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Hydrothermal deposits and associated basement rocks from the Galapagos spreading center

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ABSTRACT

– Relatively thick (up to 15 m) hydrothermal deposits from the southern flank of the Galapagos spreading center were drilled on a crust of about 0.62 myr old (magnetic age), during Leg 54 of the "Glomar Challenger" in the central Eastern Pacific Ocean. A stratigraphic sequence of ferrobasalt, pelagic oozes, and hydrothermal deposits of green clay-rich material and Fe-Mn concretions were recovered. The green clay-rich material (Fe-Si type of smectite) is also found interlayered between the pelagic ooze and filling veins, veinlets and vesicles in the drilled basement rocks. The low transitional metal content (Cu < 150 ppm), Ni < 100 ppm and Co < 200 ppm) and the nature of the green clay-rich material from the Galapagos deposits make them comparable to that of other hydrothermal products discovered from other oceanic ridges. In general, the basement rock has a higher transitional metal content than the overlying hydrothermal material. Hydrothermal fluids percolating from the basement through the sedimentary cover or precipitating from solutions emmanating from localized vents are proposed models for the origin of the hydrothermal layers. –

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RÉSUMÉ

Dépôts hydrothermaux et socle océanique associé de la dorsale d'accrétion des Galapagos

– La découverte de couches relativement épaisses (jusqu'à environ 15 m) de matériel hydrothermal a pu être réalisée à l'aide de plusieurs forages profonds dans une croûte

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de 0,62 ma pendant le Leg 54 du « Glomar Challenger » dans l'Océan Pacifique oriental. Ces forages ont permis de mettre en évidence une séquence stratigraphique allant du socle basaltique au sédiment pélagique et à des produits hydrothermaux faits de produit vert riche en argile et de concrétions de Fe-Mn. Les produits verts riches en argile (type de smectite riche en Fe et Si) sont interstratifiés dans du sédiment pélagique et existent aussi comme matériel de remplissage de veines et de vacuoles dans le socle basaltique. La faible teneur en éléments métalliques (Cu < 150 ppm, Ni < 100 ppm et Co < 200 ppm) ainsi que le type d'argile rencontré dans les dépôts des Galapagos les rend semblables aux produits hydrothermaux découverts sur d'autres dorsales d'accrétion. Chaque trou atteignant le socle a révélé l'existence de basalte riche en Fe et Ti ayant une teneur d'éléments métalliques plus importante que celle trouvée dans les dépôts hydrothermaux qui les recouvrent. L'infiltration de fluide hydrothermal à travers la couverture sédimentaire ou la précipitation de solutions émanantes par des conduits localisés sont les modèles proposés pour expliquer les différents niveaux de produits hydrothermaux.

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INTRODUCTION

Recent heat-flow (Sclater, Klitgord, 1973; Sclater *et al.*, 1974; Williams *et al.*, 1974), morphological (Hey *et al.*, 1977; Hey, 1977; Lonsdale, 1977), magnetic (Herron, Heirtzler, 1967; Sclater, Klitgord, 1973; Klitgord, Mudie, 1974) and chemical investigations (Corliss *et al.*, 1977) of the sea floor at the Galapagos spreading axis, East Pacific Ocean (Fig. 1), have shown hydrothermal fields that appear to be genetically linked to the formation, alteration, and mineralization of ocean crust at accreting plate boundaries. As examples, one field near 95°10′ W and 2°30′N consists of a thick Fe-Mn crust of hydrothermal origin on the flank of the spreading axis (Moore, Vogt, 1976), and surveys of another field near 86°10′ W and 0°35′N (Klitgord, Mudie, 1974; Lonsdale, 1970) revealed a 350 km^2 field of sediment mounds associated with high water-temperatures ($\sim$ 10°C; Crane, Normark, 1977) and high heat-flow (5 to 28 HFU; Sclater, Klitgord, 1973; Williams *et al.*, 1974). Visual observation by submersibles has permitted the recognition of recent hydrothermal activities in the mound area (Corliss, Ballard, 1977).

The sediment mounds are of particular interest to the studies of crustal hydrothermal activity because of their association with heat-flow maxima and their lineation along basement fractures and ridges parallel to the Galapagos spreading axis (Corliss *et al.*, 1977). Deep-tow surveys have shown that each mound is about 5 to 10 m high and 25 m in radius (Klitgord, Mudie, 1974; Lonsdale, 1977). The mounds consist of hard, dark-colored and flat-lying material and are highly reflective acoustically (Corliss *et al.*, 1977). In places they are associated with massive dark-colored outcrops having bright yellow patches and bands (Corliss *et al.*, 1977) and resemble the Fe-Mn crusted sediment in the hydrothermal field of transform fault "A" in the Famous area (Arcyana, 1975; Hoffert *et al.*, 1977).

In spite of the abundant geological data accumulated in recent years for the Galapagos hydrothermal field, the sediment mounds, seemingly of hydrothermal origin and critical to understanding hydrothermal activity, had yet to be lithologically characterized. Accordingly, one of the major objectives of Leg 54 of the Deep-Sea Drilling Project was to drill into and sample the sediment mounds at the Galapagos spreading center. Only by obtaining precise lithologic information for these important crustal features can we hope to address critical questions such as: (i) what is the vertical extent of hydrothermal material? (ii) what are the relationships between hydrothermal products and the associated sediment column and basement rock? (iii) is the basement

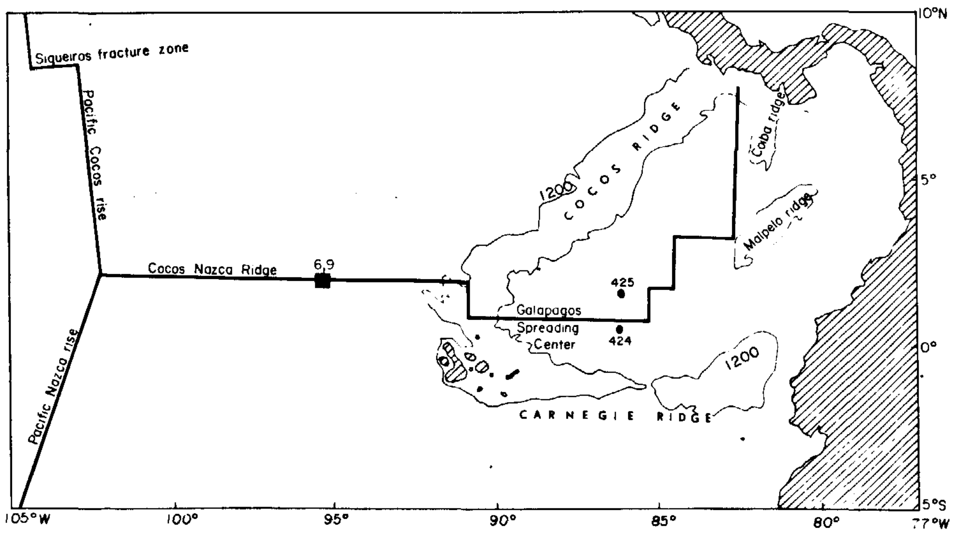

Figure 1
General bathymetric map of the Eastern Pacific Ocean showing the Dsdp sites 424 and 425 (leg 54) from the Galapagos spreading center. Dredges (D6 and D9) containing Fe-Mn crusts and studied by Moore and Vogt (1976) are reported.

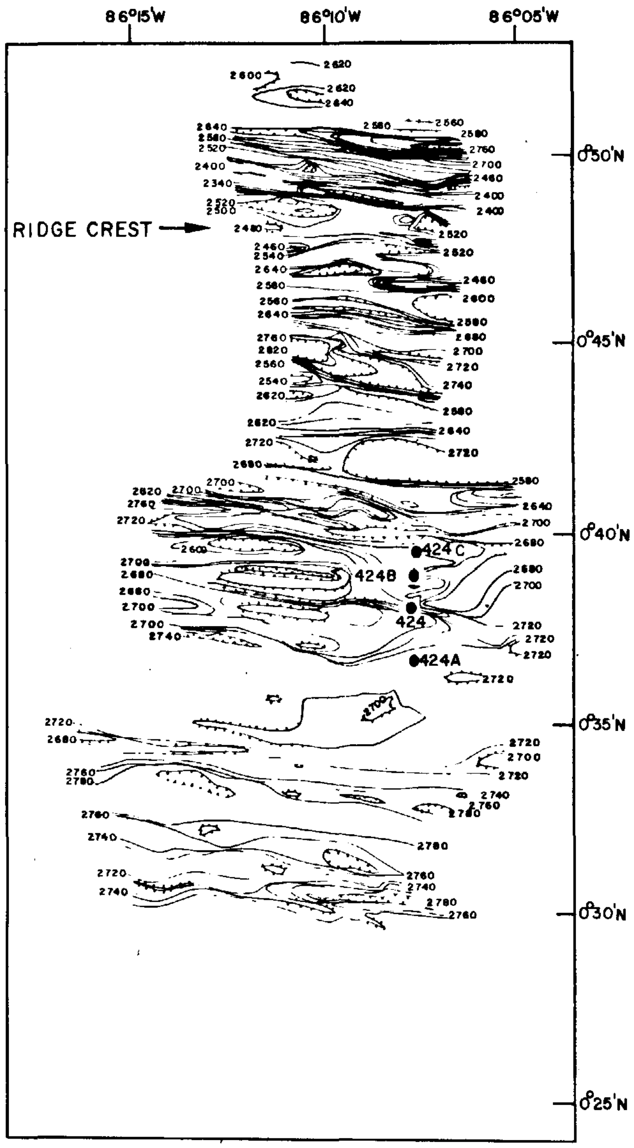

Figure 2

Bathymetric map of the Galapagos spreading center region based on near-bottom deep tow data after Klitgord and Mudie (1974) and Detrick and Klitgord (1972). The contour intervals are in corrected meters. The holes from site 424 (leg 54) are shown.

beneath the hydrothermal sediments the locus of fluid circulation? (iv) does the basement rock show evidence of hydrothermal alteration? and (v) how does the hydrothermal material from this region compare to that of other accreting plate boundaries?

GEOLOGICAL SETTING OF THE GALAPAGOS DRILLED SITES

The crustal spreading axis of the Galapagos region is a complex east-west trending fracture system extending due east from the intersection of the Pacific, Cocos, and Nazca lithospheric plates (the Nazca-Cocos-Pacific (NazCoPac) triple junction of Holden and Dietz, 1972, at 2°N and 102°W) (Fig. 1). Three major segments compose the spreading axis – the Cocos-Nazca rise, the Galapagos Spreading Center, and the Costa Rica Ridge – and combined with the Cocos and Carnegie ridges, a wedge-shaped feature (the Galapagos Gore) is formed with one apex at the NazCoPac junction (Fig. 1).

Of particular concern here is the central segment of the spreading axis, the Galapagos Spreading Center, where the topography has 200 to 400 m of relief and the rift valley is only weakly defined. Drilling near this center by the "Glomar Challenger" along a north-south traverse (Sites 424, South; Site 425, North, Fig. 2) at 86°05′ longitude revealed that the flanks of the ridge are defined by north- and south-dipping fault blocks 1 to 3 km wide and with a vertical displacement of less than 300 m (Fig. 3). The sediment cover increases away from the ridge axis and reaches about 100 m thick at 70 km distance (Fig. 3). The regional sediment blanket averages 28 to 30 m in thickness in the suspected hydrothermal area (Leg 54, Scientific Party, 1977).

Sites 424, 424 A, 424 B and 424 C were drilled about 22 km south of the Galapagos spreading center near 0°35′N and 86°07′W in about 2 700 m water depth (Figs. 1, 2, 3). The four holes were drilled about 300 m from each other along a north-south traverse (Figs. 2, 3, 4). Crustal ages as extrapolated from magnetic anomalies, are about 0.60 to 0.62 myr old,

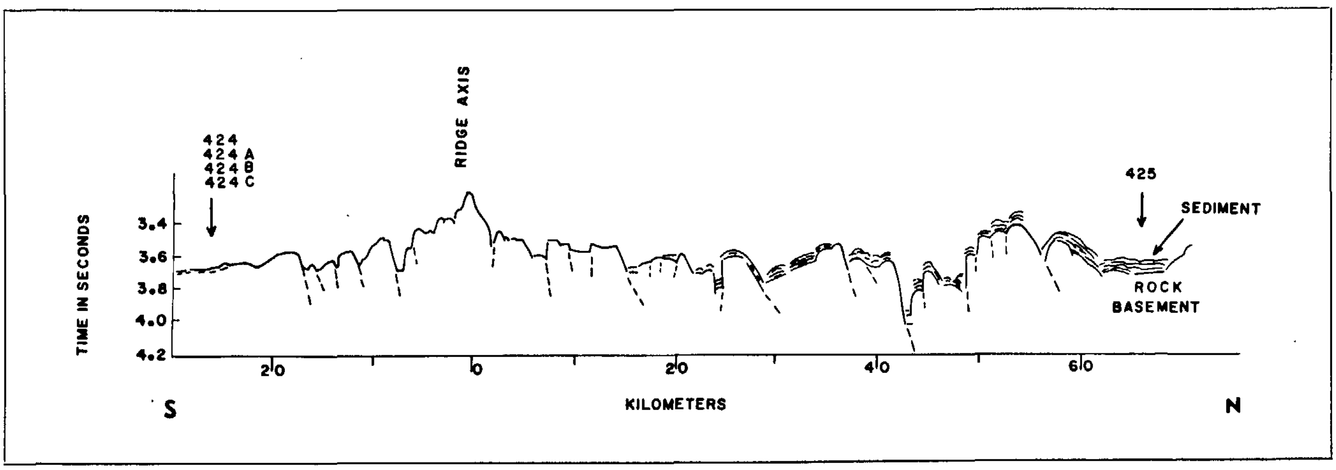

Figure 3

Line drawing of the original 3.5 kHz EDO record profile showing the fault-block structure and the sediment thickness of the Galapagos spreading center in the area of leg 54 drilling sites. The faulted structure extending into the basement is extrapolated from the surface topography.

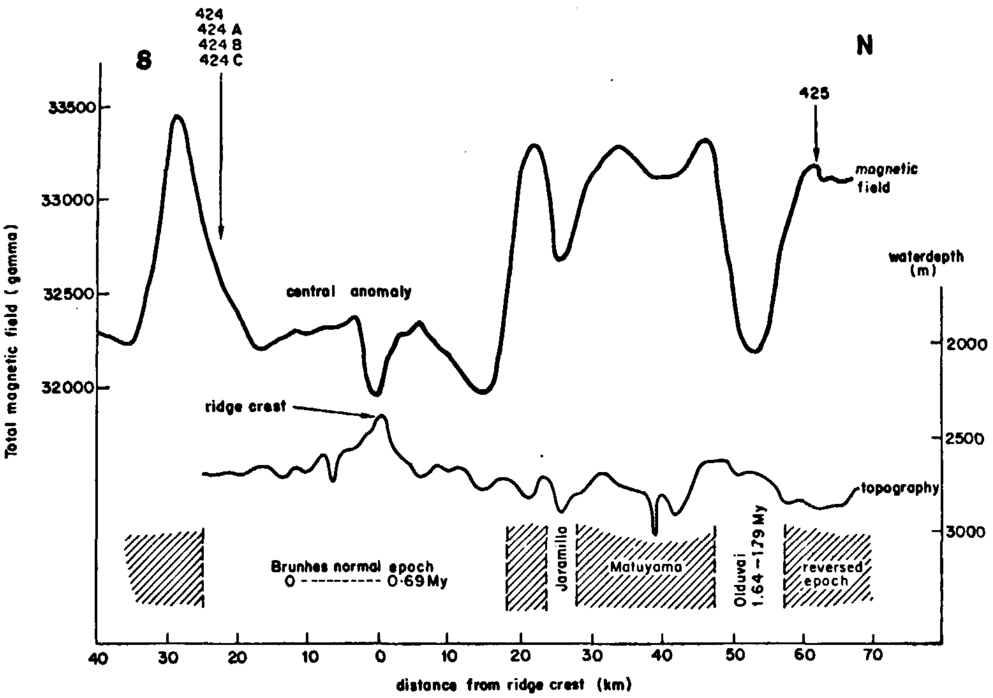

Figure 4
Total marine magnetic anomalies recorded during leg 54 of the "Glomar Challenger" near 86° W - NS transect of the Galapagos spreading center region. The drilled holes are shown on the diagram.

corresponding to the Brunhes epoch of the Heirtzler *et al.* (1968) time scale. This age is supported by the dates of the oldest sediments, 0.4 to 1.2 myr as interpreted from a radiolarian fossil zone. Further north of the Galapagos spreading axis there is a drop of the intensity of the total magnetic field to about 32 300 γ which corresponds to the Olduvai event (1.64-1.79 myr), according to the Heirtzler *et al.* (1968) time scale (Fig. 4). A second site, 425, was drilled 62 km north of the spreading center just beyond the Olduvai event at a water depth of 2 850 m (Figs. 1, 2, 3, 4, Table 1). Based on magnetic anomalies the crustal age there is about 1.8 myr old. A nanofossil age near the bottom of the hole is estimated to be 1.9 myr bp. No hydrothermal deposits were recovered in this hole.

LITHOLOGY OF THE DRILLED HOLES

One of the goals of the Galapagos drilling operation was to locate the hydrothermal mounds discussed above. This was not an easy task as previous work (Klitgord, Mudie, 1974; Lonsdale, 1977) had shown them to have a dimension of about that of the "Glomar Challenger" herself (5-20 m high, 20-50 m wide and 50-500 m long).

Table 1
Locations and depths of leg 54 drilled holes from the Galapagos Spreading Center in the Eastern Pacific Ocean.

Sites	Latitude	Longitude	Depth in meters (uncorrected)	Penetration into basement
424	0°35.63'N	86°07.82'W	2 685	76 m
424 A	0°35.33'N	86°07.81'W	2 708	34 m
424 B	0°35.82'N	86°07.82'W	2 705	46.5 m
424 C	0°35.93'N	86°07.82'W	2 699	34.5 m
425	01°23.68'N	86°04.22'W	2 850	110 m

In addition to protruding above the sea floor, the mounds are highly reflective and disrupt the acoustic continuity of the regional sediment cover (Scientific party, Leg 54, 1977). In order to drill as close as possible to a mound, these were relocated using a 20 cubic inch air-gun towed at about 3.5 knots. Precise ship positioning over the mounds was obtained by deploying the EDO sonar scanning reentry tool through the drill pipes which were hanging at about 10 m above the drill string.

Holes 424 and 424 A are on or very close to sediment mounds and were continuously cored through sediment and basalt: 31 and 45 m, respectively, for 424, and 29 and 5 m for 424 A. Recoveries from both holes are continuous layers of about 15 m of presumably hydrothermal sediment made up essentially of green clay-rich material intermixed with Fe-Mn concretions (Fig. 5). The sediments are underlain by pelagic sediments (foram-nano ooze) interlayered with less than 50 cm of material similar to that above it. To determine if the sediment mounds are the only sites of deposit of the Fe-Mn concretions and the green clay-rich material, Site 424 B was drilled about 300 m north of Site 424 in an area presumed to be away from the mounds (Figs. 2, 3, 5) and was continuously cored. Basaltic basement at 424 B was encountered at 32 m subbotom depth and penetrated 14.5 m for 3 m of recovery (Figs. 2, 3, 5). Poor recovery, however, of the top part of the hole 424 B (3 m for the first core) limits our knowledge of the thickness of the green clay-rich material (Fig. 5). However, since the bottom part of the third core contains green clay-rich material, it is assumed that there was a thickness of at least 10 m in the top of the sediment column. Below a subbotom depth of about 10 m, the sediment is essentially a foram-nano ooze interlayered with 10-70 cm layers of green clay-rich material and rare Fe-Mn concretions (< 10%) (Fig. 4). This green clay layer in Hole 424 B seems to correlate with seismic reflectors seen on deeptow profiles by Klitgord and Mudie (1974)

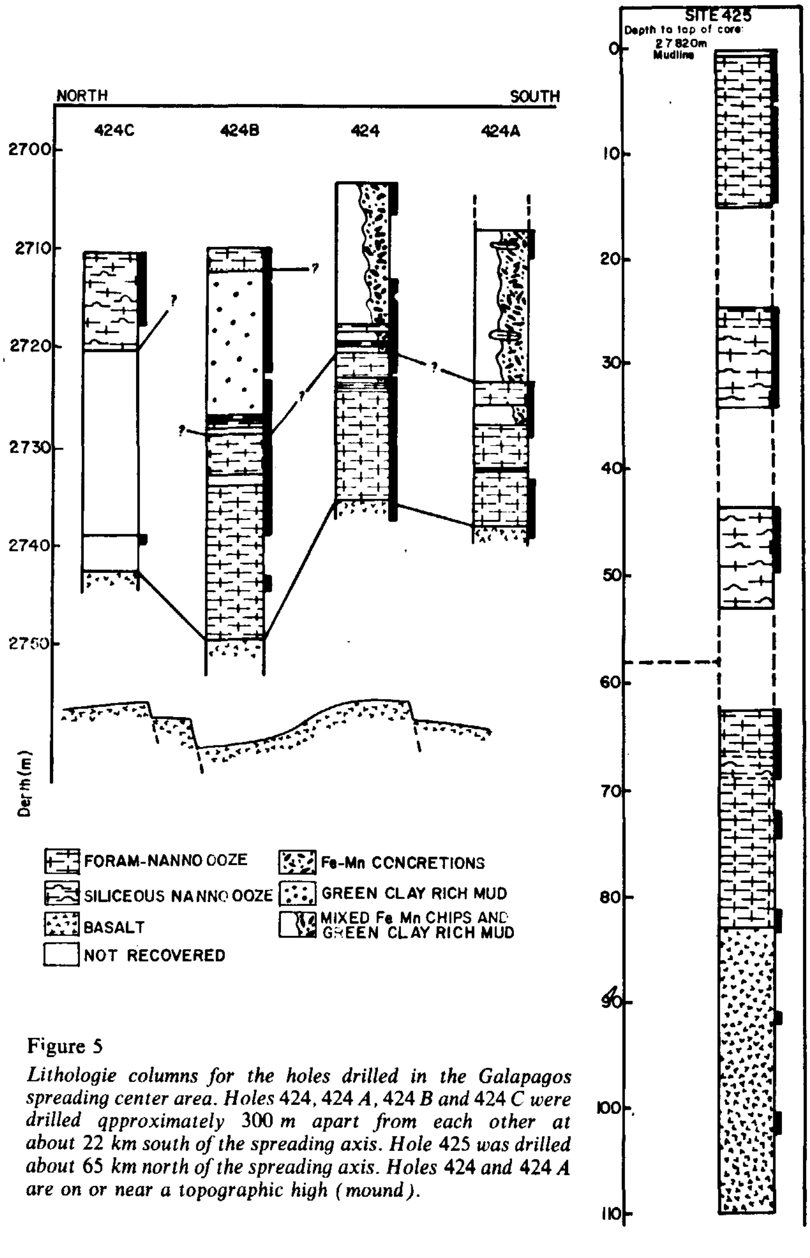

Figure 5
Lithologie columns for the holes drilled in the Galapagos spreading center area. Holes 424, 424 A, 424 B and 424 C were drilled qpproximately 300 m apart from each other at about 22 km south of the spreading axis. Hole 425 was drilled about 65 km north of the spreading axis. Holes 424 and 424 A are on or near a topographic high (mound).

and by Lonsdale (1977) throughout the Galapagos mounds area. Shipboard physical property measurements showed that the green clay-rich materials were denser and had higher sonic velocities (at least 2 km/sec.) than the carbonate ooze. If the green clay-rich layer is responsible for the reflectors in the mounds area, then it is possible that the hydrothermal deposit covers an area of more than 200 km². The major difference between cores 424 and 424 A and 424 B is that 424 B contains a smaller amount of the Fe-Mn concretions intermixed with the green clay-rich material (Fig. 5). A fourth hole, 424 C, was also intended to be a non-mound site, but was only partially cored with about 7 m of uppermost sediments recovered (Fig. 5).

On board the "Glomar Challenger", mini-core samples were taken from the cores for density and velocity measurements. The velocity measurement for the pelagic sediment is about 1.5 km/sec. The hydrothermal material in cores 424, 424 A and B range to over 1.8 km/sec. However it is estimated that the *in situ* velocities for undisturbed hydrothermal material are over 2 km/sec.

MINERALOGY AND CHEMISTRY OF THE MATERIAL RECOVERED

The deposits from the Site-424 holes are divided into two major categories according to the relative proportions of the green clay-rich fractions and the Fe-Mn concretions. This material and associated pelagic sediments and basement rock are discussed below.

Green clay-rich material

This sediment is relatively soft and consists of irregular semi-indurated chunks and small particles (0.1 to 0.5 cm) that are dusky brown, grayish olive green, greenish black, and dark yellowish-green in color (Fig. 5). The individual grains are friable under the finger nail, and under the microscope they have a very low birefringance and appear to be platy. The material is free of any organic fragments or other pelagic sediments and has no obvious bedding. The general textural features of the green clay-rich material as observed with a scanning electron microscope show agglutinated spherules forming tubes of less than 20 μm in length and arranged in a ring-like fashion (Février, personal communication). X-ray diffraction patterns of the green clay-rich material shows a 11.6 Å peak which, upon glycolation, expands up to 17 Å; it consists largely of smectite. In addition, small amounts of goethite and an amorphous silica phase were detected.

Chemically, the green clay-rich material of holes 424, 424 A and 424 B is high in Fe (about 22 wt %, average) and Si (up to 26%), and low in Mn (< 1%) and Al (< 1%) (Tables 2, 3). The transition metal content of the green clay-rich material in 424 and 424 A is remarkably low: on the average, Ni is less than 20 ppm, Cu is less than 400 ppm, and Co is less than 30 ppm (Tables 2, 3). However the composition of the green clay-rich material

Table 2

Composition of Galapagos hydrothermal sediment from Dsds sites 424 and 424 A with other sediment types for comparison.

	Fe (%)	Mn (%)	Ni (ppm)	Co (ppm)	Pb (ppm)	Zn (ppm)	Cu (ppm)	Al (%)	Mg (%)
1	21.6	0.10	16	22	60	35	14	0.12	2.54
2	5.06	0.48	211	101	68	165	323	8.4	2.1
3	7.25	33.0	81	16	48	126	39	0.15	1.65
4	11.96	19.78	6 340	3 350	846	680	3 920	3.06	1.71

1. Average values in 11 Galapagos Green Clays from Mounds Area (This work) (*).
2. Average of Pacific Pelagic Clay (Cronan, Tooms, 1969; Turekian, Wedepohl, 1961).
3. Ferromanganese Concretions from Mounds Area (This work) (*).
4. Average of Pacific Manganese Nodules (Cronan, 1972).
(*) Analyses by Atomic Absorption Spectrophotometry.

of 424 B departs slightly from the others by its higher Zn (about 120 ppm) and Cu contents (about 100 ppm) (Table 3). Overall, the green clay-rich sediments differ considerably from average Pacific pelagic sediment (Co = 100 ppm, Ni = 211, Cu = 323 and Zn = 165 ppm) and from average manganese nodules of the Pacific (Co = 3 350 ppm, Ni = 6 340 ppm, Cu = 3 920 ppm, Zn = 680 ppm) (Table 2).

In their general characteristics, the green clay-rich deposits show similarities to the clay-rich hydrothermal deposits found in transform fault "A" in the Famous area (Hoffert *et al.*, 1978) (Fig. 7). The Ni and Co contents in deposits from both the Galapagos and Famous areas are less than 100 ppm, or less than half the average values for pelagic clay and basement rock of basaltic compositions (Fig. 7). Chemical variations among the various types of hydrothermal material, and also between these and other types of deposits, are shown in the (Cu + Ni + Co)-Fe-Mn ternary diagram of Figure 8. The field of the green clay-rich material is well separated from the others by its relative abundance in Fe (Fig. 8). The Pacific nodules and the Fe-Mn coating of basaltic rocks are far more enriched in Cu + Ni + Co than any of the green clay-rich deposits (Fig. 8).

Fe-Mn concretions

This type of deposit is disseminated throughout the green clay-rich material with no observed concentrations, except in 424 A where it mainly occurs in discrete portions of Cores 1 (section 2, 2-2.5 m depth in the hole) and 2 (sections 1 and 2, 11-11.5 m in the drilled hole). The thickness of the layers containing abundant concretions is less than 1 m. The site 424 Fe-Mn concretions usually occur in individual botryoidal chunks having irregular shapes (3 to 4 cm in diameter) and often with black and dark gray metallic lusters (Fig. 6). One tubular fragment found in Hole 424 (core 1, section 2; 1.7-2.0 m in the hole) has a shape resembling a cone and was presumably formed around an organism (Figs. 5, 6).

The concretions are distinctive in composition. Relative to the green clay-rich material (Mn < 1 wt%; Fe = 22%), they are rich in Mn (about 33 wt%) and relatively poor in Fe (about 12%), and compared to Pacific Mn-nodules,

Table 3

Chemical analyses of representative samples from the Galapagos spreading center (Leg 54). Samples 424-1-1 (90 cm), 424-2-4 (30-33 cm) and 424-3-5 (35-40 cm) were analysed by X ray fluorescence (P. Cambon and J. Etoubleau, analysts, COB). Samples 424-2-2 (11-13 cm), 424-4-6 (39-41 cm), 424 B-2-2 (50-52 cm) and 424 A-2-2 (9-11 cm) were analysed by arc spectrometry (Université de Strasbourg). (Ign) indicates ignition loss at 1 000°C.

	Green clay-rich material					Foram-nano ooze	Fe-Mn concretions
Oxides (wt %)	424-1-1 90 cm	424-2-2 11-13 cm	424-2-4 30-33 cm	424 A-2-2 9-11 cm	424 B-2-2 50-52 cm	424-4-6 39-41 cm	424-3-5 35-40 cm
SiO_2	49.35	53.3	45.95	51.4	53.9	12.3	0.71
Al_2O_3	0.52	0.20	0.32	0.2	0.50	2.60	0.78
Total Fe as Fe_2O_3	30.38	30.6	28.12	29.0	29.5	2.2	0.34
MnO	0.14	0.17	0.06	0.12	0.06	1.03	70.89
MgO	2.37	4.41	3.71	4.43	3.60	1.73	3.19
CaO	0.05	0.30	0.17	0.6	0.40	41.5	1.37
Na_2O		2.08	1.43	2.2	2.47	0.06	–
K_2O	2.27	3.39	3.65	3.91	2.96	0.05	0.28
TiO_2	0.03	0.02	0.02	0.02	0.04	0.10	–
Ign.	13.9	6.79	15.84	6.81	6.37	36.00	25.15
Total	99.01	100.26	99.27	98.81	99.80	99.41	100.91
Fe (wt %)	21.27	21.42	21.89	20.30	20.65	1.54	0.24
Mn (wt %)	0.11	0.13	0.05	0.09	0.05	0.96	54.90
Co (ppm)	–	3	–	15	3	2	–
Cu	–	30	–	61	100	32	–
Zn	–	53	–	108	118	45	–
Ni	–	10	–	34	16	55	–
Pb	–	55	–	23	62	10	–
Cr	–	9	–	10	13	15	–

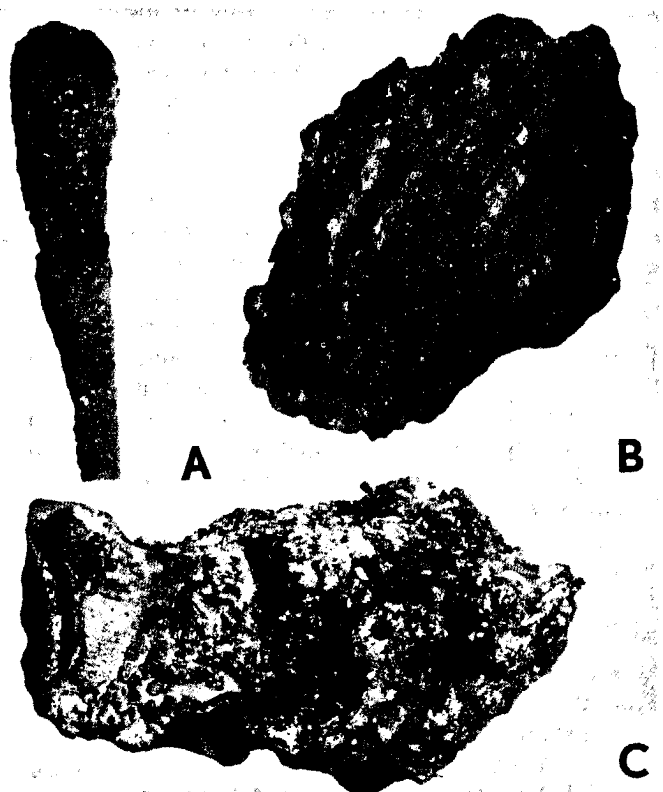

Figure 6
Photograph of hydrothermal deposit from hole 424: A, *Tube of organism replaced by Fe-Mn material (about* 2.5 *cm long)*; B, *Green clay-rich material* (3.6 *cm in length) (sample* 424-2-4-30-33 *cm)*; C, *Chunk of Fe-Mn concretion (about* 4.2 *cm in length) (sample* 424-3-4-120-122 *cm)*.

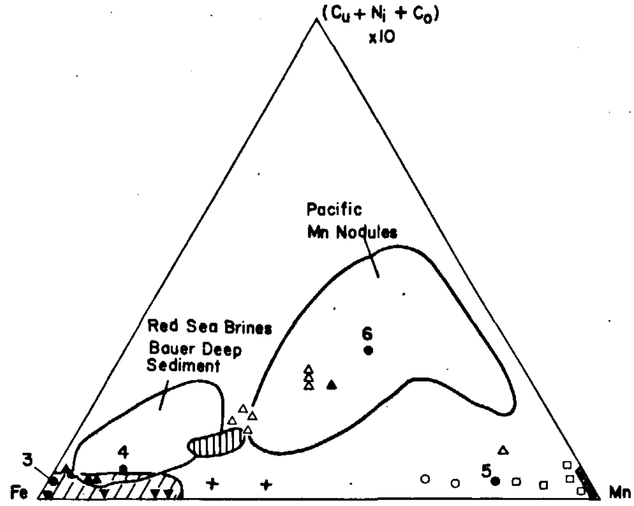

Figure 8
(Cu + Ni + Co) × 10 *Fe-Mn ternary diagram showing the field of Pacific polymetallic nodules, the metalliferous sediment from the Red Sea Brines (Bischoff,* 1969) *and from the Bauer Deep (Sayles, Bischoff,* 1973) *and the hydrothermal deposits from the Atlantic, Pacific and Indian Oceans.* (3) *average of* 11 *green clay-rich sediments from leg* 54. (5) *average of* 1 *composite Fe-Mn concretion from leg* 54. (6) *average of Pacific nodules.* (4) *average of Pacific pelagic sediment.* (0) *Fe-Mn concretions from Transform fault "A" in the Famous area.* ▨ *field of Green Clay-rich deposit from Transform fault "A".* ▥ *field of Fe-Mn coatings of basaltic rock from the Famous area (Hoffert* et al., 1978). (□) *Fe-Mn concretions from the Gulf of Aden (Cann* et al., 1977). (+) *green clay and Fe-Mn mixture from the Gulf of Aden (Cann* et al., 1977). (▼) *nontronite and Fe-oxide coats from the Galapagos Rift zone (Corliss* et al., 1977). (■) *Fe-Mn concretions from the Galapagos Rift Zone (Corliss* et al., 1977) *and from the TAG area (Scott* et al., 1974). (△) *Fe-Mn coatings from a Pacific seamount (amph. D.Z.; Bonatti, Joensuu,* 1966). (▲) *Fe-Mn coatings from the TAG area in the Atlantis F.Z. (Scott* et al., 1974).

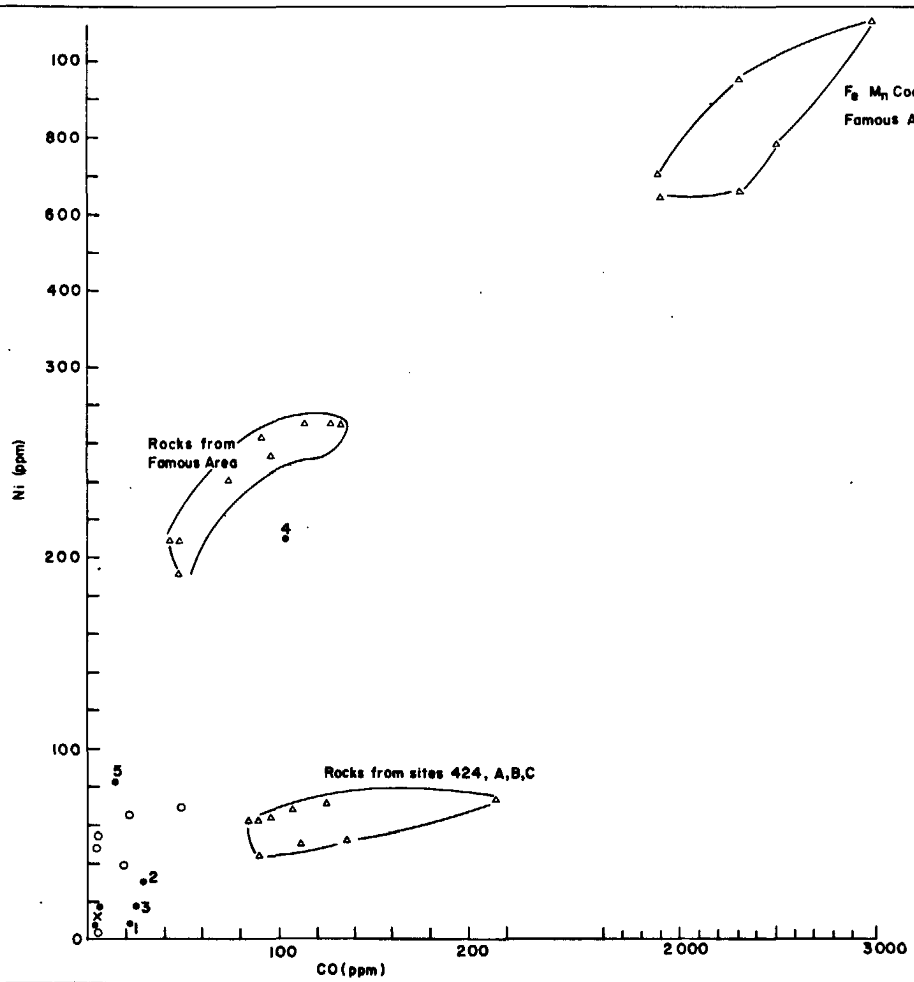

Figure 7
Ni-Co variation diagram of hydrothermal material and associated basaltic rocks from the Galapagos area (Pacific Ocean) and from the Famous area near 37°*N (Atlantic Ocean).* (•) *indicates the green clay-rich material from the Galapagos spreading center.* (1) *is the maximum value of Ni-Co obtained from the analyses of green clay-rich material (Table* 2). (2) *is a minimum value and* (3) *is the average value found from the analysed samples of green clay-rich material (Table* 2). (5) *indicates the analyses of a composite of Fe-Mn concretions from the Galapagos spreading center.* (×) *is a sediment from hole* 424 *core* 4 *section* 6 (39-41 *cm) (Table* 3). (4) *indicates the average values of pacific pelagic clay (Table* 2).

they have a much lower concentration of transitional metals (Zn < 200 ppm; Cu < 50 ppm; Ni < 100 ppm) (Table 2. Fig. 7). It should be noticed that the Fe-Mn concretions include scattered particles of the green clay-rich material, and the chemical analyses may reflect slightly contaminated samples (Table 2, 3). The concretions are, however, similar to hydrothermal deposits from the Famous area (Hoffert *et al.*, 1978) and from other mounds in the Galapagos spreading region (Corliss *et al.*, 1977), the Gulf of Aden (Cann *et al.*, 1977), and the TAG area near 26°N in the Mid-Atlantic Ridge (Scott *et al.*, 1972; 1974).

The Fe-Mn concretions are compositionally similar in some respects to the "diagenetic" ferromanganese oxide concretions found in marginal areas of the eastern Pacific (Cronan, Tooms, 1969) where manganese has become separated from other elements by its diagenetic remobilization and migration from buried reducing sediments (Lynn, Bonatti, 1965). However, in the present case, the separation of Mn from Fe is unlikely to have been affected by diagenetic processes; instead it is probably the result of a fractional precipitation of iron following a mixing of the hydrothermal solution with seawater (Krauskopf, 1957). It is of interest that ferromanganese oxide deposits of similar composition can be formed by two quite different fractionation processes.

Pelagic sediment

The presumed hydrothermal deposits from the mounds area of the Galapagos spreading center lie on a pelagic sediment cover (Fig. 3). Although there is interlayering of the hydrothermal mineral deposits and pelagic sediments, the contact is generally sharp (Fig. 5). However some of the hydrothermal material, mainly the green clay-rich deposits, is intermixed by up to 10 volume % with the pelagic sediment in certain zones (424, core 3, at 18-18.5 m in the hole, section 5; 424 A, core 2, section 1, at 10-11 m depth; section 3, at 14.5 m depth, and 424 B, core 3, section 5 and all sections of core 4 down to 32 m depth in the hole; Fig. 5).

The pelagic sediment is made up essentially of foram-nano fossil ooze containing about 15 to 20 volume % forams, 55 to 70% nanos, and about 15 to 20% clay particles of a primarily detrital nature. A siliceous nanofossil ooze is found only near the top of hole 424 C and consists of about 50 to 65% nanos, 10 to 15% forams, about 10% clays, 5 to 20% diatoms, and about 5% sponge spicules. This later core did not contain any noticeable amount of hydrothermal material (Fig. 5). Partial chemical analyses of a foram-nano ooze show Cu, Zn, Ni, and Co contents comparable to those of the presumed hydrothermal material found stratigraphically above (Table 3). The sediment differs from the hydrothermal material by its greatly lower Fe and Si, and higher Mn contents (Table 2, 3). The Mn content is about the same as that of the average pelagic clay, while Zn, Cu, Co, and Ni are relatively depleted (Table 2, 3). At Site 424 A the basal sediments (Core 3, sections 2 and 3, below 20 m depth) show strong gradients in velocity and density just above the basalt contact. The increase in density may be due to the observed dissolution of siliceous organisms and may suggest a percolation of hydrothermal fluids through the pelagic sediment.

Basement basaltic rocks

Basement penetration in holes 424, 424 A, 424 B and 424 C was, respectively, 54, 5, 14.5 and 3 m. The basaltic rocks encountered are fresh and are all similar in composition, consisting of ferrobasalts relatively rich in total iron ($Fe_2O_3 + FeO = 13$ to 15 wt%) and in TiO_2 (~ 1.9 wt%) with respect to mid-Atlantic ridge basaltic rocks (Table 4). Transition metal determinations of these basaltic rocks show slightly higher Cu (90 to 200 ppm) and Co (~ 60 ppm) contents and similar Ni contents when compared to the hydrothermal deposits associated with them (Fig. 7; Tables 2, 3). Similarly, in the Famous area, the Co (40 to 800 ppm) and Ni (up to 300 ppm) contents of the basaltic rocks are only slightly higher than the nearby hydrothermal deposits (Fig. 7). Modal analyses of some specimens indicate that the majority of these basalts are free of or have only small amounts of olivine (< 1 vol. %), and that the main phases present are plagioclase (30 to 45 vol. %), clinopyroxene (15 to 43 %), and glassy matrix. The opaques (< 11 vol. %) are mainly titanomagnetite and sulfides of pyrite, chalcopyrite, and pyrrhotite as spherules and as irregular grains.

The closest we came on Leg 54 to recovering hydrothermally altered basement rocks was at Site 425 located 62 km North of the Galapagos spreading center (Fig. 1). Scattered throughout the basalt are the patches and vesicle fillings (up to 4 vol.%) of green clay-like material similar in appearance to the hydrothermal products found at Site 424. X-ray diffraction and chemical analyses of a similar type of material found in a vein at Site 425 (core 9, section 2 at about 92 meters depth in the drilled hole) indicates an Fe-rich smectite (up to 39% FeO) which is probably nontronitic in nature. The high FeO and SiO_2 (up to 37%), and the low Al_2O_3 (< 1%) contents indicate that this material is comparable in composition to that found in the hydrothermal sediments at Site 424. Intimately associated with the smectite in the veins, there is a dark, reddish-brown, amorphous-like material, which is principally composed of FeO (55-70%), SiO_2 (6-12%) and MgO (1-3%). In addition sulfide compounds are found to fill voids and veins at various depth in the basalt which also has a bleached appearance (Site 425). The presence of these secondary alteration products suggests the passage of fluid solutions through the basement rocks.

SUMMARY AND CONCLUSIONS

Leg 54 of the Deep-Sea Drilling Project drilled four holes on the southern flank of the Galapagos spreading center on a crust about 0.62 myr old. The lithological sequences of three holes (424, 424 A, 424 B) consist essentially of hydrothermal deposits up to 15 m thick lying on foram-nano ooze and siliceous ooze (up to

Table 4

Chemical and modal analyses of basement rocks from the Galapagos spreading center area. Chemical analyses done by X-ray fluorescence (L. Briqueu, analyst).

Oxides	424 A 4-1 45-47	424 B 5-1 44-48	424 B 5-2 52-56	424 B 6-1 110-120	424 C 2-1 8-15	424 C 3-1 44-57	424 5-1 9-14	424 5-1 131-136	424 5-3 20-23	424 6-1 32-36	424 7-1 0-10
SiO_2	50.12	50.65	49.84	50.67	50.69	50.92	50.33	49.90	50.37	50.30	50.59
Al_2O_3	12.85	12.80	12.54	12.60	12.74	12.76	12.70	12.53	12.75	12.64	12.85
Fe_2O_3	3.76	4.73	4.47	4.30	3.77	4.41	3.35	5.20	4.68	4.82	4.44
FeO	9.95	9.19	9.48	9.63	10.26	9.57	10.47	8.54	9.34	9.34	9.17
MnO	0.21	0.21	0.22	0.21	0.22	0.22	0.21	0.21	0.20	0.20	0.21
MgO	5.57	5.70	6.14	6.02	6.09	5.89	6.51	6.67	6.90	6.71	6.77
CaO	10.65	10.68	10.47	10.59	10.52	10.65	10.56	10.39	10.47	10.39	10.79
Na_2O	2.31	2.37	1.88	2.02	2.26	2.37	1.99	2.00	2.07	1.94	1.86
K_2O	0.18	0.14	0.04	0.10	0.06	0.14	0.15	0.08	0.06	0.01	0.16
TiO_2	1.90	1.90	1.85	1.88	1.86	1.88	1.89	1.86	1.87	1.89	1.85
P_2O_5	0.15	0.16	0.13	0.17	0.17	0.15	0.19	0.19	0.17	0.18	0.19
Ign.	0.76	0.48	0.36	0.19	0.33	0.19	0.62	1.10	0.10	0.29	0.43
Total	98.40	99.00	97.41	98.37	98.93	99.14	98.96	98.66	98.97	98.70	99.30
Co (ppm)	114	–	89	106	136	91	217	99	94	84	122
Cr	91	112	80	–	86	102	161	82	83	77	112
Ni	48	46	63	68	49	43	91	63	64	62	74
V	447	443	424	428	421	427	439	433	440	440	444
Sr	–	–	–	62	64	66	66	–	–	66	–
Zr	–	114	–	92	123	126	119	110	110	119	110
Mn (wt %)	.16	.16	.17	.16	.16	.17	.16	.16	.15	.15	.16
Fe (wt %)	10.38	10.40	10.5	10.5	10.6	10.51	10.49	10.28	10.54	10.64	10.25
Norm :											
Q	11.27	11.45	13.02	13.05	11.94	11.48	11.97	11.76	11.36	12.53	12.10
Or	1.06	0.82	0.23	0.59	0.35	0.82	0.88	0.47	0.35	0.05	0.94
Ab	19.54	20.05	15.90	17.09	19.12	20.05	16.83	16.92	17.51	16.41	15.73
An	24.16	23.87	25.65	25.01	24.35	23.76	25.27	24.97	25.32	25.75	26.24
Di	21.55	21.84	19.79	20.55	20.79	21.86	20.13	19.71	19.85	19.16	20.27
Hy	3.87	4.06	6.11	5.46	5.52	4.53	6.87	7.47	7.97	7.82	7.46
Mt	7.29	10.42	9.76	9.09	7.47	9.48	6.00	12.05	10.31	10.70	9.63
Ilm	3.60	3.60	3.51	3.57	3.53	3.57	3.58	3.53	3.55	3.58	3.51
Ap	0.35	0.37	0.30	0.40	0.40	0.35	0.44	0.44	0.40	0.42	0.44
Iln	4.91	2.00	2.74	3.35	5.10	3.03	6.32	0.22	2.22	1.95	2.52
Modal (vol. %) :											
Olivine	–	Tr	–	–	–	–	–	0.3	–	–	–
Clinopyroxene	–	15.4	31.7	24.8	–	–	–	42.4	–	31.6	–
Plagioclase	–	43.0	32.0	32.0	–	–	–	30.3	–	40.7	–
Opaques	–	8.0	–	–	–	–	–	9.0	–	10.2	–
Glass	–	33.0	35.5	38.9	–	–	–	14.5	–	17.7	–
Clay-phillosilicates	–	–	0.7	1.5	–	–	–	3.6	–	–	–
Vesicles	–	1.0	0.1	3.0	–	–	–	0.8	–	–	–

20 m thick). The fourth hole (424 C) contained only foram ooze. The basement in the drilled area consists of a ferrobasalt type of rock and the maximum penetration obtained did not exceed 40 m. The green clay-rich material and the Fe-Mn concretions found at the Galapagos Spreading Center region are thought to be the products of hydrothermal activity near a spreading ridge axis because (i) they are enriched in Fe and Mn, respectively and relatively low in transition metal contents (Cu, Ni and Co < 200 ppm); (ii) they are associated with high heat-flow, high water-temperatures, and a fractured crust; and (iii) they are texturally and compositionally similar to hydrothermal deposits found elsewhere in the ocean floor.

Drilling in the Galapagos Spreading Center region through the hydrothermal products, the sedimentary column and into the ferro-basaltic basement provides new insight on the origin of oceanic hydrothermal fields. Of particular significance is the common occurrence of Fe-Si rich nontronitic clay found in the hydrothermal material, in the pelagic sediment, and in the underlying basalt. Small amounts of this green Fe-Si rich clay material occur in veins, veinlets and as vesicle fillings within unaltered primary mineral phases and in the preserved texture of the basement rock. The discharge of the hydrothermal fluid solution into seawater must have occurred rapidly. This is suggested by the limited thickness and intermixing of the hydrothermal deposit with the sediment and also by the low Ni, Co, Cu and Zn content of the solution on discharge into seawater.

Our interpretation for the origin of the hydrothermal deposits is based largely on the basalt/sediment/hydrothermal/products comparison and on the detailed stratigraphy as determined by continuous sediment coring. To explain the mode of emplacement of these hydrothermal deposits we propose two models:

1) one possibility is that the hydrothermal deposits were formed by the precipitation of fluids that percolated up from the basaltic basement and were locally dispersed through the regional sediment cover. Fact which could support this model is the interlayering of the hydrothermal material within the carbonate and the siliceous oozes. This in turn indicates the formation of Fe- and Mn-rich compounds during the passage of the fluids through the sediment or represents precipitates formed earlier and diluted with sediment. Because of the

absence of extended alteration in the ferro-basalt, underneath the hydrothermal deposits, immediately below the sediment-basement interface, fluid solutions capable of precipitating the clay-rich material and Fe-Mn concretions must either have been derived from basalt alteration at depths greater than those drilled or the alteration is not pervasive and is confined to narrow cracks and fractures within the basement rocks;

2) a second possible model assumes that the mounds represent narrow vents whose fluids, from a basement source, do not interact with sediments, but instead, emanate directly into seawater at mound peaks. Exposure of the fluids to the seawater above the mounds results in the formation of clay-rich material and Fe-Mn concretions. The clays and concretions then precipitate on the sea-floor in the region immediately surrounding the vents (mound peaks). If this model holds, our drill holes were slightly off any mound peaks and through areas where hydrothermal material had precipitated onto the oozes. The observed interlayering between the hydrothermal deposits and the oozes would represent variations in the dilution of the regional sedimentation pattern. The apparent unaltered nature of the basalt immediately underlying the hydrothermal deposits is most compatible with this second model.

Further work in the Galapagos area near 86°10′ W should include both extensive gravity coring and deep-sea drilling operations in order to establish the real extent and stratigraphic sequences of the hydrothermal material. This will also permit a better understanding of the nature and the effect of the various secondary fluid precipitates through the basaltic basement underlying the hydrothermal deposits.

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