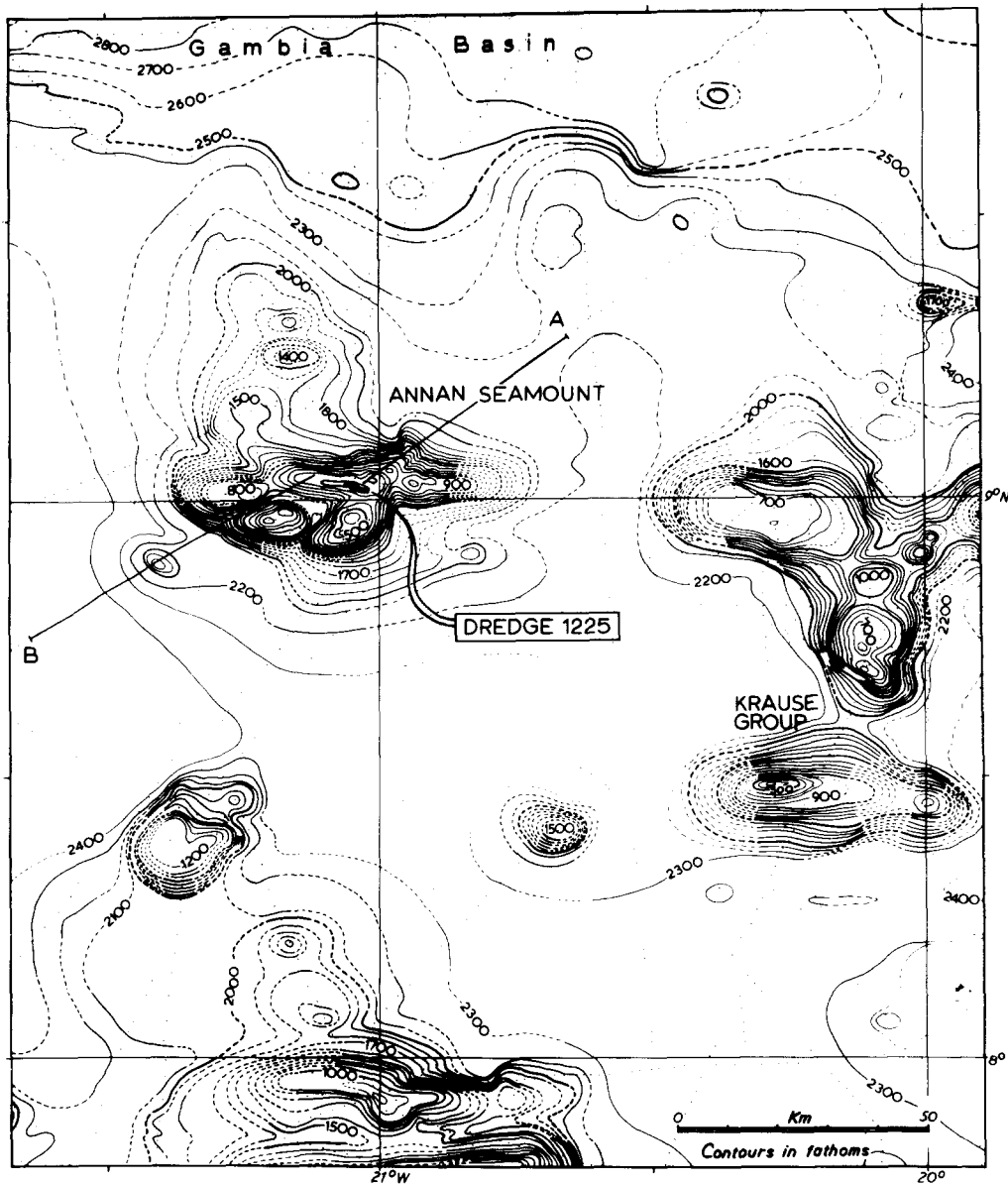
Fig. 2. Bathymetry of Annan Seamount with track of dredge station 1225 indicated. 100 fathoms = 183 m. An airgun seismic profile along A–B is reproduced in Fig. 3. The minimum water depth recorded on Annan Seamount is 688 m.

reflection profile in Fig. 3 shows, much of the seamount near the dredge site lacks a seismically detectable cover of unconsolidated sediments, the latter only appearing as a well-defined layer in water depths exceeding 3530 m or approximately 4.7 s of reflection time. The dredge was towed along a 1.8-km section of the summit region, beginning in a water depth of 969 m and ending in 699 m. Our best estimate of the mid-point of the dredging track using satellite navigation is 9° 1.4′N, 21° 2.4′W. Approximately 120 kg of sedimentary

rocks were obtained, together with a collection of Recent ahermatypic corals. No igneous material was recovered, although it must form the core of the seamount in view of the substantial magnetic anomalies near the dredge site (Fig. 3). The base of the capping of consolidated sediments is not observed on the reflection profile.

MINERALOGY AND CHEMISTRY OF DREDGED SAMPLES

Eighteen sedimentary rocks, varying from 0.2 to 32 kg, were present in the dredge haul (Table 1). The majority are bioclastic limestones clearly of shallow water origin. Generally light brown on freshly cut surfaces, they are primarily poorly sorted skeletal debris ranging from calcarenite to calcirudite grade, with corals, crustose coralline algae, bryozoa, molluscs, echinoderm spines, and foraminifera forming the main components. Non-skeletal material consists of rounded or sub-rounded, internally structureless pellets and lumps, together with trace amounts of detrital quartz, feldspar, and brown volcanic glass (Table 1). Each block is encrusted with a 1 to 5 mm hard coating of ferromanganese oxides, which gives the samples highly polished, black exteriors.

Table 1. *Descriptions of rock samples dredged from Annan Seamount (Sta. 1225; Fig. 2)*

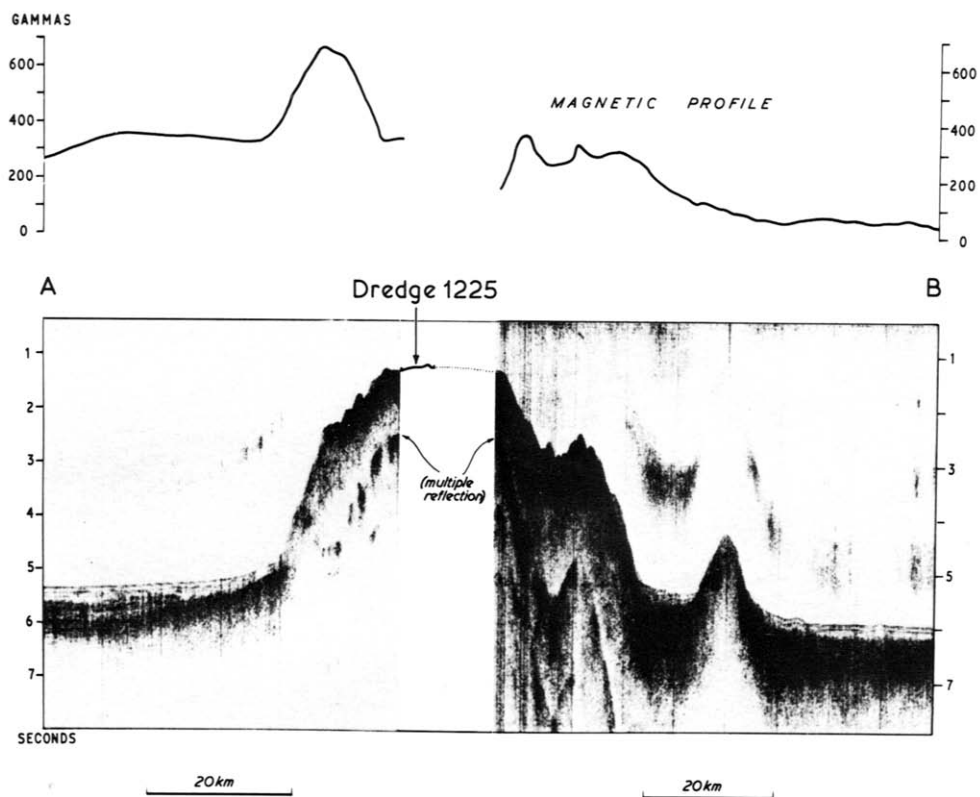| Sample no.	Weight (kg)	Age	Description
S-1225-1, 2* (same block)	32.0	? Palaeocene or Eocene	Phosphatized block of crustose coralline algae
S-1225-3*	18.5	,,	Phosphatized bioclastic limestone containing bryozoa, crustose coralline algae, corals and foraminifera; traces of authigenic and detrital quartz; minor infiltration of non-phosphatized foram ooze
S-1225-4*	3.0	,,	Recrystallized phosphatized limestone containing algal fragments and pellets. Minor detrital grains present in scarce void spaces
S-1225-5*	13.0	,,	Partly recrystallized phosphatized bioclastic limestone, containing minor amounts of basaltic glass and angular quartz detritus in voids
S-1225-6*	2.4	,,	Phosphatized limestone containing mainly bryozoan fragments and minor amounts of detrital quartz in voids
S-1225-7*	13.0	,,	A phosphatized and recrystallized calcarenite with cracks filled with ferromanganese oxide and micrite
S-1225-8*	12.5	,,	Phosphatized limestone containing coralline algal and bryozoan fragments. Detrital quartz and sparry calcite occur in voids
S-1225-9*	3.4	,,	Phosphatized limestone composed of algal, bryozoan and molluscan fragments and echinoderm spines. A shark's tooth is present. Detrital quartz occurs in voids in minor amounts
S-1225-10*	3.2	,,	A phosphatized piece of crustose coralline algae
S-1225-11*	3.0	,,	Phosphatized limestone containing algal and bryozoan fragments. Minor amounts of detrital quartz, amphibole and brown glass shards in the voids. Non-phosphatized foraminiferal ooze of ? Miocene age has infiltrated larger pore spaces
S-1225-12*	4.5	,,	Phosphatized limestone composed of bryozoan fragments and minor amounts of algal and molluscan debris. Minor detrital quartz, brown glass and feldspar are present

GAMMAS

MAGNETIC PROFILE

600

400

200

0

600

400

200

0

A

Dredge 1225

B

(multiple
reflection)

SECONDS

20km

20km

Fig. 3.   Magnetic and airgun reflection profile along line A–B in Fig. 2. A cover of unconsolidated
or semi-consolidated sediments is only apparent in water depths greater than 4.7 s of total reflection
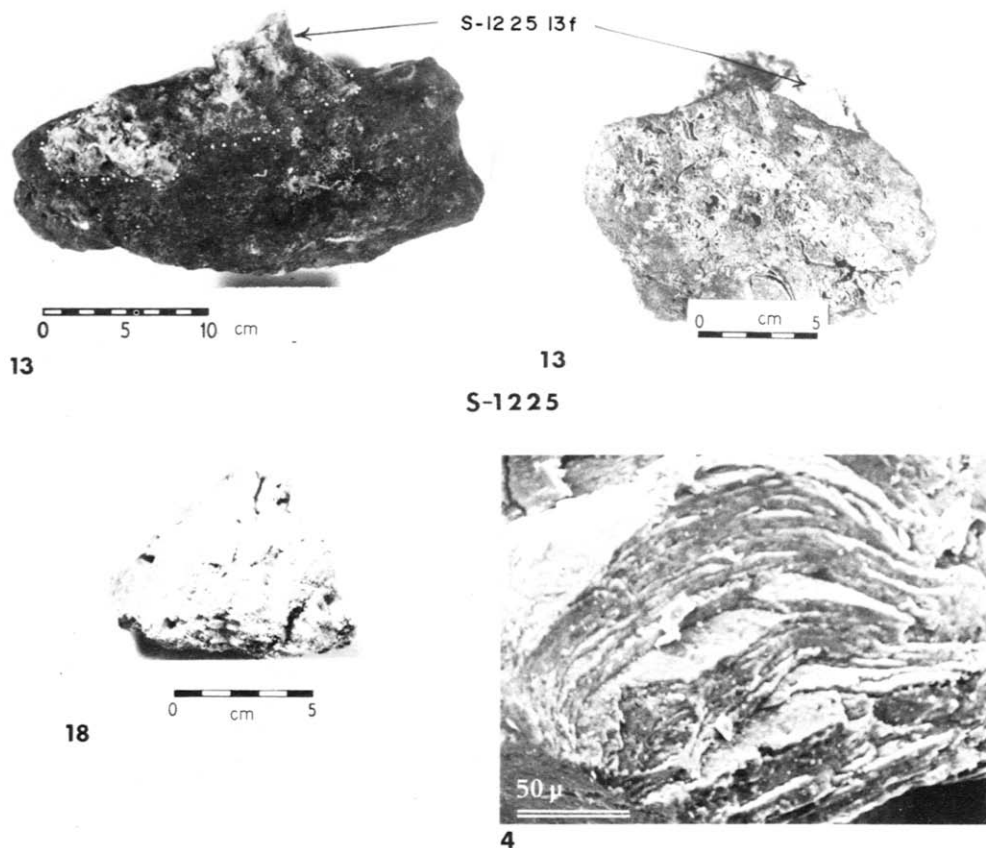time (approximately 1930 fathoms or 3530 m), 1 nT = 1 gamma.

Fig. 4. Sedimentary rocks recovered at dredge station 1225 on Annan Seamount. *S-1225-13* (Upper left) Phosphatized bioclastic limestone of ? Palaeocene or Eocene age coated with non-phosphatized foraminiferal limestone (13f) and ferromanganese oxides. A section through the block (upper right) shows the coarse bioclastic material and its partial covering of fine-grained, light-coloured limestone, which contains Middle Miocene and younger planktonic foraminifera. The ferromanganese coating around the main parts of the dredge sample continues as a distinct layer between the bioclastic and the foraminiferal limestones. *S-1225-18* (Lower left) Upper Eocene foraminiferal limestone that has not undergone extensive phosphatization. Note the absence of a ferromanganese oxide coating. *S-1225-4* (Lower right) Stereoscan photograph of ferromanganese oxide encrustation showing concentric microlaminations.
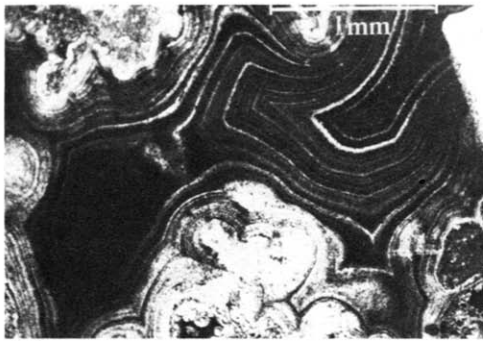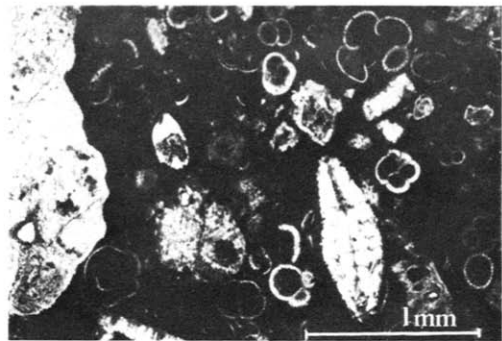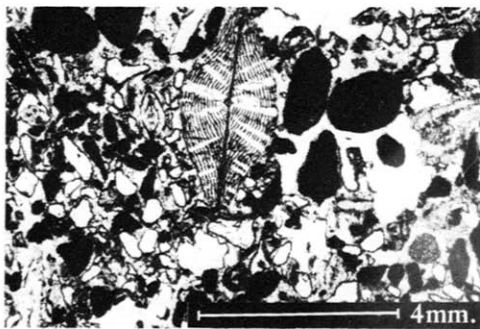
Fig. 5. Photomicrographs of rocks dredged from Annan Seamount. *S-1225-15.* Phosphatic banding in ? Palaeocene or Eocene bioclastic limestone. *S-1225-13f* Middle Miocene or younger foraminiferal limestone attached to sample S-1225-13 (see Fig. 4) *S-1225-18* Upper Eocene foraminiferal and algal limestone consisting predominantly of large foraminifera of the genus *Lepidocyclina. S-1225-17.* Upper Eocene algal and foraminiferal limestone.

Sample no.	Weight (kg)	Age	Description
S-1225-13*	5.5	,,	Phosphatized limestone containing algal and bryozoan fragments. Minor detrital quartz and brown glass occur in voids
S-1225-13f	—	M. Miocene or younger	Foraminiferal limestone attached to S-1225-13. Contains planktonic foraminifera, remains of coralline and algae coated with ferromanganese oxides and phosphatic fragments
S-1225-14*	1.5	? Palaeocene or Eocene	Phosphatized limestone composed of algal and bryozoan fragments. Sample exhibits striking phosphatic banding
S-1225-15*	4.5	,,	Phosphatized limestone containing algal and bryozoan fragments, pellets and lumps. Phosphatic banding present. Minor amounts of sparry calcite, detrital quartz, glass and feldspar occur in voids
S-1225-16*	1.0	,,	Phosphatized limestone made up of bryozoan, coralline, molluscan debris. Minor sparry calcite, detrital quartz and brown glass in voids
S-1225-16f	—	? U. Eocene	Non-phosphatized limestone containing abundant coralline algal fragments and small amounts of detrital quartz. The limestone is attached to sample S-1225-16
S-1225-17	0.5	U. Eocene	Non-phosphatized foraminiferal limestone containing *Lepidocyclina* and *Archaeolithothamnium*. Minor amounts of sub-rounded, detrital quartz and basaltic glass
S-1225-18	0.2	,,	Non-phosphatized foraminiferal limestone consisting primarily of *Lepidocyclina* (>90%). A few algal fragments are present. The sample is extensively burrowed and contaminated with Pliocene–Recent planktonic foraminifera

* Indicates that the sample is encrusted with ferromanganese oxides.

In addition to the coarse bioclastic material, two small pieces of foraminiferal limestone containing algal fragments were recovered (S-1225-17, 18; Table 1). These fine-grained limestones lack an outer ferromanganese layer. Foraminiferal limestone was also found as a partial coating on two of the ferromanganese-encrusted specimens made up of shallow water elements (Fig. 4).

Mineralogical examination reveals extensive phosphatization of the shallow-water bioclastic material. In thin section the dredged blocks mainly consist of the virtually isotropic collophane, which has replaced pervasively the original skeletal material together with much of the calcareous cement. By contrast, the foraminiferal limestones show no evidence of such diagenetic alteration. Although the replacement of the bioclastic limestones has been extensive it is possible to determine the nature of the original biogenic components in most parts of the rock. In some sections the pseudo-spherulitic structure and interbanding of the collophane and anisotropic francolite or dahllite is present. Thin phosphatic layers lining voids are visible, for example in samples S-1225-13 and S-1225-15 (Fig. 5). Similar textures in phosphatized limestones from other areas have been described (BRAITHWAITE, 1968). Laminations such as those in Fig. 5 appear to have arisen from the primary deposition of phosphatic material, the voids probably acting as important avenues for the introduction of phosphate-rich solutions into the main body of the limestone.

The optical indications of phosphatization of the shallow water limestones have been confirmed by X-ray diffraction using CuKα radiation. Diffractograms from two specimens
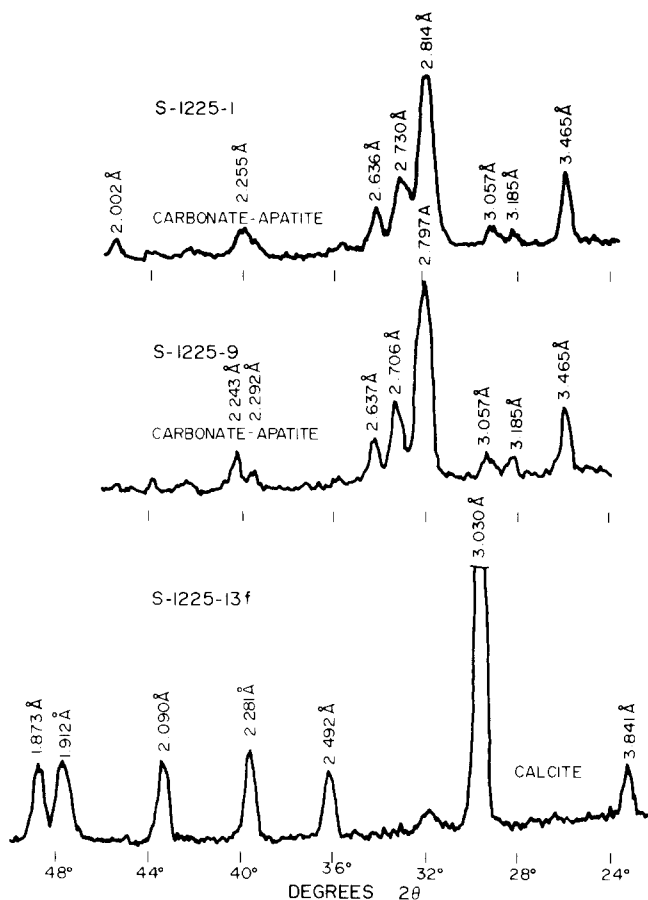
Fig. 6. Diffractograms of bioclastic (S-1225-1 and 9) and foraminiferal (S-1225-13f) limestones dredged at station 1225 on Annan Seamount. The traces were obtained using CuKα radiation (with Ni filter).

of the bioclastic material can be compared with one from a foraminiferal limestone in Fig. 6. The four principal peaks characteristic of the former are $d = 2.814$ Å (100), $d = 2.730$ Å (40), $d = 3.465$ Å (40), and $d = 1.841$ Å (30), with subsidiary peaks occurring at $d = 2.636$ Å, $d = 2.255$ Å, $d = 3.185$ Å, and $d = 3.057$ Å. Other specimens of the bioclastic material give the same results, which are typical of carbonate apatite. Peaks characteristic of calcite were not observed in the phosphatic rocks, indicating that if calcite is present, it is less than 3% by weight, the minimum detectable by X-ray methods (Silverman, Fuyat and Weiser, 1952). Diffractograms of samples S-1225-13f (Fig. 6), 1225-16f, 1225-17, and 1225-18 are those expected from pure limestone, the main peaks being $d = 3.841$ Å (12), $d = 3.030$ Å (100), $d = 2.492$ Å (14), $d = 2.281$ Å (18), $d = 2.090$ Å (17), $d = 1.912$ Å (17), and $d = 1.873$ Å (16).

Chemical analyses of crushed samples taken from the interior of each dredged block have been carried out using a Unicam SP90A atomic absorption spectrophotometer (Fe, Mn, Mg, Sr), an EEL flame photometer (Na, K) and a Unicam SP 8000A ultra-violet recording spectrophotometer (P_2O_5), following the technique outlined by Chester and Hughes

(1967). CO_2 was measured using a Collins calcimeter and H_2O^- and H_2O^+ were determined using the loss-on-ignition method, heating to 110 and 1000°C (Table 2). An average composition for the phosphatized samples is given in Table 3, where it can be compared with other phosphatic deposits.

The high P_2O_5 content of the bioclastic material (samples 1–16, excluding 13f; Tables 1 and 2) is of special interest. It is well in excess of 18%, the figure adopted by BUSHINSKII (1969) for the minimum P_2O_5 content of a phosphorite. Values cover only a small range, from 37.04% to 41.07%, and average 39.48% or 86% TPL [Triphosphate of lime; $Ca_3(PO_4)_2$], the weight percentage often employed in commercial descriptions of phosphate deposits. When compared with phosphorites mined on land (BRITISH SULPHUR CORPORATION, 1971), it is clear that the TPL contents of the dredge samples place them well within the category reserved for high grade deposits (>79% TPL; BRITISH SULPHUR CORPORATION, 1971). Furthermore, a comparison with other submarine phosphorites (Table 3) shows that phosphatization of the Annan Seamount samples has been taken to an unusually advanced stage. The paucity of terrigenous material, a consequence of the isolated position of the seamount, may have been an important factor in the production of such a high grade deposit, in which the CaO/P_2O_5 ratios approach that of pure dahllite (Table 3). Many submarine phosphatic accumulations lying close to coastal regions, such as those off northwest Africa and western South America (Table 3), tend to be significantly lower in P_2O_5 but higher in Fe_2O_3 than the dredge samples from Annan Seamount. This difference may reflect stronger terrigenous influences on the continental margin. On the other hand, MgO in the Annan Seamount phosphorites is appreciably lower than in phosphatic deposits on the Morrocan shelf, which often are dolomitic (SUMMERHAYES, 1971). CO_2 in the bioclastic material varies from 3.71 to 7.12%, much less than the foraminiferal limestones from the same dredge, which average about 40% CO_2 (samples 13f and 17; Table 2). MnO tends to increase with increasing Fe_2O_3, with sample 14 being an obvious exception to the general trend. The average MnO content is less than in the well-known phosphorites of the Phosphoria Formation (Table 3; GULBRANDSEN, 1966) but appears to be significantly greater than MnO in phosphorites accumulating off northwest and southwest Africa (Table 3; CALVERT, 1976). SrO shows some variation in the bioclastic samples (0.02 to 0.27%), but the values clearly are significantly higher than in the foraminiferal limestones (0.07%). Relatively high SrO is not unexpected as strontium enrichment appears to be typical of many Tertiary–Recent phosphorites (TOOMS, SUMMERHAYES and CRONAN, 1969; CALVERT, 1976), such as those in North Carolina and on Remire Island in the Indian Ocean (Table 3). The strontium probably substitutes for calcium in the carbonate apatite lattice (GULBRANDSEN, 1966).

Although the foraminiferal limestones have not undergone the same extensive phosphatization as the bioclastic limestones the P_2O_5 values are, nevertheless, about an order of magnitude higher than expected for a calcareous pelagic sediment, a value of 0.2% or less being typical (EL WAKEEL and RILEY, 1961; MANHEIM, ROWE and JIPA, 1975). Textural and palaeontological evidence presented below suggests that the P_2O_5 enrichment is a result of the incorporation of reworked clasts of original phosphatic material into the pelagic sediment.

FERROMANGANESE OXIDE ENCRUSTATIONS

As described in the previous section, each block of phosphatized bioclastic limestone is encrusted with ferromanganese oxides. The layers average about 1 mm thick but reach

Table 2. Chemical compositions of rocks recovered from Annan Seamount (Sta. 1225)

Sample no.	1	3	4	5	6	7	8	9	10	11	12	13	13f*	14	15	16	17
Fe_2O_3	0.07	0.51	0.10	0.40	0.30	0.30	0.43	0.81	0.24	0.31	0.07	0.20	0.21	0.13	0.29	0.16	0.07
MnO	0.05	0.12	0.07	0.19	0.35	0.08	0.25	0.51	0.40	0.10	0.03	0.15	0.27	0.72	0.15	0.09	0.06
MgO	0.35	0.25	0.22	0.27	0.36	0.23	0.30	0.22	0.22	0.28	0.20	0.17	1.06	0.20	0.33	0.35	0.51
Na_2O	1.15	0.85	0.46	0.96	0.82	0.59	0.38	0.97	0.61	0.78	0.67	0.61	0.40	0.75	1.15	0.94	0.42
K_2O	0.09	0.17	0.08	0.09	0.16	0.11	0.05	0.20	0.11	0.16	0.07	0.15	0.14	0.12	0.14	0.11	0.05
CaO	46.45	46.40	49.86	49.02	49.02	49.49	48.17	50.16	48.09	47.90	49.72	50.74	51.42	50.49	50.85	49.93	54.07
P_2O_5	39.19	39.57	40.24	39.14	39.06	39.94	40.84	37.04	41.07	38.83	39.73	40.12	4.03	38.06	40.00	39.41	3.05
CO_2	5.08	5.74	3.71	4.76	4.28	4.09	5.81	5.46	5.45	7.12	5.36	5.08	40.73	5.27	6.82	4.78	40.00
SrO	0.24	0.24	0.20	0.22	0.27	0.20	0.27	0.21	0.22	0.24	0.25	0.27	0.07	0.26	0.21	0.28	0.07
H_2O^+	3.63	4.60	3.76	3.70	3.69	2.66	2.60	4.54	1.99	3.40	1.42	1.29	0.98	1.81	1.28	3.06	1.05
H_2O^-	4.78	1.47	1.11	1.11	1.53	1.25	1.13	0.82	1.99	1.76	2.94	2.17	0.32	1.72	1.41	1.38	0.26
Total	101.08	99.92	99.81	99.86	99.84	98.94	100.23	100.94	100.39	100.88	100.46	100.95	99.63	99.53	102.63	100.49	99.61

* Foraminiferal limestone which forms a partial coating on sample S-1225-13 (see Fig. 4).

Table 3. *Average chemical composition of phosphatized limestones from Annan Seamount compared with other phosphate deposits*

	1	2	3	4	5	6	7	8	9
SiO_2	ND	2.78	ND	ND	nil	22.13	1.33	11.9	0.01
Fe_2O_3	0.29	0.59	ND	0.34	0.03	2.85	0.10	1.1	NQ
MnO	0.22	0.01	ND	ND	nil	NQ	0.001	0.4	NQ
MgO	0.26	0.80	1.05	0.10	0.34	1.07	0.60	0.3	0.30
Na_2O	0.78	NQ	0.87	nil	0.80	0.85	1.17	0.6	NQ
K_2O	0.12	0.13	nil	nil	0.05	1.30	0.06	0.5	NQ
CaO	49.09	50.40	45.18	53.94	51.44	33.93	49.87	44.0	56.47
P_2O_5	39.48	25.30	37.90	38.13	39.92	22.61	30.97	30.5	35.75
CO_2	5.25	NQ	3.60	3.40	2.72	NQ	4.83	2.2	3.36
F	ND	NQ	2.40	3.71	0.03	2.22	3.60	3.1	NQ
SrO	0.24	0.13	0.26	ND	nil	NQ	0.30	0.12	NQ
H_2O^+	2.90	NQ	2.53*	0.46	2.83	NQ	3.88	2.2‡	3.91
H_2O^-	1.77	NQ	1.81†	0.01	0.80	NQ	NQ	0.6	0.53
(LOI)		0.70§					8.78	2.1§	
Total	100.38	80.84	95.60	100.09	98.96	95.74	96.71	97.86	100.33
CaO/P_2O_5	1.24	1.99	1.19	1.41	1.29	1.50	1.61	1.45	1.58

ND—not determined; NQ—not quoted; * $H_2O-150°$; † $H_2O+150°$; ‡ total H_2O; § organic matter.

1. Phosphatized limestone from Annan Seamount (average of 15 samples; 1 and 3–16, Table 2).

2. Pelletal conglomeratic phosphorite of Tertiary age, northwest African continental shelf (SUMMERHAYES, 1971; also quoted by CALVERT, 1976).

3. Lithoclast of phosphate rock (allochems replaced by phosphate), Remire Island, Indian Ocean (BRAITHWAITE, 1968).

4. Francolite, Wheal Franco, Devon (SANDELL *et al.*, 1939).

5. Analysis of dahllite (McCONNELL, 1960).

6. Average of 15 analyses of phosphorite nodules from the continental margin of Peru and Chile (BURNETT, 1977).

7. Phosphate pellets, North Carolina (ROONEY and KERR, 1967).

8. Phosphoria Formation. Average of 60 analyses (GULBRANDSEN, 1966).

9. Guano filling cracks in dunite, St Paul's Rocks, equatorial Atlantic (HUTCHINSON, 1950).

5 mm in surface depressions on the larger specimens. The crusts have hard, polished surfaces and are made up of strikingly even microlaminations between 3 and 10 µ thick (Fig. 4). Powder photographs show that the encrustations consist of an admixture of todorokite and δ-MnO_2.

Element abundances in the crusts on blocks S-1225-4, 7, and 10 are given in Table 4. The compositions are not typical of the majority of ferromanganese deposits from the deeper parts of the Atlantic region, a feature emphasized by the high Mn/Fe ratios. Usually less than unity in the Atlantic, Mn/Fe ranges from 1.19 to 1.30 on Annan Seamount. In this respect the samples resemble encrustations from the Blake Plateau (CRONAN, 1975, 1976) which, it is interesting to note, also have been formed around blocks of phosphorite (PRATT and McFARLIN, 1966). As high Mn contents are generally found in areas of low terrigenous input (HORN, HORN and DELACH, 1972) the high Mn/Fe ratios probably reflect, at least in part, low rates of sediment deposition. It is also significant that Co is richer in the dredged samples than in typical Atlantic ferromanganese, while Cu is lower (Table 4). Low Cu values might be anticipated on an elevation such as Annan Seamount because of the likelihood of an oxidizing environment at its crest, which would inhibit the formation of todorokite (CRONAN, 1976). Large Cu concentrations tend to be associated with todorokite-rich deposits formed in deeper water. The Co enrichment on the seamount may be due to its incorporation in δ-MnO_2 under highly oxidizing conditions at its crest.

Table 4.   *Element abundances in ferromanganese oxide crusts on bioclastic limestones at Sta.* 1225 (*Annan Seamount*) *compared with compositions of manganese nodules and encrustations from other parts of the Atlantic*

	Annan Seamount			Atlantic*			Blake Plateau*
	S-1225-4	S-1225-7	S-1225-10	Max	Min	Avg	
Fe	17.86	17.13	17.70	41.79	4.76	21.55	12.95
Mn	21.29	22.22	21.49	37.69	1.32	15.97	19.84
Na	1.260	1.190	2.040	4.77	0.365	1.88	1.01
K	0.198	0.270	0.230	2.71	0.110	0.57	0.32
Ca	3.410	2.330	2.300	17.10	1.24	2.90	8.39
Mg	1.380	1.520	1.650	13.20	0.931	1.86	2.88
Cu	0.032	0.027	0.030	0.884	0.022	0.115	0.095
Zn	0.049	0.046	0.059	0.806	0.038	0.086	0.058
Ni	0.243	0.271	0.262	1.41	0.019	0.312	0.637
Co	0.921	1.000	1.010	1.01	0.017	0.318	0.381
Insol. residue	0.37	0.11	0.37				
Mn/Fe	1.19	1.30	1.21				
Fe/Co	19.38	17.15	17.59				
Mn/Ni	87.58	82.07	82.02				

* From CRONAN (1975).

Evidence is presented below to suggest that the crusts were formed before the seamount had undergone appreciable subsidence.

AGES OF THE DREDGED SAMPLES

(i) *Phosphatized bioclastic limestones*

The age of the phosphatized limestones has been determined from the abundant coralline debris they contain, the remaining constituents (algae, foraminifera, bryozoa, molluscan fragments) being either long-range forms or in a state of poor preservation. A detailed examination of the corals has been made by Dr ANTONIO RUSSO of the Università di Modena (personal communication, 1978). He assigns a firm Palaeocene–Eocene age to the limestones, a dating primarily based on the occurrence of the colonial *Stylophora* and *Astrocoenia*. The species of *Stylophora* compares closely with *S. vaughani* Gregory from the Palaeocene Ranikot series of Pakistan. Six septa are always present while the columella is styliform and united with the septa. Corallites are characteristically widely spaced. Dr Russo also has noted that the bioclastic material bears a strong resemblance to the Eocene limestones of the *Stylophora* group in Jamaica (Port Olarie, Port Antonio, Cambridge district, etc.), which contain *Stylophora contorta* Leym., *S. cambrigiensis* Wells, and *Stylophora* sp.

The form of the reef-building *Astrocoenia* in the dredge collection is closely similar to *A. gibbosa* Duncan from the Ranikot series. The corallites are closely spaced. A well developed columella is present and eight septa occur, together with an additional two or three only weakly developed or even absent.

(ii) *Foraminiferal limestones*

Two pieces of foraminiferal limestone were found in the dredge haul (S-1225-17 and S-1225-18; Table 1, Fig. 4). Foraminiferal limestone also occurs as a partial coating on two blocks of phosphatized bioclastic limestone (S-1225-13f and S-1225-16f; see Fig. 4).

Sample S-1225-17 contains abundant large foraminifera and unphosphatized algal remains indicative of shallow water depositional conditions. Dr G. F. Elliott of the British Museum (Natural History) kindly examined the algae in thin section and has identified *Archaeolithothamnium* sp., finding the closest similarity with the form of *Archaeolithothamnium* in the Upper Eocene of Saipan, reported by JOHNSON (1957; Plate 37, Fig. 10). In a study of the same block, Dr C. G. Adams of the Natural History Museum found numerous *Lepidocyclina* (*Isolepidina*) *mauretanica* Bourcart and David, together with a common, but indeterminable, operculinid, miliolids and other non-diagnostic benthonic foraminifera. The occurrence of *L.* (*I.*) *mauretanica* is particularly significant as it is a large foraminifera that has been described from the late Eocene of northwest Africa. It is undoubtedly a junior synonym of one of the numerous American Eocene "species". Its presence, together with *Archaeolithothamnium*, indicates that the S-1225-17 limestone is of Upper Eocene age and, furthermore, that shallow water conditions prevailed on the crest of Annan Seamount at the time of its accumulation. Block S-1225-18 consists of more than 90% *L. mauretanica*, but unlike S-1225-17, the specimen is burrowed and contaminated with the Pliocene *Globorotalia puncticulata* Deshayes and younger species.

In contrast to samples 17 and 18, the foraminiferal limestones coating blocks S-1225-13 and S-1225-16 are appreciably younger and provide indications of greater water depths at the time of deposition. Although they contain specimens of *L.* (*I.*) *mauretanica*, these are reworked and intimately associated with abundant Middle Miocene or younger planktonic foraminifera. The latter include *Orbulina*, *Globigerinoides* spp, *Sphaeroidinellopsis* sp., and *Globorotalia* (keeled forms) (C. G. ADAMS, personal communication, 1978). Small, rounded lumps of phosphatic material, probably derived from the older bioclastic limestones in the vicinity, also occur and are likely to be the source of the significant quantity ($\sim 4\%$) of P_2O_5 in these samples. The presence of foraminifera as old as Middle Miocene suggests that the pelagic coating on the two blocks of shallow water limestone started to form at that time. The younger species probably were incorporated into the deposit as a result of frequent reworking, possibly by burrowing organisms.

PHOSPHATIZATION OF THE BIOCLASTIC LIMESTONES

A remarkable feature of the dredge collection is the pervasive phosphatization of the shallow-water limestones which, as we emphasized earlier, have been converted to phosphorites of high economic grade. P_2O_5 averages 39.5% (86% TPL), roughly 140 times its mean crustal abundance. In this respect, the rocks closely resemble the Eocene phosphorites of western Senegal, where up to 39.2% P_2O_5 (86% TPL) has been reported (BRITISH SULPHUR CORPORATION, 1971). It is also interesting to note that an analysis of a concentrate from the Taiba mine near Dakar (BRITISH SULPHUR CORPORATION, 1971) had a P_2O_5 content of 37.68% (82% TPL), close to that of our unbeneficiated dredged samples.

Within broad limits, the time at which phosphatization occurred can be determined from the present assemblage of samples. Faunal and textural evidence indicates that both the deposition and the extensive diagenesis of the bioclastic material took place in Palaeocene–Eocene time. Phosphatization evidently had ceased before the close of the Eocene when the crest of Annan Seamount was still close to sea level, because the Upper Eocene *Lepidocyclina* limestones (S-1225-17 and 18) have not been subjected to the same pervasive alteration (Fig. 4; Table 2). Nor have the deeper-water Neogene samples (S-1225-13f and

16f) undergone *in situ* phosphatization. The phosphatized limestones appear to be of a similar age and, therefore, may be linked genetically to many of the extensive Palaeocene or Eocene phosphorites along the African margin, which are well developed in Senegal, Mauritania, Spanish Sahara, and Morocco (British Sulphur Corporation, 1971) and also further south in Dahomey and Togo (Visse, 1953).

Phosphatic deposits have been dredged from other seamounts (e.g. Hamilton, 1956), and it is well known that they can form significant accumulations on some continental shelves and marginal plateaux (Murray, 1885; Murray and Renard, 1891; Calvert, 1976). Contemporary formation of phosphorite has been demonstrated in some instances (Baturin, 1971; Veeh, Burnett and Soutar, 1973; Manheim *et al.*, 1975), but in the majority of areas much of the phosphorite appears to be pre-Pleistocene. In their study of the Moroccan shelf, Tooms, Summerhayes and McMaster (1971) invoked Tertiary phosphorites as the major source of the highly phosphatic surface sediments in the region. A provenance other than older phosphatic accumulations on the continental margin clearly has to be considered for the deposits of Annan Seamount because of its isolated position. There are three possibilities: local volcanoes, guano, or seawater.

The rôle of local submarine volcanism in the formation of phosphorites was stressed by Rooney and Kerr (1967) after their examination of Miocene phosphorites from North Carolina. Finding zeolites and volcanic glass in abundance, they concluded that pyroclastic activity was responsible for the death of large numbers of marine organisms, whose subsequent decay then contributed phosphorus to the sediments. Thin sections of our dredged samples contain occasional shards of basaltic glass and a few feldspar grains, but as they are present in only trace quantities it is unlikely that volcanic detritus of local origin can be considered either as a significant source of phosphorus or as an agent that could have produced a mass mortality in the vicinity of the seamount.

In view of the proximity of the seamount to sea level in the Eocene, subaerial phosphatization of the limestones by guano is possible. The crest may have remained emergent for a sufficiently long period to allow significant accumulations of guano, a process that would have been aided by low rainfall at these low latitudes (within $10°$ of the equator during the Eocene according to the Atlantic reconstructions of Phillips and Forsyth, 1972) and high primary productivity in the waters around the seamount. Modern guano contains 10 to 12% P_2O_5 while in leached deposits values can exceed 20% (Hutchinson, 1950; McKelvey, 1967). Guano filling cracks in the dunite of St Paul's Rocks, some 1300 km southwest of Annan Seamount, has, for example, P_2O_5 concentrations of about 36% (Table 3). Leaching of such surface accumulations by percolating groundwaters can lead to extensive alteration of the underlying deposits, as a study of the phosphatized limestones on Remire Island has demonstrated (Braithwaite, 1968); similar processes may have operated on Annan Seamount during the Early Tertiary.

The alternative source of phosphorus is the organic matter produced in the water column, for there is a high probability that before subsidence occurred the immediate region around Annan Seamount was a highly productive zone because of vigorous local upwelling. Production of phosphate-rich pore waters in the limestones may thus have followed a similar pattern to that in areas of strong upwelling such as off Namibia and Peru where nutrient-rich organic sediments are presently accumulating; these are now known to be favourable environments for interstitial precipitation of calcium phosphate (Baturin, 1971; Veeh *et al.*, 1973; Manheim *et al.*, 1975). Thus, the deposition of a thick blanket of organic-rich marine sediments over the bioclastic material at times of high primary

productivity and crestal submergence may have been a vital early stage of the phosphatization on Annan Seamount, resulting in phosphate-rich pore waters that pervaded the limestones and led to their extensive diagenesis. Under these conditions phosphatization could have been assisted by a high primary porosity and frequent reworking of the calcareous capping and also by only a small influx of terrigenous matter into the area, a result of the isolated position of the seamount.

The high strontium contents of the phosphatized rocks in comparison with the unphosphatized specimens (Table 2) may be due to uptake from seawater during diagenesis. The only feature of the phosphorite chemistry that appears to be incompatible with the above mode of formation is the appreciable MnO content of the interior of each dredged block (Table 2). Although MnO is not always quoted in published analyses, it seems to be significantly higher than in many phosphorites recovered from areas of present-day upwelling (CALVERT, 1976). Nevertheless, high MnO does not rule out the supply of phosphorus from nutrient-rich marine sediments, because manganese could have been introduced at a late stage under favourable redox conditions.

The relative inputs of the most likely sources of phosphorus on Annan Seamount, organic-rich marine sediments and guano, cannot yet be determined. The problem of provenance is particularly difficult to resolve because a high degree of reworking of the sedimentary cap is likely to have occurred. It is clear, however, that phosphatization is a result of replacement of pre-existing calcareous material, a process that has produced a phosphorite that is among the richest in P_2O_5 yet recovered from an offshore area. The chemistry and textural observations on the rocks conform to the suggestion of AMES (1959), based on laboratory studies of the system Na_3PO_4–$CaCO_3$–H_2O, that calcite–aragonite replacement can play a dominant rôle in phosphorite formation. Evidence for direct precipitation of carbonate apatite in the dredged blocks appears only in primary void spaces, although the isotropic pellets and lumps seen in thin section may have developed by interstitial accretion in the manner suggested by D'ANGLEJAN (1967) for phosphorites off Baja California.

The thin ferromanganese encrustations on the dredge samples were formed after lithification and phosphatization had occurred, because the oxides are confined to the surfaces of the phosphatized blocks and do not coat individual clasts within them. Like phosphatization, ferromanganese accumulation appears to have ceased in shallow water before the end of the Eocene, for the Upper Eocene *Lepidocyclina* limestones show no signs of a ferromanganese coating or infilling. Palaeogene deposition is also consistent with our observations on a section cut from block S-1225-13 (Fig. 4). In this specimen the dark-coloured oxide layer lies between the phosphatized limestone and the outer cover of foraminiferal limestone (S-1225-13f), which shows neither textural nor chemical evidence of manganese infiltration (Fig. 4; Table 2). The ferromanganese deposit clearly was present when the deeper-water foraminiferal deposits began to accumulate, possibly during the Middle Miocene.

As we noted earlier, the low Cu and high Co concentrations in the ferromanganese crusts are typical of seamounts and suggest deposition under highly oxidizing conditions. As such an environment is not compatible with the vigorous upwelling associated with phosphatization, a marked reduction in upwelling intensity following the introduction of P_2O_5 into the bioclastic limestones is indicated. That such a reduction occurred in the Early Tertiary is suggested by the absence of *in situ* phosphatization of the Late Eocene *Lepidocyclina* limestones. Furthermore, the rounded and highly polished surfaces of the

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phosphorite blocks are likely to have been produced by abrasion while the top of the seamount was within reach of strong currents, which also implies an oxygen-rich environment.

THE SUBSIDENCE OF ANNAN SEAMOUNT

The total vertical movement of Annan Seamount, as indicated by present water depths and the shallow-water *Lepidocyclina* limestones, is of the order of several hundred metres, but it cannot be determined very precisely because an undisputed sea level curve for the Tertiary and Quaternary is not yet available. If we accept the curve published by PITMAN (1978; Fig. 4), obtained from calculations of oceanic ridge volumes, we can assume that sea level at the time the unphosphatized *Lepidocyclina* limestones were laid down was about 180 m higher than at present, which implies a minimum post-Eocene subsidence of about 900 m.

The Tertiary phase of vertical movements is unexpected in view of the presence of Jurassic and Lower Cretaceous crust in the Gambia Basin to the north and the well-documented history of late Cretaceous and Tertiary sedimentation at DSDP Site 366 (Fig. 1) on the Sierra Leone Rise (LANCELOT *et al.*, 1977a). Rather than revealing structural continuity with adjacent areas, the dredge samples from Annan Seamount provide evidence for reactivation of part of an old fault line (the Guinée Fracture Zone of KRAUSE, 1964) which, as the displaced M-series magnetic anomalies in Fig. 1 show (JONES and MGBATOGU, 1977), was a major tectonic element during the early stages of Atlantic opening (LE PICHON and HAYES, 1971). The vertical motions may be indicative of local volcanism, which directly preceded the deposition of the Palaeocene or Eocene limestones and which was followed by crustal contraction. Such activity was probably fault-controlled because Annan Seamount has a pronounced east–west elongation. Renewal of movements along this part of the fracture zone may reflect a local response to the changes in plate motions in the North Atlantic region, which have been discussed by PITMAN and TALWANI (1972). Some evidence for an early Tertiary period of volcanism appears to exist at DSDP Site 367, some 400 km north of the dredge site. Drilling has revealed a thick Lower-Middle Eocene section of zeolitic clays in this location (LANCELOT *et al.*, 1977b). As no Eocene extrusive activity has been documented from either the Cape Verde Islands or the nearby continental margin, Annan Seamount may have provided a partial source for these volcanogenic sediments.

The length of the fracture zone affected by Tertiary subsidence is not yet known. However, we suggest that such activity was not confined to Annan Seamount. Further east lies a complex group of seamounts (named Krause in Fig. 2), which have either flat or gently-domed crests and summit levels similar to Annan Seamount. Lying on the line of the Guinée Fracture Zone (Fig. 1), these also may have had a similar volcanic, sedimentary, and subsidence history. They may be capped by Tertiary phosphorites of high economic grade, which could be particularly extensive on the relatively flat area enclosed by the 700-fathom contour near 9°N, 20°15'W. More widespread subsidence along the fracture zone can be inferred from a seismic reflection profile of HOBART, BUNCE and SCLATER (1975), which shows sedimentary reflectors in Kane Gap dipping westwards towards the northeastern flank of the Krause Group.

PALAEO-OCEANOGRAPHIC IMPLICATIONS

The conclusion that the phosphatization of the early Tertiary bioclastic limestones had stopped and that ferromanganese had accumulated on the phosphorites before the late

Eocene implies that upwelling around the seamount was reduced significantly by this time also. As the phosphatization appears to have ceased while the crest of the seamount was close to sea level, this indicates that the change in upwelling intensity was unrelated to local topography but rather was connected with regional modifications of the oceanographic regime. The termination in the Eocene of the major early Tertiary period of phosphorite formation in northwest Africa would support this view.

Important oceanographic changes in the Eocene are also supported on independent grounds, including the patterns of deep-water Tertiary deposition in the North Atlantic, revealed by seismic reflection profiles, drilling and core data (JONES, EWING, EWING and EITTREIM, 1970), a comprehensive faunal investigation (BERGGREN and HOLLISTER, 1974), a sudden fall of ocean temperatures near the Eocene–Oligocene boundary (SHACKLETON and KENNETT, 1974), and experiments by LUYENDYK, FORSYTH and PHILLIPS (1972) using the planetary vorticity models of VON ARX (1957). Furthermore, the stratigraphic distribution of siliceous sediments, indicative of times of high surface fertility, at drill sites in the Atlantic suggests that major changes in primary productivity took place in Middle or Upper Eocene time (PETERSON, EDGAR, VON DER BORCH and REX, 1970; RAMSAY, 1971). Thus the cessation of phosphorite formation on Annan Seamount and along the northwestern margin of Africa and the termination of the Eocene phase of siliceous deposition in the North Atlantic may all be related to the same oceanographic changes which, in turn, may be linked to motion of the major lithospheric plates.

Post-Eocene subsidence along the eastern part of the Guinée Fracture Zone also may have had important consequences in terms of the regional palaeo-oceanography because of its effects on bottom water transport in Kane Gap, the deep transverse passage (EGLOFF, 1972) separating the Sierra Leone Rise from the continental margin of West Africa (Fig. 1). HOBART et al. (1975) report significant bottom water flow through this channel. The direction of transport cannot be interpreted unequivocally from their temperature observations, but a bottom photograph showing sediment movement during a coring station suggests a northerly flow. This direction is favoured by LE PICHON, MELGUEN and SIBUET (1978), who showed a component of Antarctic Bottom Water flowing northwards along the West African margin after its passage through the Romanche Fracture Zone. According to HOBART et al. (1975), the layer of cold, bottom water in Kane Gap is only 320 m thick and is well defined by a large temperature gradient at its upper limit. Changes in the sill depth of Kane Gap would thus exert a vital control on the transfer of Antarctic Bottom Water between the Sierra Leone and Gambia basins. If our inference is correct that extensive subsidence of the order of several hundred metres has taken place along parts of the eastern section of the Guinée Fracture Zone, this would imply that significant penetration of Antarctic Bottom Water through Kane Gap may not have occurred until after the close of the Eocene when the sill became sufficiently deep for water transfer. Such a conclusion would be compatible with recent drilling results in the Gambia Basin (Fig. 1). A striking feature of the Tertiary sequence at DSDP Site 367 is the greatly condensed Oligocene section (LANCELOT et al., 1977b), which can be interpreted as reflecting conditions of slow deposition and, perhaps, erosion brought about the vigorous flow of bottom water in the Gambia Basin after its passage through Kane Gap.

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