

## 18. THE SEDIMENTARY DEPOSITS OF SUIKO SEAMOUNT (LEG 55, SITE 433): FROM THE REEF ENVIRONMENT TO THE PELAGIC SEDIMENTATION

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### INTRODUCTION

The four holes (including a re-entry hole) drilled at Site 433 allow determination of the sedimentary sequence of Suiko Seamount in the Emperor chain. The holes are in a small graben basin situated within a lateral lagoon on the seamount. The sedimentary deposits range from the Paleocene to the upper Pliocene and are not uniform and continuous. A major hiatus exists at the top of the lower Eocene reef sediment, below the lower and upper Miocene pelagic sediments. The depositional history and succession of environments are shown by mineralogical and geochemical changes in the sediments.

### LITHOLOGY

The diversified sedimentary sequences recovered from the four holes (433, 433A, 433B, and 433C) are described in the site reports (this volume), and the biostratigraphic results are summarized by Koizumi, Butt, Ling, and Takayama (this volume). The composite sequence comprises six lithologic units the thicknesses of which can only be approximated from the recovered material because of the drilling disturbance. These lithologic units are as follows:

Unit 1: 0.0–1.5 meters:	Upper Pliocene and lower Pleistocene foraminiferal nannofossil ooze.
Unit 2: 1.5–14.5 meters:	Upper Pliocene sandy diatom-nannofossil ooze.
14.5–43.0 meters:	Upper Miocene and lower Pliocene marly siliceous nannofossil ooze.
Unit 3: 43.0–51.5 meters:	Upper Miocene calcareous ooze and chalk.
Unit 4: 51.5–52.0 meters:	Lower Miocene siliceous ooze.
52.0–52.5 meters:	Lower Miocene sandy tuffaceous mud.
Unit 5: 52.5–168.0 meters:	Late and middle Paleocene reef sand, sandy mud with algal concretion, and calcarenite.
Unit 6: 177.5–181.5 meters:	Volcanic reef sand interlayered between basalt Flow Units 1 and 2.

In the upper part of the sedimentary sequence, the lithologic units do not correspond exactly to the paleontological partitions. There are several biostratigraphic hiatuses: between Units 1 and 2; in Unit 2; and the ma-

jor hiatus between Units 3 and 4, in which can be differentiated two separate periods of hiatus — at the lower part of Unit 3 during middle Miocene, and before the reef sedimentation (Unit 5) in the Paleocene. From Unit 4 to Unit 1 the fossil assemblages are generally reworked, and the sediment accumulation rate of this section, about 13 m/m.y., is relatively high.

### MINERALOGY

The mineralogical analyses using the X-ray diffraction techniques as described by Karpoff et al. (this volume) were performed on bulk sediments. Descriptive data are given in Table 1. The uniform calcareous character of the deposits masks, on the X-ray diffraction charts, the occurrence of small amounts of other minerals.

*Calcite* prevails and forms the pelagic biogenic component as foraminifers and nannofossils in Units 1 to 4 and the reef deposits in the lower Units 5 and 6.

*Amorphous silica*, from the siliceous biogenic component as diatoms, is well represented in Unit 2.

*Clays* include illite, kaolinite, smectites, and trace amounts of chlorite; they are abundant in Units 2, 3, and 4.

*Detrital silicates*, as volcanic glass, quartz, plagioclases, and trace amounts of amphiboles, occur in Units 1 and 2, and prevail in the coarse fraction ( $>63\mu\text{m}$ ) of the sandy volcanic layer (Unit 4).

*Authigenic minerals* occur in some units. Unit 2 contains small amounts of carbonate-apatite; this mineral occurs also in Unit 4 associated with barite and the zeolite harmotome. In the reef sand (Unit 5), gypsum appears in trace amounts in some samples, and pyrite forms concretions which can be separated from the bulk material (e.g., Sample 433A-8-1, 180–182 cm).

The mineral assemblage — calcite, clays, amorphous silica, and detrital components — is constant in the upper part of the pelagic deposits from Unit 1 to Unit 3, with only a change in the proportions of minerals. The sandy volcanic mud is mineralogically distinct from the pelagic sediments and the calcareous lagoonal formation containing low concentrations of gypsum, pyrite, and clays. The occurrence of authigenic zeolites in this section, described by McKenzie et al. (this volume), is not observable on the X-ray diffraction charts.

### GEOCHEMISTRY

#### Results and Characteristics of the Successive Lithologic Units

The bulk chemical compositions of the samples from Site 433 are given in Tables 2 and 3. The same bulk ma-

TABLE 1  
Mineralogical Results from X-Ray Diffraction of Non-Oriented  
Powders for Site 433 (Holes 433, 433A, 433B, 433C).  
Descriptive Data Only

Sample (Interval in cm)	Unit	Calcite	Quartz	Plagioclase	Amorphous and Biogenic SiO <sub>2</sub>	Clays	Halite	Apatite	Other Minerals
433-1-1, 60-62	1	+	+	+			+		Tr Amphibole
-1-1, 129-131	1	+	+	+		+			
433A-1-1, 7-9	1	+	+	+	(and K-feld)				
-2-1, 70-72	1	+	+	+					
-3-1, 80-85	1	+					+		
-3-6, 21-23	1	+					+		
433-1-2, 40-42	2	+	+	+		+			
-1-2, 127-129	2	+	Tr	+					
-1-3, 7-9	2	+	+				+		
-1-3, 104-106	2	+	+						
-1-4, 26-28	2	+		+					Amphibole?
433A-4-1, 7-8	2	+	+		+				
-4-2, 66-68	2	+	+		+	+			
-4-2, 68-70	2	+	+		+	+		Tr	
-4-2, 100-105	2	+	+		+	+	+		
-4-3, 55-60	2	+	+		+	+			
-4-3, 85-90	2	+	+		+	+		Tr	
-4-4, 60-62	2	+	+	Tr	+	+	+		
-4-6, 92-95	2	+	+			+	+		
-5-2, 130-132	2	+					Tr		
-5-4, 20-22	2	+	+	Tr			+		
5-5, 110-112	2	+	+			+	+		
-6-1, 50-53	3	+					Tr		
-6-3, 140-144	3	+	Tr				+		
-6-6, 60-62	3	+	+			+	+		
-6-6, 120-122	3	+	Tr			+	Tr		
-6-7, 20-22	4	+	+		+	+		+	
-6-7, 36-38	4	+		+	+	+			Barite
-6,CC	4	+	+	+		+		+	Barite-zeolites (harmotome)
-7-1, 90-92	5	+							
-7-6, 100-102	5	+							
-8-1, 120-122	5	+							
-8-1, 120-122b	5	+							Pyrite
-8-3, 15-17	5	+				+			
-8-7, 40-42	5	+							
-9-2, 30-32	5	+					+		
-10-1, 71-73	5	+							Gypsum
-10-7, 3-5	5	+							
-12-1, 72-74	5	+							
-13-1, 20-22	5	+							
-16-1, 58-60	5	+							
-16,CC (4-7)	5	+							
-19-1, 23-25	5	+							
433B-1-4, 119-120	5	+							
-1-4, 120-126	5	+							
-2-1, 0-150	5	+							
-3-1, 20-60	5	+					+		
433C-3-2, 103-106	6	+		+	+				

Clays: Illite, kaolinite, and smectites.

terial as studied in the X-ray diffraction analyses were analyzed here, using the spectrometry techniques described by Karpoff et al. (this volume). Results are shown in Figure 1.

In accordance with the mineralogical composition, the two prevalent elements are calcium and silicon, in proportions which vary with the lithology. The variation of the Si/Al ratio (Table 4) follows the relative abundances of silicates as clays and volcanic fragments and of amorphous biogenic silica as diatoms.

**Unit 1.** The deposits are composed of calcareous material (high Ca, Sr) associated with clays and other detrital minerals, and are characterized by a low Si/Al ratio; they contain relatively high concentrations of Fe, Ti, Mg, Na, K, and the trace elements Mn, V, Ni, Cr, Cu, Zn, and Pb.

**Unit 2.** From top to bottom, the silicon content decreases with a correlative increasing calcium content. The greater amount of diatoms and other siliceous organisms in the upper part of this unit is indicated by the increase in the Si/Al ratio and in silicon, barium, and lead contents. The occurrence of Ba and Pb in the siliceous organisms is well known, and high concentrations of these elements in pelagic siliceous oozes are often described, (El Wakeel and Riley, 1961; Arrhenius, 1963; Brongersma-Sanders, 1967; Turekian, 1968; Chow and Goldberg, 1970; Boström et al., 1973; Hoffert et al., 1978).

The authigenic silicates in the same upper part of Unit 2 are clays, and their occurrence is marked by an increased boron content (Landergreen and Carjaval, 1969; Kukal, 1971). In this unit, trace elements such as Co, Cr, Ni, Zn, Cu, and Mn increase with increasing Fe, Mg, Na, and K.

**Unit 3.** This lithologic unit has the same composition as the overlying part of Unit 2, with a slight increase in the silicon content.

**Unit 4.** The two sub-units, siliceous ooze and volcanic sandy mud, have the lowest carbonate contents and correspondingly higher concentrations of other elements. The two sub-units differ in their silica and boron contents on the one hand, and on the other in their iron and trace-element contents, corresponding to the siliceous organisms and authigenic clays, and the volcanic detrital fragments, respectively. The presence of other minerals, such as barite and carbonate-apatite, is indicated in the two levels by the barium and phosphorus contents. These two layers are of the same geochemical facies, and differ only in the planktonic and mineral contributions.

**Units 5 and 6.** The reef calcareous sandy mud is characterized by its low contents of all elements other than calcium. A peculiarity of these calcareous deposits is their very low strontium contents. The pyrite concretion contains small amounts of silicon, barium, and nickel. Unit 6 is a mixture of lagoonal sand and volcanic fragments, and accordingly contains higher concentrations of elements from the volcanic phases.

### Strontium Variations in the Sedimentary Deposits of Site 433

The positive correlation between strontium and calcium in carbonate sediments is well known. At Site 433, the calcareous biogenic phases differ, below and above the sandy volcanic mud (Unit 4), in their strontium contents. According to data from Turekian (1964), the Sr/Ca ratios range from 20 to 5 in reef formations and deep-sea carbonates, respectively. In the Site 433 lagoonal sandy mud (Units 5 and 6), the Sr/Ca ratio is very low, and increases in the overlying volcanic layer and diatom-calcareous oozes (Table 4). The CaO-Sr diagram (Figure 2) shows the relative positions of the different lithologic units. In the pelagic siliceous and calcareous oozes (Units 1, 2, and 3), the Sr and CaO contents are strongly correlated, with normal concentrations. In the volcanic layer and the siliceous ooze from Unit 4 with a low biogenic calcium content, the Sr con-

TABLE 2  
Chemical Analyses of Sedimentary Deposits from Site 433, Leg 55, Suiko Seamount. Major Elements (%)

Sample (Interval in cm)	Unit	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	MgO	CaO	Fe <sub>2</sub> O <sub>3</sub>	Mn <sub>3</sub> O <sub>4</sub>	TiO <sub>2</sub>	BaO	Na <sub>2</sub> O	K <sub>2</sub> O	Ign	Total
433-1-1, 60-62	1	35.6	7.8	1.35	27.5	3.0	0.057	0.36	0.09	1.35	0.62	23.12	100.85
-1-1, 129-131	1	36.3	7.6	1.51	26.1	3.4	0.047	0.35	0.15	1.13	0.69	22.74	100.02
433A-1-1, 7-9	1	37.3	7.5	1.54	24.4	3.7	0.055	0.38	0.14	1.31	0.80	21.25	98.57
-2-1, 70-72	1	45.8	9.3	1.87	18.5	4.8	0.061	0.45	0.14	1.80	1.28	14.97	98.97
-3-1, 80-85	1	12.0	0.5	0.38	47.0	0.2	0.012	0.03	0.09	0.05H	0.05H	40.06	100.37
-3-3, 21-23	1	9.8	0.7	0.32	49.1	0.2	0.013	0.03	0.09	0.05H	0.05H	40.15	100.41
433-1-2, 40-42	2	46.4	7.1	1.71	19.9	4.6	0.046	0.37	0.20	1.65	0.87	17.70	100.55
-1-2, 127-129	2	26.8	0.6	0.50	37.5	0.4	0.010H	0.04	0.15	0.09	0.05H	33.87	100.01
-1-3, 7-9	2	34.7	3.1	0.92	31.1	1.8	0.022	0.16	0.16	0.49	0.34	28.12	100.91
-1-3, 104-106	2	28.1	1.7	0.74	35.0	1.1	0.018	0.08	0.17	0.26	0.11	32.17	99.45
-1-4, 26-28	2	28.5	0.5	0.36	36.4	0.1H	0.010H	0.02	0.12	0.07	0.05H	33.76	99.89
433A-4-1, 7-8	2	33.8	1.0	0.55	33.2	0.6	0.019	0.05	0.27	0.21	0.12	30.69	100.51
-4-2, 66-68	2	58.9	3.2	1.73	10.7	3.7	0.022	0.17	0.73	1.87	1.63	15.76	98.41
-4-2, 68-70	2	59.3	3.4	1.88	10.0	4.3	0.026	0.18	0.67	2.13	1.85	14.63	98.37
-4-2, 100-105	2	57.2	1.6	1.02	15.8	0.9	0.010H	0.08	0.53	1.08	1.09	20.43	99.74
-4-3, 55-60	2	45.3	1.5	0.92	23.5	1.0	0.024	0.09	0.40	0.90	0.73	25.31	99.67
-4-3, 85-90	2	36.7	1.1	0.59	30.7	0.5	0.015	0.05	0.30	0.25	0.20	29.60	100.01
-4-4, 60-62	2	35.4	1.2	0.52	30.3	0.8	0.022	0.06	0.32	0.36	0.25	30.31	99.64
-4-6, 92-95	2	30.3	1.3	0.45	35.2	0.5	0.022	0.05	0.20	0.22	0.20	31.47	99.91
-5-2, 130-132	2	18.8	0.4	0.33	43.8	0.2	0.020	0.03	0.12	0.05	0.05H	36.76	100.56
-5-4, 20-22	2	19.2	0.8	0.52	43.3	0.3	0.012	0.04	0.19	0.05	0.05H	35.94	100.40
-5-5, 110-112	2	26.7	1.3	0.76	37.1	0.6	0.014	0.07	0.31	0.12	0.05H	33.61	100.63
-6-1, 50-53	3	14.1	1.0	0.47	46.5	0.4	0.022	0.05	0.27	0.05H	0.05H	38.02	100.93
-6-3, 140-144	3	23.0	1.1	0.56	38.4	0.4	0.017	0.05	0.29	0.08	0.05H	35.46	99.41
-6-6, 60-62	3	19.8	1.2	0.59	40.8	0.5	0.018	0.06	0.32	0.05H	0.05H	35.88	99.27
-6-6, 120-122	3	6.4	0.7	0.44	50.4	0.4	0.041	0.04	0.49	0.07	0.05H	40.68	99.71
-6-7, 20-22	4	65.9	3.9	1.54	3.5	3.4	0.022	0.39	2.45	2.19	1.78	10.95	96.02
-6,CC	4	40.0	9.2	2.23	14.8	8.6	0.049	1.07	1.46	2.26	2.63	11.76	94.06
-1-7, 90-92	5	1.7	0.3	0.77	54.5	0.2	0.010H	0.04	0.03	0.09	0.05H	43.02	100.71
-7-6, 100-120	5	3.0	0.7	0.84	52.3	0.8	0.010H	0.13	0.05	0.08	0.05H	41.63	99.56
-8-1, 120-122	5	0.5	0.2H	0.72	53.7	0.1H	0.010H	0.03	—	0.08	0.05H	43.83	99.09
-8-1, 120-122b	5	5.1	0.4	0.12	2.3	59.5	0.060	0.04	0.05	0.15	0.15	32.47	100.34
-8-3, 15-17	5	0.6	0.2H	0.71	53.6	0.1	0.010H	0.03	—	0.07	0.05H	43.71	99.04
-8-7, 40-42	5	0.7	0.2H	0.71	52.6	0.1	0.010H	0.03	—	0.07	0.05H	43.93	98.35
-9-2, 30-32	5	0.8	0.2H	0.79	54.2	0.1	0.010H	0.03	—	0.09	0.05H	43.60	99.87
-10-1, 71-73	5	1.8	0.5	0.86	52.0	0.4	0.010H	0.10	—	0.08	0.05H	42.86	98.66
-10-7, 3-5	5	2.1	0.4	0.94	52.8	0.4	0.010H	0.09	—	0.09	0.05H	43.04	99.92
-12-1, 72-74	5	1.2	0.2	0.85	54.7	0.2	0.010H	0.04	—	0.10	0.05H	43.25	100.60
-13-1, 13-22	5	2.0	0.6	1.05	53.8	0.7	0.010H	0.09	—	0.08	0.05H	41.99	100.36
-16-1, 58-60	5	1.6	0.5	0.96	52.9	0.7	0.012	0.09	—	0.08	0.05H	41.83	98.71
-16,CC (4-7)	5	1.2	0.3	0.99	53.4	1.1	0.018	0.05	—	0.09	0.05H	42.65	99.87
-19-1, 23-25	5	2.7	0.7	1.08	50.9	1.2	0.098	0.12	—	0.15	0.06	41.88	98.89
433B-1-4, 119-120	5	1.6	0.5	0.92	51.9	0.5	0.010H	0.08	—	0.06	0.05H	43.27	98.89
-1-4, 120-126	5	1.5	0.5	0.93	53.3	0.6	0.011	0.08	—	0.06	0.05H	42.26	99.29
-2-1, 0-150	5	1.8	0.6	0.94	52.9	0.7	0.014	0.10	—	0.06	0.05H	42.07	99.23
-3-1, 20-60	5	0.9	0.3	0.96	53.6	0.5	0.026	0.05	—	0.07	0.05H	43.03	99.53
433C-3-2, 103-106	6	20.3	5.9	2.58	34.7	6.6	0.116	1.23	0.02	1.24	0.45	26.94	100.07

Note: Total iron and manganese are calculated as Fe<sub>2</sub>O<sub>3</sub> and Mn<sub>3</sub>O<sub>4</sub>; Ign is ignition loss at 1000°C. 433A-6-7, 20-22 cm: P<sub>2</sub>O<sub>5</sub> = 1.0%; 433A-6,CC: P<sub>2</sub>O<sub>5</sub> = 3.4%.

centration is higher than that of the detrital volcanic material, when compared with the concentration in the first underlying basalt flow (chemical analysis from shipboard report). The reef sequence (Units 5 and 6) is characterized by a low Sr content. In shallow water, strontium is removed from sea water by calcareous organisms, specifically the coral-oölite-algae association (Turekian, 1964; Bathurst, 1971). It appears that the Sr-impoverishment of the reef facies is a result of diagenesis. The diagenetic evolution of these shallow-water carbonates is discussed by McKenzie et al. (this volume). They describe the dissolution of aragonite and

formation of blocky calcite and zeolites in the upper part of the sequence. Thus, the strontium moves to the overlying volcanoclastic deposits, and is retained in the authigenic zeolites, barite, or carbonate-apatite of this formation.

#### EVOLUTION ALONG THE SEDIMENTARY SEQUENCE AT SITE 433: INFLUENCES OF VOLCANISM, SUBSIDENCE, HIATUS, AND ACCUMULATION RATES

The mineralogical and geochemical data, compared with the biostratigraphic results, allow construction of a

TABLE 3  
Chemical Analyses of Sedimentary Deposits from Site 433, Leg 55, Suiko Seamount. Trace Elements (ppm)

Sample (Interval in cm)	Unit	Sr	Ba	V	Ni	Co	Cr	B	Zn	Ga	Cu	Pb
433-1-1, 60-62	1	1104	676	74	30	11	43	72	114	11	26	36
-1-1, 129-131	1	1402	1308	75	33	15	49	42	123	12	23	37
433A-1-1, 7-9	1	890	1025	61	28	17	53	57	84	7	18	139
-2-1, 70-72	1	933	1013	106	38	22	64	73	124	16	18	25
-3-1, 80-85	1	2015	841	5H	2	2H	5H	13	4H	2H	2H	2H
-3-6, 21-23	1	2151	818	5H	3	2H	5H	24	8	2H	2	2H
433-1-2, 40-42	2	1368	1803	101	63	34	80	80	192	17	25	28
-1-2, 127-129	2	2436	1937	5H	21	6	9	52	38	3	8	13
-1-3, 7-9	2	2217	1532	42	38	8	34	79	95	6	26	24
-1-3, 104-106	2	2127	1967	35	46	32	18	68	68	3	12	29
-1-4, 26-28	2	3084E	1867	33	20	35	7	68	33	3	3	23
433A-4-1, 7-8	2	2710	2683	17	22	33	27	71	102	4	6	17
-4-2, 66-68	2	678	4570	107	74	47	72	157	112	13	49	99
-4-2, 68-70	2	561	3971	102	77	49	80	152	122	14	43	63
-4-2, 100-105	2	1029	3763	64	46	11	30	115	57	6	47	67
-4-3, 55-60	2	1396	3180	24	33	31	16	135	62	4	18	26
-4-3, 85-90	2	2115	3042	16	32	22	10	103	71	4	8	16
-4-4, 60-62	2	2309	3123	24	29	17	22	96	113	6	0	20
-4-6, 92-95	2	2586	1958	14	17	10	5H	50	55	5	9	22
-5-2, 130-132	2	2598	1074	5H	7	2H	5H	28	2	2	2H	2
-5-4, 20-22	2	2705	2099	5H	19	2H	5H	37	13	2	2H	2H
-5-5, 110-112	2	3258E	4549	47	32	36	14	51	72	6	6	17
-6-1, 50-53	3	3014E	3015	5H	17	2H	5H	5H	23	2	2H	2H
-6-3, 140-144	3	2441	3709	10	21	2H	5H	33	56	3	3	6
-6-6, 60-62	3	3338E	3314	36	29	38	30	75	11	3	2H	22
-6-6, 120-122	3	3822E	6213E	33	19	38	13	5H	13	4	2	11
-6-7, 20-22	4	908	S	76	104	38	94	266	60	13	58	36
-6,CC	4	1178	S	173	107	38	270	178	176	22	83	20
-1-7, 90-92	5	777	249	9	7	2H	15	20	19	3	2	2H
-7-6, 100-120	5	624	364	26	12	2H	34	15	24	2	3	2H
-8-1, 120-122	5	680	9	9	10	3	14	25	8	2H	42	10
-8-1, 120-122b	5	33	293	5H	107	2H	7	5H	2H	2H	16	4
-8-3, 15-17	5	609	10	8	19	2H	48	5H	10	3	4	2H
-8-7, 40-42	5	602	8	22	9	2H	16	5H	25	5	5	5
-9-2, 30-32	5	574	45	5H	7	2H	8	5H	9	2H	2	67
-10-1, 71-73	5	818	7	42	13	31	25	21	24	4	6	5
-10-7, 3-5	5	755	6	16	3	2H	19	26	17	3	4	2H
-12-1, 72-74	5	613	12	6	9	2H	13	13	11	4	4	26
-13-1, 20-22	5	811	17	5	9	2H	20	5H	16	2	6	76
-16-1, 58-60	5	757	23	16	13	2H	21	5H	16	3	11	80
-16,CC (4-7)	5	695	101	9	13	2H	35	30	18	3	4	31
-19-1, 23-25	5	497	26	6	8	2H	27	5H	17	2H	10	7
433B-1-4, 119-120	5	715	16	5H	15	2H	16	5H	12	2	4	20
-1-4, 120-126	5	613	29	5H	10	2H	14	5H	2	2H	4	11
-2-1, 0-150	5	543	19	5H	11	2H	15	5H	3	2H	2	57
-3-1, 20-60	5	488	10	5H	2H	2H	5H	5H	2H	2H	4	20
433C-3-2, 103-106	6	575	103	163	40	13	63	21	100	11	24	27

Note: H: value below the lower detection limit; S: value over the upper detection limit; E: extrapolated value.

depositional history of the Suiko seamount sedimentary sequence.

### The Paleocene Shallow Warm Water Sedimentation

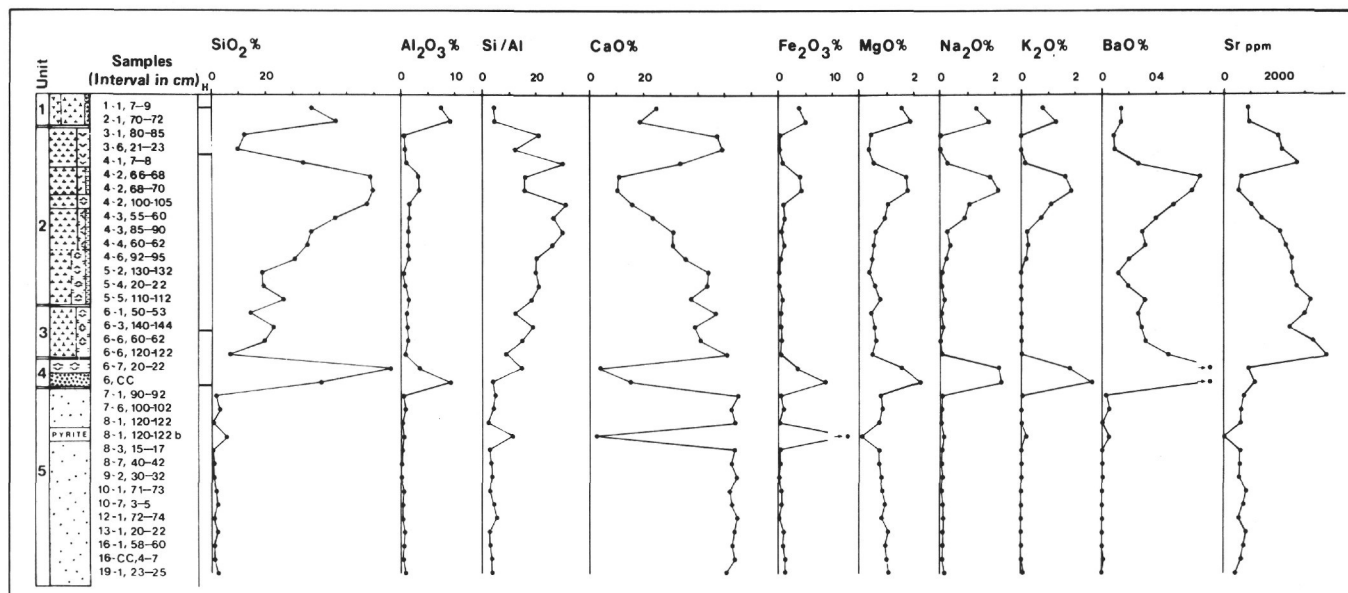
The reef calcareous sand lies on the eroded surface of an alkalic basalt flow, and ranges upward to a carbonate mud. In the sequence the diagenesis described by McKenzie et al. (this volume) has occurred, as the constant volcanic influence induced the dissolution of aragonite and the formation of calcite and zeolites. The occurrence of diagenetic zeolites in sedimentary rocks is common in a volcanic environment (Coombs et al.,

1959; Staples, 1965; Sheppard and Gude, 1973), but is generally related to the alteration of volcanic glass enclosed in the deposits (Hay, 1966; Cronan, 1974; Hof-fert et al., 1978).

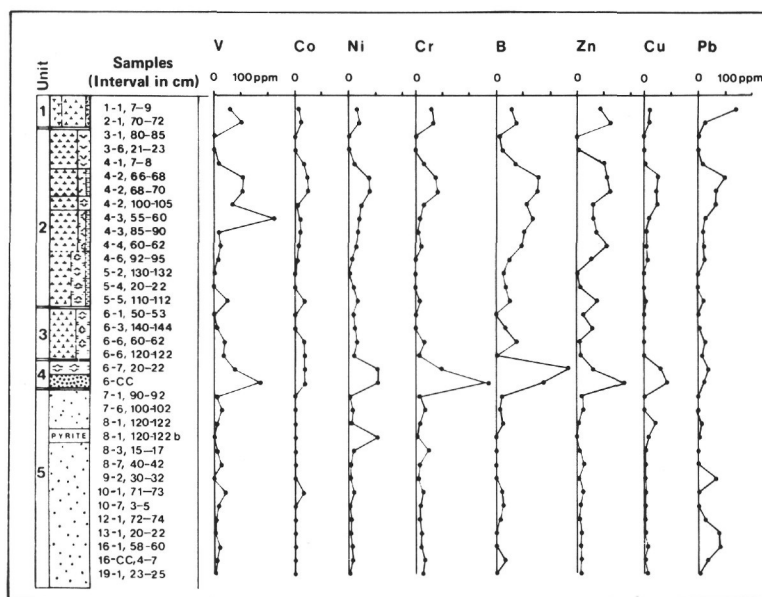
Another authigenic mineral in the upper part of the lagoonal sequence is pyrite, which occurs in two forms, framboids (Plate 1) in the pores of reef organism fragments and massive concretions of centimeter size.

Authigenic pyrite is a well-known constituent of sediments, whose geographic and stratigraphic occurrences were reviewed by Love and Amstutz in 1966, and since that time it has often been observed (Hein and





A



B

Figure 1. (A) Variations in contents of major elements (%) and Sr (ppm) and in Si/Al ratio along the sedimentary column of Hole 433A. The thickness is not to scale. (B) Variations in trace-element contents (ppm) along the sedimentary column of Hole 433A.

Griggs, 1972; Marchand, 1974; Odent and Prouvost, 1974; Dell, 1975). Organic activity in a reducing environment is the commonly hypothesized mechanism for framboidal pyrite formation; different explanations of the process are given by Rickard (1970); Sweeney and Kaplan (1973); and Goldhaber and Kaplan (1974). High organic content of the calcareous deposits is also responsible for the very small amount of gypsum present (Arrhenius, 1963; Siesser and Rogers, 1976; Briskin and Schreiber, 1978).

The source of S and  $\text{SO}_4^{2-}$  could be steams migrating through the volcanic terrace. This volcanic influence promotes the formation of the nickel-rich pyrite concretions. The occurrence of pyrite in zones of high vol-

canic activity has been described by Goldhaber and Kaplan (1974) and by Bonatti et al. (1976).

The association of zeolite, pyrite, and scarce gypsum in the lagoonal deposits appears to be a result of simultaneous organic and volcanic influence in shallow warm water environment.

#### The Period of the Miocene Hiatus

At the end of the Paleocene, a period of non-sedimentation began, and the Eocene and Oligocene are not represented in the section. In the interval below the upper Miocene pelagic sediment and overlying the lagoonal formation, the sedimentary deposits are composed of a volcanic mud and siliceous ooze (Unit 4) and

TABLE 4  
Element-Ratios in Sedimentary Deposits from Site 433

Sample (Interval in cm)	Unit	Si/Al	Mn/Fe	Fe/Ti	Sr Ca $\times 10^3$
433-1-1, 60-62	1	6.86	19.6	9.67	5.62
-1-1, 129-131	1	4.20	14.2	11.27	7.52
433A-1-1, 7-9	1	4.38	15.3	11.29	5.11
-2-1, 70-72	1	4.33	13.1	12.37	7.06
-3-1, 80-85	1	21.12	61.8	7.73	6.00
-3-6, 21-23	1	12.32	66.9	7.73	6.14
433-1-2, 40-42	2	5.75	10.3	14.42	9.63
-1-2, 127-129	2	39.31	25.7	11.60	9.10
-1-3, 7-9	2	9.85	12.6	13.05	9.98
-1-3, 104-106	2	14.55	16.8	15.95	8.51
-1-4, 26-28	2	50.16	103.0	5.80	11.87
433A-4-1, 7-8	2	29.74	32.6	13.92	11.43
-4-2, 66-68	2	16.20	6.16	25.25	8.87
-4-2, 68-70	2	15.35	6.23	27.71	7.86
-4-2, 100-105	2	31.46	11.5	13.05	9.12
-4-3, 55-60	2	26.58	24.7	12.89	8.32
-4-3, 85-90	2	29.36	30.9	11.60	9.65
-4-4, 60-62	2	25.96	28.96	15.47	10.67
-4-6, 92-95	2	20.51	45.3	11.60	10.29
-5-2, 130-132	2	19.36	103.0	7.73	8.31
-5-4, 20-22	2	21.12	41.12	8.70	8.75
-5-5, 110-112	2	18.07	24.0	9.94	12.30
-6-1, 50-53	3	12.41	56.6	9.28	9.08
-6-3, 140-144	3	18.40	43.7	9.28	8.90
-6-6, 60-62	3	14.52	37.0	9.67	11.46
-6-6, 120-122	3	8.05	105.5	11.60	10.62
-6-7, 20-22	4	14.87	6.7	10.11	36.33
-6, CC	4	3.83	5.8	9.32	11.15
-1-7, 90-92	5	4.99	51.6	5.80	1.99
-7-6, 100-120	5	3.77	12.8	7.14	1.67
-8-1, 120-122	5	4.20	103.0	3.87	1.77
-8-1, 120-122b	5	11.22	104.0	1725.50	2.01
-8-3, 15-17	5	2.64	103.0	3.87	1.59
-8-7, 40-42	5	3.08	103.0	3.87	1.60
-9-2, 30-32	5	3.52	103.0	3.87	1.48
-10-1, 71-73	5	3.17	25.7	4.64	2.20
-10-7, 3-5	5	4.62	25.7	5.16	2.00
-12-1, 72-74	5	5.28	51.5	5.80	1.57
-13-1, 20-22	5	2.93	14.6	9.02	2.11
-16-1, 58-60	5	2.82	17.6	9.02	2.00
-16, CC (4-7)	5	3.52	16.9	25.52	1.82
-19-1, 23-25	5	3.39	84.1	11.60	1.37
433B-1-4, 119-120	5	2.82	20.6	7.25	1.93
-1-4, 120-126	5	2.64	18.9	8.70	1.61
-2-1, 0-150	5	2.64	20.6	8.12	1.44
-3-1, 20-60	5	2.64	53.6	11.60	1.27
433C-3-2, 103-106	6	3.03	18.10	6.22	2.32

a calcareous ooze, in the lower part of Unit 3, which contains pyrite concretions. These formations appear to be lower Miocene, but show considerable reworking and contain organisms of diversified age.

#### The Two Levels of Lithologic Unit 4

The mineralogical and geochemical data show that the volcanic layer, in Unit 4, contains barite, apatite, and zeolites associated with plagioclases, quartz, detrital volcanic minerals, and calcareous components. This layer is enriched in barium and strontium.

The scanning-electron microscope photographs (Plate 2) show the evolution of the mineral assemblage in the coarse fraction. The feldspars are often well preserved, and their low degree of alteration consists of exfoliated

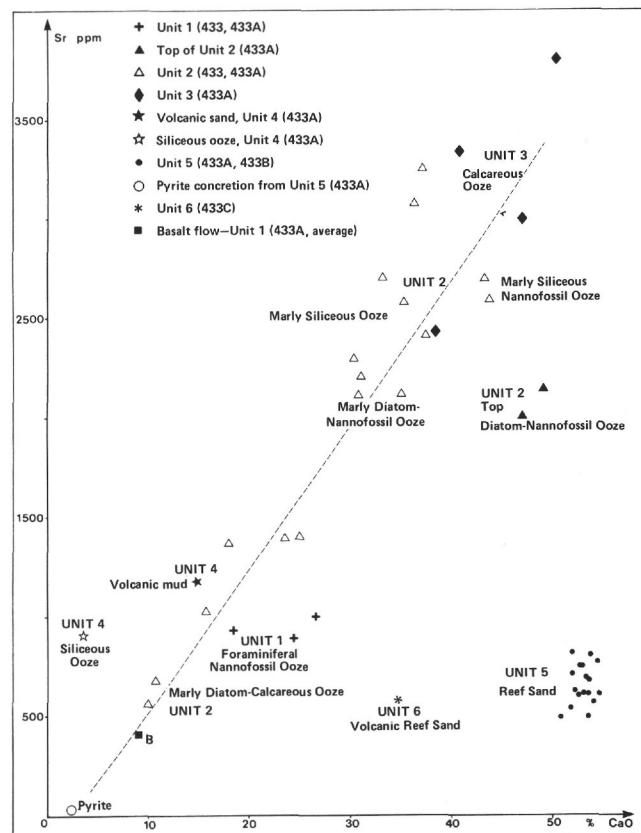


Figure 2. Relation between CaO (%) and Sr (ppm) contents in bulk sediments from Site 433 (Holes 433, 433A, 433B, 433C).

fine sheets (figure 1). The volcanic debris occurs as rounded grains of volcanic glass, in which phenocrysts are associated with authigenic components as twinned crystals of zeolites (figures 2 and 3). They have been progressively coated by clays, calcareous debris (coccoliths), carbonate-apatite, barite, and secondary zeolites (figure 4). Figures 5, 6, 7, and 8 show these diversified components overlying a twinned crystal of zeolite. The barite crystals are very small and enclosed in the clays and phosphate matrix. Within the coating the nannofossil fragments are altered. In the pores, a very well crystallized secondary zeolite is associated with clays. Finally, the primary twinned crystals of zeolite are completely coated and form rounded indurated particles (figure 9).

These observations indicate that the tuffaceous level is a volcanic sand deposited in a marine environment and show its evolution to an indurated and consolidated layer. Such phenomena of alteration of volcanic sand and induration by authigenic processes in shallow sea water containing calcareous organisms are not unknown. Indurated sedimentary layers have been described by Morgenstein (1967) and by Hoffert et al. (1978), with reference to the same conditions, in shallow warm water.

Nevertheless, in the altered volcanic layer at Suiko Seamount the cementation processes have not formed a continuous consolidated layer with the final deposition

of ferromanganese oxides. The high-activity environment maintained the sandy facies. The occurrence of carbonate-apatite and barite, and the high Sr contents of the authigenic minerals, also differentiate this tuffaceous layer from the indurated sediments from the South Pacific, and bring to mind the cemented formations from continental margins and seamounts of the Atlantic Ocean (Tooms et al., 1969; Le Lann, 1972; Karpoff et al., in preparation).

The occurrence of barite is reviewed by Cronan (1974); its formation under volcanic or shallow hydrothermal coastal environment and in sediments rich in organic material is cited by Goldberg et al. (1969), Sakai (1971), and by Dean and Schreiber (1978).

The volcanic sandy deposits have been altered and the authigenic process developed in relatively confined shallow water, in an active environment and under volcanic influence in the restricted basin on Suiko Seamount.

The upper part of Unit 4 is a siliceous ooze which has the same mineral and geochemical assemblages, with different ratios, as the underlying tuffaceous layer. The siliceous fauna comprises radiolarians ranging from lower Miocene to Pliocene. The reworked nannofossils are lower Miocene (Scientific staff, this volume; Schaff, personal communication).

The highly reworked character of Unit 4 and the mineral and planktonic assemblages allow me to interpret the two levels of this unit as resulting from grain-size and mechanical sorting of mixed volcanic and biogenic deposits.

#### Evolution of Unit 4

Thus, from the late Paleocene until the Miocene, sedimentation in our small graben basin on Suiko Seamount was very irregular. The hiatus at the end of lagoonal sedimentation corresponds to a period of non-sedimentation.

The onset of the pelagic sedimentation started with deposition of volcanic fine sand and pelagic material, probably introduced into the basin by currents during a period of tectonic activity and irregular, intermittent submergence of the seamount.

The high-energy environment induced a sorting of the biogenic and detrital material. The volcanic deposits were altered, with authigenesis taking place probably at the same time as the diagenetic evolution of the underlying lagoonal deposits. The contribution of components coming from the diagenetic reef formation, from volcanic steam, from the altered volcanoclastic material, and from the degraded organic matter, promoted authigenesis of silicates, sulfates, and carbonates.

The deposition of fresh volcanoclastic particles and reworked planktonic organisms was continuous during the early Miocene. This material was mixed with the older altered and authigenic components, which started to form an indurated sedimentary level in shallow warm-water environment.

At the top of the lower Miocene, the sedimentary deposits are more calcareous, and form the lower part of lithologic Unit 3. Near its top, this pelagic section

contains pyrite concretions formed under volcanic influence, similar to those of the lagoonal deposits.

This sequence corresponds to a phase intermediate between the high-energy depositional environment with volcanic influences (Unit 4) and the pelagic sedimentation of Unit 2. The accumulation rate was very high during this period, and the shallow water became cooler. The hiatus occurring at middle Miocene can be interpreted as non-sedimentation during the subsidence of Suiko Seamount, and a period of tectonic activity in the basin.

#### The Period of Pelagic Sedimentation

After the middle Miocene hiatus, sediment accumulation resumed with formation of siliceous-calcareous deposits. The increase in siliceous components and the decrease of calcareous organisms from Unit 3 to Unit 2 are gradual. The sediment accumulation rate was very high (5 cm/1000 years), and the material has been reworked. A change in the environment shown by the fauna assemblage (Butt, this volume) is due to the gradual cooling of the water mass.

The change in the siliceous/calcareous biogenic ratio is a result of the increase in depth of the sedimentation to deeper and cooler water. Under the hypothesis of a lysocline higher than the actual CCD, carbonate material would be selectively dissolved. Nevertheless, the grading can also be the result of reworking and sorting in an active environment.

The geochemical data indicate that the lower Pliocene hiatus, located in the upper part of Unit 2, started early in the sedimentary history with a recrudescence of calcareous deposits. The authigenic processes are also indicated by the increase in boron within clays above the hiatus.

The lower Pliocene hiatus marks a sharp change in the depositional environment to a more typical recent siliceous calcareous pelagic deposit. The upper two Units, 2 and 1, are distinguished by their sedimentological constitution, and the last hiatus during the late Pliocene did not induce geochemical or mineralogical changes in Unit 1. The top of the sedimentary column is a typical Recent pelagic deposit.

#### CONCLUSION

The sedimentary depositional history at Suiko Seamount comprises three major periods during the subsidence of the seamount: (1) The reef period, during which the calcareous lagoonal deposits had a diagenetic evolution, finishes at the upper Paleocene. The environment involved shallow warm water, volcanic steam influence, and a confined basin. (2) Deposition of a detrital volcanic sand mixed with siliceous biogenic material. The authigenetic process started producing an indurated level. The environment was characterized by high-energy reworking, sorting, volcanic influence, shallow warm water in a restricted basin. (3) Pelagic sedimentation in progressively cooler environment started in the late Miocene. The sediments are reworked up to the upper Pliocene.

The depositional environment and the sedimentary sequence at Site 433 on Suiko Seamount differ from those of the other seamounts of the Emperor chain. This is a result of the location of the studied site in a tectonic basin within the lateral lagoon of the seamount. This situation induces sluggish exchange with the open sea. The tectonic activity and intermittent pulses during the subsidence and submergence of the island favored reworking of the successive deposits, and gave rise to periods of non-sedimentation. In the meantime, diagenetic and authigenetic phenomena transformed the sedimentary deposits.

#### ACKNOWLEDGMENTS

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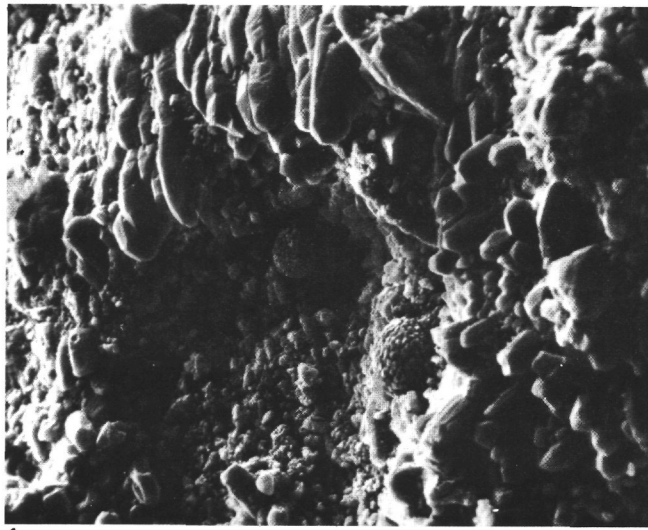
The analytical work was carried out with the technical support of the Institut de Géologie (Strasbourg, France). The S. E. M. microphotographs are the work of Irène Peterschmitt.

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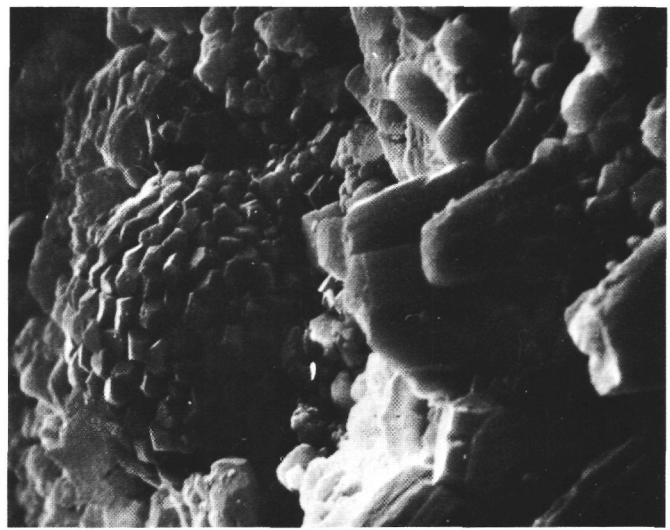
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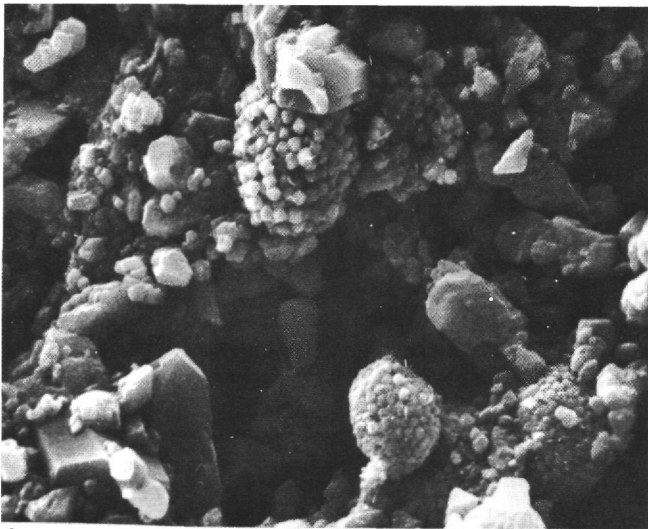
## PLATE 1



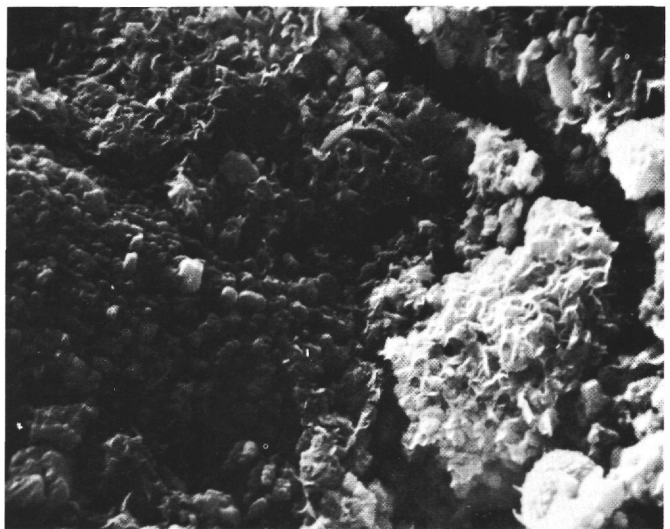
1 25 μm



2 5 μm



3 5 μm



4 5 μm

## PLATE 1

S.E.M. photomicrographs of bryozoan fragments from reef sand composing Unit 5 at Site 433. Authigenic clays and framboidal pyrite occur in bryozoan pores which are calcite-recrystallized.

- Figure 1 General view of a bryozoan pore with framboids of pyrite; recrystallized calcite fringes the pore.
- Figure 2 High magnification of figure 1, showing framboid of pyrite.
- Figure 3 Very small framboids of pyrite in another pore.
- Figure 4 Authigenic clays as smectites growing in a bryozoan pore.

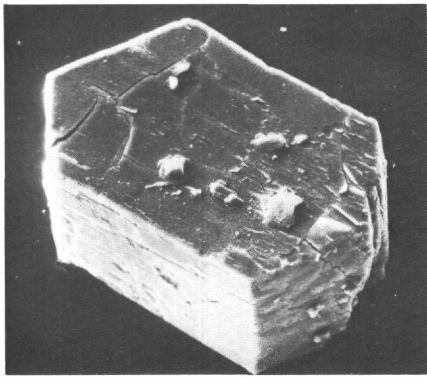


PLATE 2

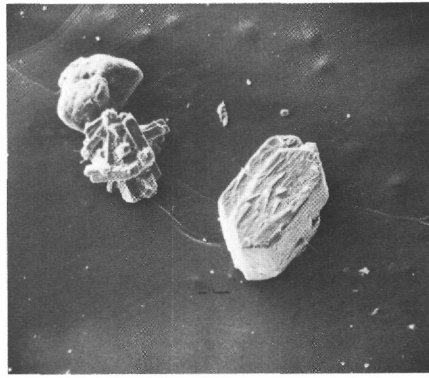
S. E. M. photomicrographs of particles from the coarse fraction ( $> 63\mu\text{m}$ ) of the volcanic sand making up sedimentary Unit 4 from Hole 433A. (All minerals were determined by X-ray dispersive energy spectroscopy tests.)

- Figure 1      Well-preserved crystal of plagioclase. The beginning of alteration is shown by small sheets released from the crystal surface.
- Figure 2      In the coarse fraction, well-preserved crystals of plagioclase associated with authigenic twin crystals of zeolites (harmotome).
- Figure 3      Authigenic twin crystals of zeolite with a fine deposit of calcareous debris and clays.
- Figure 4      The primary twin crystals of zeolite are coated with calcareous debris clays and secondary silicates as zeolites.
- Figure 5      High magnification of figure 3, showing coating of clays, coccolith fragments, and secondary zeolites.
- Figure 6      In the coated material, the primary twin zeolites, small crystals of barite (B) occur with the clays and coccolith fragments.
- Figure 7      A secondary well-crystallized zeolite growing in pore of cemented primary twin zeolites.
- Figure 8      Detail of small secondary zeolite (phillipsite or harmotome) with fine deposits of clays.
- Figure 9      Finally, the primary twin crystals of zeolite are completely coated and cemented by the secondary deposits (clays, coccoliths, barite, and secondary zeolites) and form rounded aggregated particles.

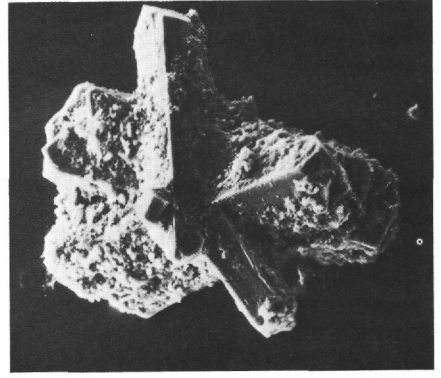
PLATE 2



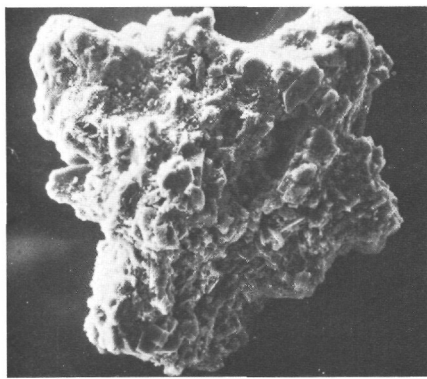
1 50  $\mu$ m



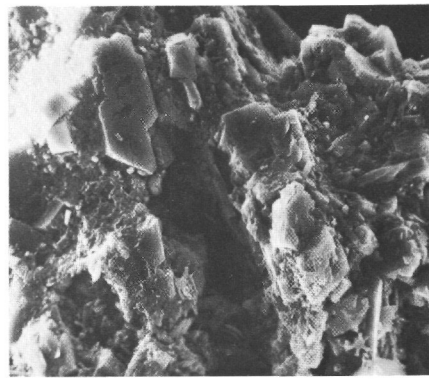
2 250  $\mu$ m



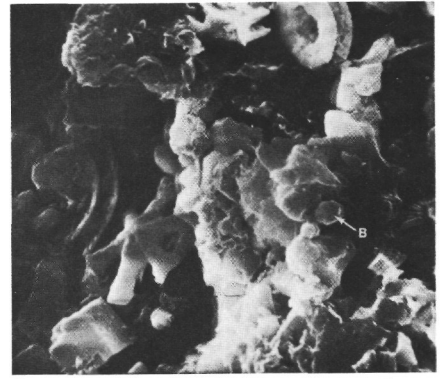
3 50  $\mu$ m



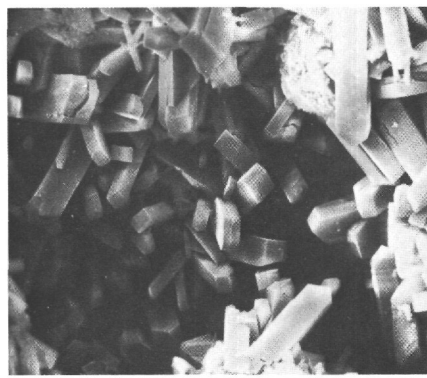
4 50  $\mu$ m



5 25  $\mu$ m



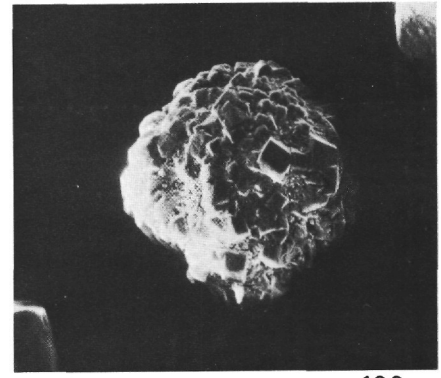
6 5  $\mu$ m



7 25  $\mu$ m



8 10  $\mu$ m



9 100  $\mu$ m