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COMPARISON BETWEEN DEEP-SEA HYDROTHERMAL DEPOSITS RECOVERED FROM RECENT SPREADING RIDGES

R. HEKINIAN (*) and M. FÉVRIER (*)

ABSTRACT. — Deep-sea hydrothermal deposits from the accreting plate boundaries of the Rift valley in the gulf of Aden, of the Galapagos spreading center, of the Rift valley on the Mid-Atlantic Ridge near 26° North, and from Transform Fault « A » on the Mid-Atlantic Ridge near 37° North, are studied and compared. Two main types of products are found occurring in all these areas : 1) Dark-brown Fe-Mn concretions made up essentially of todorokite and birnessite and 2) A variegated clay-rich material composed mainly of Fe-Si-rich smectite. In general the textural appearance, the mineralogy and the chemistry of the hydrothermal material from the various localities are similar. Secondary alteration products found in basaltic rocks are compared with the clay-rich material from the various hydrothermal deposits.

RÉSUMÉ. — Les dépôts hydrothermaux sous-marins situés aux frontieres de plaques divergentes tels ceux de la dorsale Médio Atlantique dans la faille Transformante « A » pres de 37° N ; de la vallée du Rift pres de 26° N ; de la vallée du Rift dans le Golfe d Aden (Ocean Indien) et de la dorsale des Galapagos (Pacifique Est) ont été étudiés et comparés. En general ces depôts sont constitués de deux types de produits : 1) Des concrétions de Fe-Mn de couleur brun foncé formees essentiellement de Todorokite et Birnessite et 2) Un materiel de couleurs variees riche en une argile de type Smectite (enrichi en Si et Fe). La structure, la mineralogie et la chimie de ces produits hydrothermaux sont semblables malgre leur situation géographique. Les produits d'altérations secondaires observes dans les roches basaltiques sont aussi compares avec le materiel d origine hydrothermale.

INTRODUCTION

The circulation of water through fissures, large fractures, and between pillow lava surfaces may reach deep-seated formations in order to be heated an then emerge at the surface of relatively hot springs carrying various metals in solution. The concentration of hydrothermal deposits due to subsea-floor convection system has been a widely accepted hypothesis (Spooner and Fyfe, 1973 ; Hutchinson, 1973 ; Sillitoe, 1973 ; Bonatti, 1975). The study of hydrothermal circulation in the oceanic crust is of primary importance for understanding its effect on the alteration of ocean floor rocks. Another advantage in studying the phenomenon of hydrothermalism is the resulting knowledge about the heat budget of the oceanic crust. Williams *et al.* (1974) and others have suggested that 20 % of the earth's total heat loss is derived entirely from hydrothermal circulation. The dissipation and/or concentration of heat through the circulation of fluids in the ocean crust may play an important role in the dynamics of ocean floor volcanism and tectonism. Also it is not excluded that a concentration of heat through fluid circulation might generate zones of weakness and enhance tensional motions in the crust.

The economic importance of ocean floor hydrothermalism is not to be overlooked even if at the present time a lack of technology makes the extraction of mineral resources from the sea prohibitive. We are still in the phase of exploration and in order to ascertain the economic value of any transitional metals content in the oceans we should have more insight into the mechanism of supply, transport and removal affecting the basement rocks and the sediment-seawater interface.

It is only recently, less than ten years ago, that metalliferous sediment related to hydrothermalism was recognized as occurring in deep ocean floor environments. The difficulty in recognizing hydrothermal products is primarily due to our lack of detailed observations in limited regions of the oceans. It would not be surprising to find a fair amount of material stored in various oceanographic institutions having the characteristics of hydrothermal material, such as an unusually thick manganese crust, veins of heavy transitional metals, and clays of dubious origins found in association with basaltic rocks. However, since there has not been a general criteria for the recognition and classification of hydrothermalism on ocean floor material, it is difficult to evaluate the importance of this phenomenon and its distribution.

* Centre Océanologique de Bretagne, B.P. 337, 29273 Brest Cedex.
Contribution n° 610 du Département Scientifique, Centre Oceanologique de Bretagne.

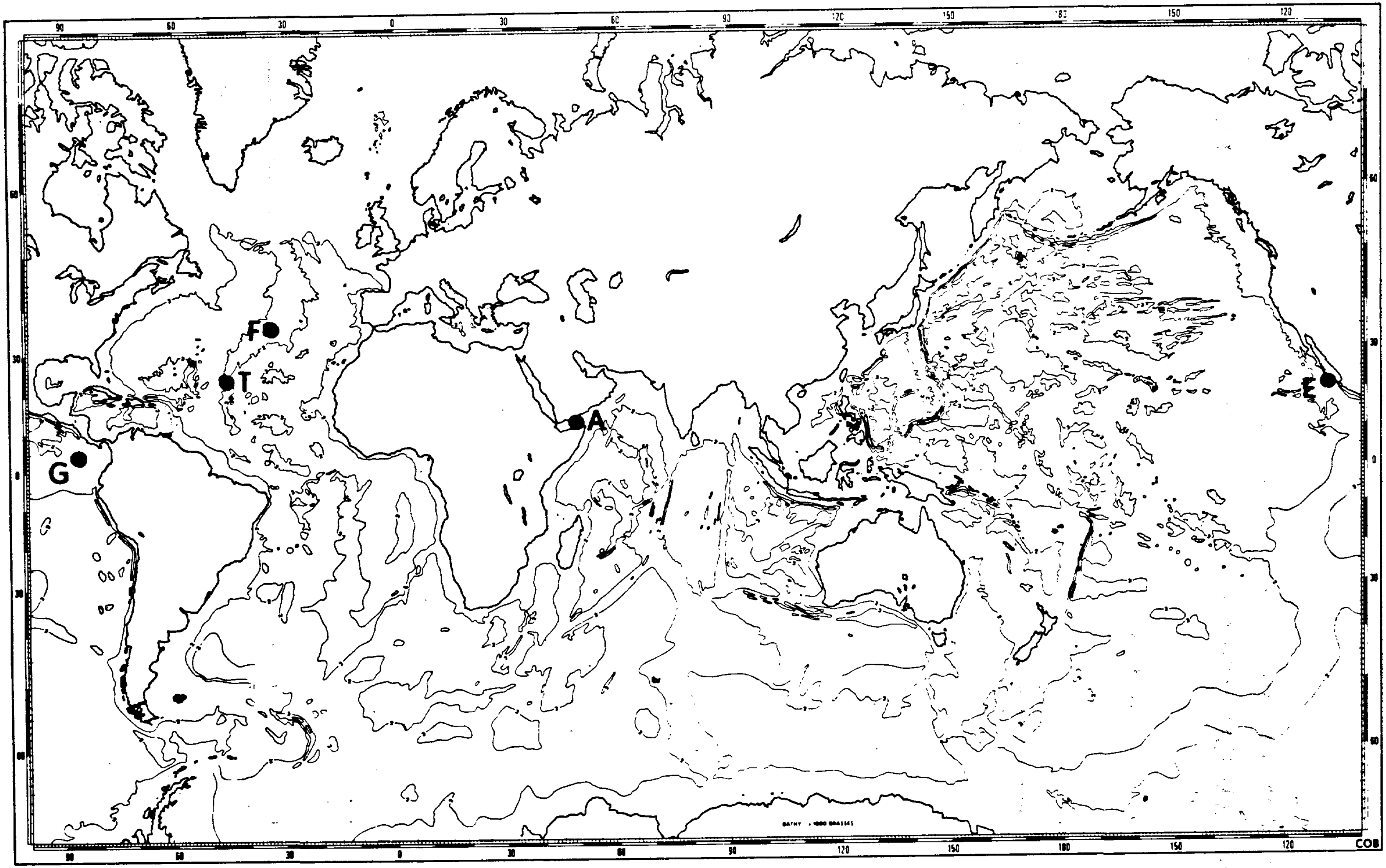


FIG. 1. – Hydrothermal deposits plotted on a chart of the world.
(F) indicates the deposits found near 37°N in Transform fault "A" (FAMOUS area) (T) indicates the Fe-Mn crust of hydrothermal origin located near 26°N on the Mid-Atlantic Ridge (TAG area) (Scott *et al.*, 1974) (G) indicates the hydrothermal deposits from the Galapagos area (Leg 54 Scientific Party, 1977) (E) indicates deposit located on the East Pacific Rise near 21°N. Cyamex, 1978. (A) indicates deposits from the Gulf of Aden (Cann *et al.*, 1978).

In a broad sense and for our purpose, the various materials recovered which could directly be related to hydrothermalism in general were classified in three main categories :

1. The hydrothermal deposits in *sensu stricto* where the structural setting indicates a local origin and is hence likely to be the direct discharge of deep-seated fluids reaching the floor of the ocean. The structures appear as small ridges or mounds on top or interlayered with sediment of variable thickness (Corliss and Ballard, 1978; Arcyana, 1975; DSDP Scientific Party of Leg 54, 1978).
2. The metalliferous deposits (e.g. Bauer Deep and Red Sea deposits) where pelagic sediments are intermixed with hydrothermal material in *sensu stricto* and where basement rocks are not prominent in the immediate surroundings.
3. Hydrogenous deposits (including Mn-nodules and Fe-Mn crusts) which are due to the transport and precipitation of metalliferous material from seawater and may be indirectly related to hydrothermal emanations.

Metalliferous sediments and hydrogenous deposits are know to occur in several localities of the world's oceans as shown by Cronan (1969) and Rona (1978). The limited number of sites recognized as being hydrothermal deposits in *sensu stricto* makes difficult any far reaching conclusion based on the interrelationship between the various types of products.

The purpose of this paper is to review and to give new analytical data on the several hydrothermal deposits in *sensu stricto* known to occur in the various oceans. Similar mineralogical and chemical techniques are used in order to have homogeneous data on the material which by itself appears to be made up of heterogeneous compounds which are intimately associated. In addition, in order to understand the problem of basement floor alteration, it is important to compare secondary products of alteration found in the rocks and the hydrothermal deposits in *sensu stricto* as defined above. It is also our aim to point out the compositional difference existing among the basement rocks associated with the hydrothermal deposits.

REGIONAL DISTRIBUTION OF HYDROTHERMAL DEPOSITS

The known hydrothermal deposits in *sensu stricto* discovered and recognized as such are up to now found in association with ocean floor divergent boundary zones (fig. 1). Five deposits of this type were recognized and studied by various students and different laboratories (Corliss *et al.*, 1978; Hoffert *et al.*, 1978; Hékinian *et al.*, 1978), and their geological settings are briefly summarized below :

1) The Galapagos Spreading Center Hydrothermal field was first recognized by deep tow (Klitgord and Mudie, 1974; Lonsdale, 1977) and heat flow measurement (Williams *et al.*, 1974). The deep-tow survey in the area recognized the existence of mounds (5-20 m high, 20-50 m wide, conical in shape, and elongated, 1-2 km long) paralled to the direction of the Galapagos spreading axis. Submersible work in the area (Corliss and Ballard, 1977) recognized and sampled material from the mounds. During Leg 54 of the Glomar Challenger, a N-S drilling transect (holes 424, 424 A, 424 B and 424 C) were made in the region of the hydrothermal mounds on a crust of about 0.62 millions years old and at a depth of about 2 700 m (Scientific Party of Leg 54, 1977) (fig. 2). The data presented here from the Galapagos area are published elsewhere (Scientific Party, Leg 54, 1977; Hékinian *et al.*, 1978).

2) The Mid-Atlantic Ridge near 37° N (FAMOUS area) hydrothermal field was discovered by direct visual observation from a submersible (Arcyana, 1975). Two deposits extending on a surface of about 60 m in diameter were sampled from an E.W. trending scarp at a depth of 2 670-2 690 m (Arcyana, 1975; Hoffert *et al.*, 1978) (fig. 3).

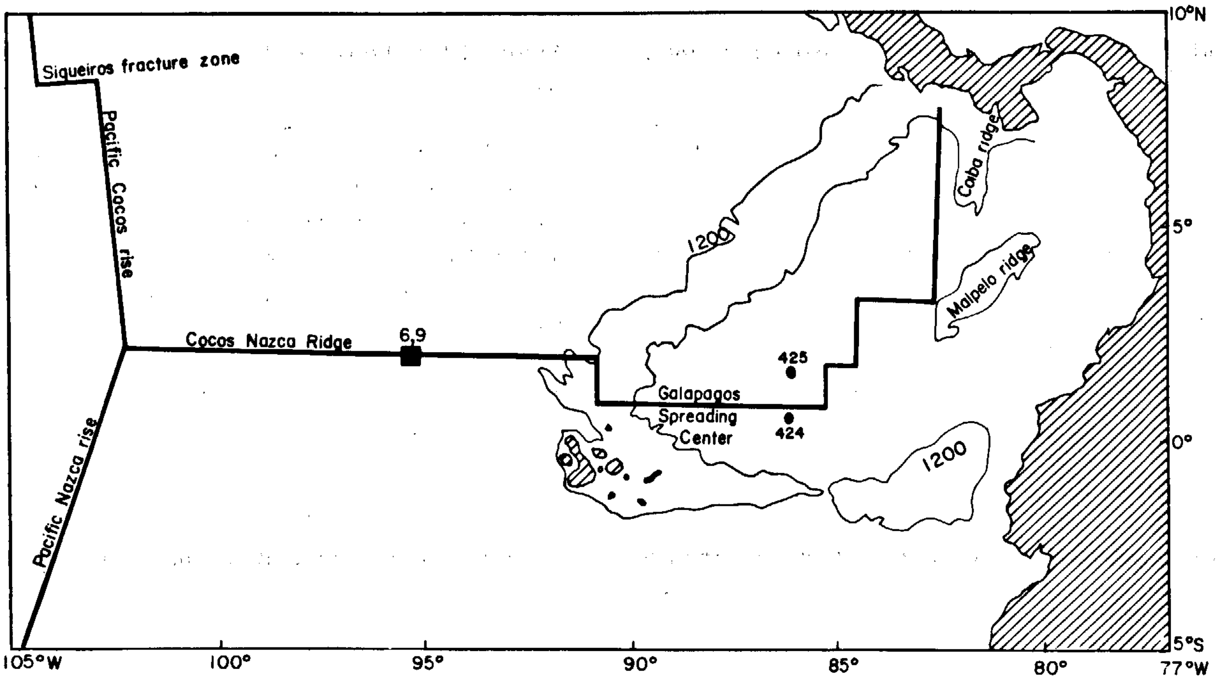
3) The Mid-Atlantic Ridge near 26-30° N (T.A.G. area) hydrothermal deposit was reported to consist of unusually thick Fe-Mn crusts located in three different areas (Scott *et al.*, 1974; Rona *et al.*, 1976). Two of these areas are located on the spreading axis and one on the Atlantis Fracture Zone (Scott *et al.*, 1974). The sample studied here was taken from the axial zone of the Rift Valley near 26° N (sample 73-2 A) (fig. 3).

4) The Gulf of Aden hydrothermal deposits were dredged from the Rift Valley region between 12° 31.1 N; 47° 39.2 E (2 550 m depth) and 12° 35.0 N; 47° 39.9 E (2 260 m depth) and consist of brownish lumps of Fe-Mn concretions, yellowish-green clay-rich material, and aphyric plagioclase-olivine bearing basalts (Cann *et al.*, 1978) (fig. 3).

5) Hydrothermal activities on the East Pacific Rise near 21° N was first suspected during a deep-tow survey which detected a near-bottom thermal gradient in a region (within 6 km) of the spreading axis (Crane and Normark, 1977). Recently a submersible study near (< 1 km) the spreading axis of the East Pacific Rise near 21° N recognized the existence of hydrothermal mounds (Cyamex, 1978). This material is now being analyzed and the data will be published elsewhere.

MORPHOLOGY OF HYDROTHERMAL MATERIAL

Samples of hydrothermal material were obtained from the various localities mentioned above, i.e. Gulf of Aden, Mid-Atlantic Ridge (near 36° N and 26° N), from



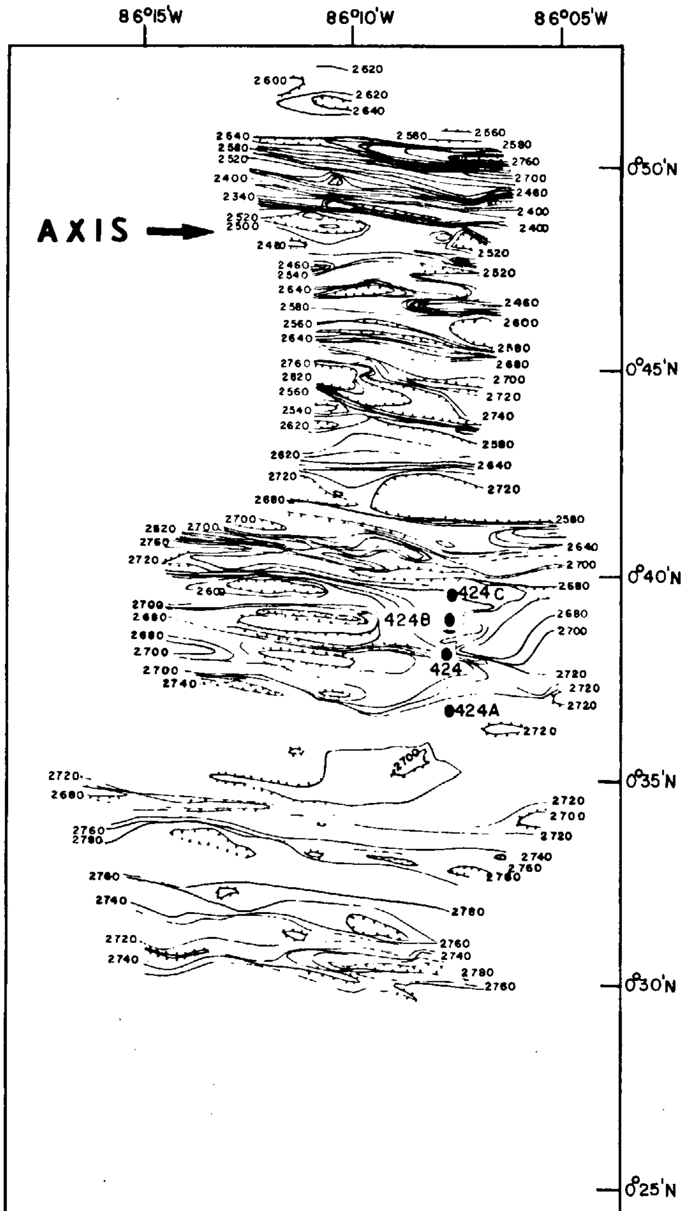


FIG. 2. – Detailed bathymetric map of the Galapagos spreading center region based on a near-bottom deep-tow survey after Klitgord and Mudie (1974) showing Leg 54 drilled holes (Scientific Party, Leg 54, 1977). The generalized map of the Galapagos area shows the location of the drilled sites and the dredges containing Fe-Mn crust (6, 9; Moore and Vogt, 1976).

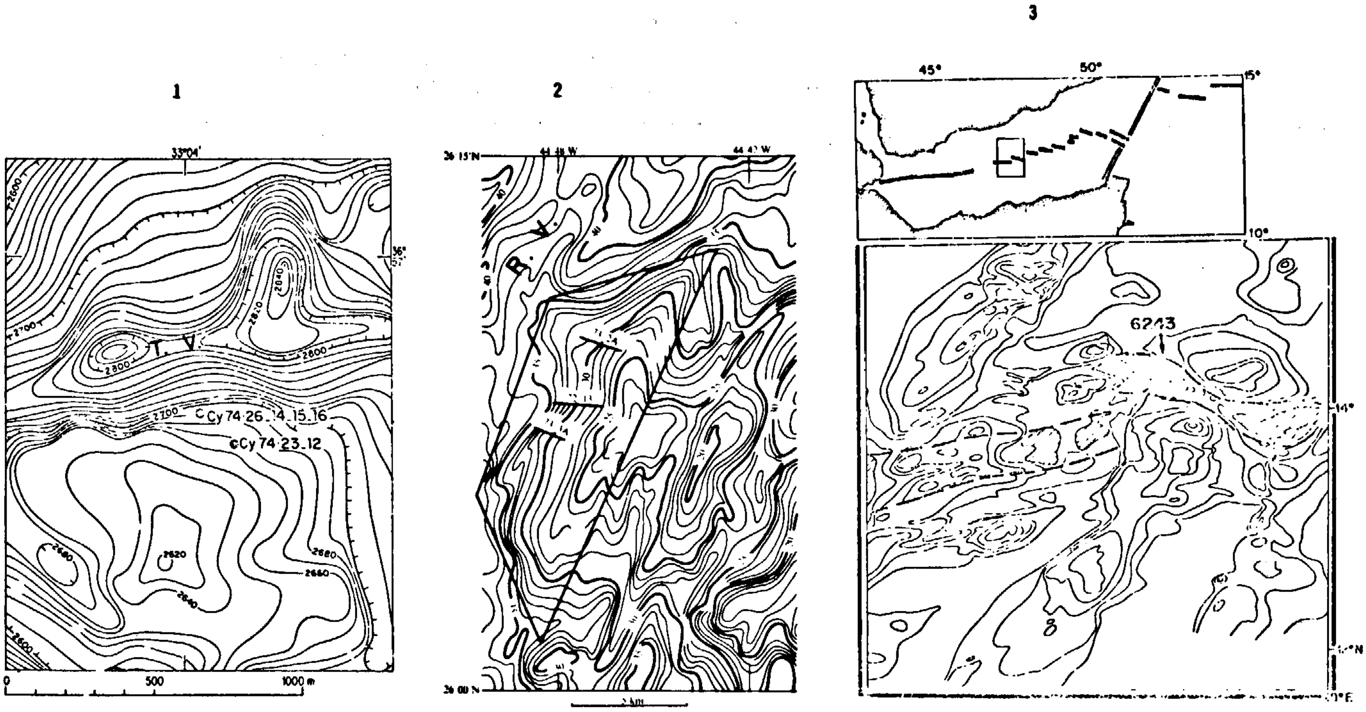


FIG. 3. – Detailed bathymetric map of regions where hydrothermal deposits were found. (1) shows a map of Transform Fault "A" in the FAMOUS area near 36°N. The two hydrothermal sites are shown (Hoffert *et al.*, 1978). (2) shows a map location of the T.A.G. area on the Mid-Atlantic Ridge near 26°N (Scott *et al.*, 1974). (3) shows a map from the Gulf of Aden with the location of the Rift Valley (shaded area), and the hydrothermal field (Cann *et al.*, 1977).

the Galapagos Spreading Center area and the East Pacific Rise near 21° N. In addition Mn nodules selected according to their various transitional metals content collected from an area located between the Clarion and Clipperton fracture zone were examined.

The hydrothermal material, except for the sample from 26° N in the Atlantic ocean (T.A.G. area, Scott *et al.*, 1974), is made up essentially of Fe-Mn concretions and variegated clay-size material. As far as the Fe-Mn crust from the T.A.G. area (Scott *et al.*, 1974) is concerned it is fairly homogeneous and no traces of clay-sized material were noticed.

In general the hydrothermal materials in *sensu stricto* are very little or not intermixed with any pelagic sediment. However some of the samples (FAMOUS area) show intermixing with rock fragments cemented by the hydrothermal material. Because of their fragile nature, the material recovered occur as chunks of half to about 5 centimeters in diameter. The main structural features observed in the collected samples consist of cryptic lamination of variegated material made up essentially of clay-size components which crumbled under finger nails. From field observations (Galapagos and FAMOUS area) it was noticed that black manganese-like coating characterizes the top part of the deposits. Hand specimen of this material shows laminae (< 1 cm-thick) of black Fe-Mn crust which could be exfoliated into few millimeters thick sheets. The surface probably at direct contact with sea-water assumes a mamelonar and/or scoriaceous-like appearance which on freshly-cut section shows metallic luster. Other black Fe-Mn laminae of 2 millimiters or even less in thickness also occur as interlaying or as irregularly contorted veinlets with lighter colored clay size material. This clay size material shows variegated colors ranging from yellowish brown through reddish brown, pale olive, grayish green to dark green and to yellowish green units. There is not a detectable intermixing between the various colored material. The various shades of colored clay-size material form distinct entity from each other. Sometimes the greenish clay-size material assumes a spheroidal shape of a few millimeters (< 0.5 mm in diameter).

MINERALOGY AND CHEMISTRY OF HYDROTHERMAL DEPOSITS

The hydrothermal material was classified according to their morphological, mineralogical and chemical characteristics into two main groups: 1. – The black Fe-Mn concretions and 2. – the variegated clay-size material.

Fe-Mn CONCRETIONS

Electron microscopic studies of the Fe-Mn concretions show globular-reticulated structures. The shape of these globules (mamelon forms) does not vary between the various deposits, and the only changes observed are their size (20-35 μm in diameter for the Galapagos

TABLE 1

X-ray fluorescence analyses of clay-rich material from hydrothermal deposits. Data from the Galapagos are from Hékinian et al. *(1978).*

Wt %	GULF OF ADEN			GALAPAGOS	LEG 54	TRANSFORM FAULT "A"	
	6249-24 yellow	6243%24 green	6243-12 green	424-2-4 (30-33) green	424-2-2 (11-13) green	CYP 74-26 15 green	CYP 74-26 15-2 yellow
SiO_2	42.63	45.24	45.09	45.95	53.3	45.5	32.32
Al_2O_3	0.88	0.90	0.91	0.32	0.20	·0.20	2.49
FeO	29.74	28.73	28.94	25.33	27.56	34.11	44.89
MnO	–	–	–	0.06	0.17	0.10	2.30
MgO	3.16	3.39	3.28	3.71	4.41	2.91	2.89
CaO	0.09	0.21	0.76	0.17	0.30	0.6	4.81
Na_2O	1.88	1.96	1.85	1.43	2.08	1.71	n.d.
K_2O	2.43	3.12	3.28	3.65	3.39	3.23	0.67
TiO_2	0.03	0.02	0.03	0.02	0.02	0.02	0.17
P_2O_5	0.06	0.05	0.03	0.12	–	–	0.86
H_2O 110°	12.2	9.83	9.42	6.94	–	9.88	14.30
H_2O 1 050°	6.04	6.08	6.38	8.90	6.79	6.22	10.95
Co (ppm)	–	–	–	–	3	2	–
Cu	–	–	–	–	30	46	–
Zn	–	–	–	–	53	6	–
Ni	–	–	–	–	10	10	–

TABLE 2

X-ray fluorescence analyses of Fe-Mn concretions ans Mn-nodules. The data from the Galapagos are from Hékinian et al. *(1978).*

Wt % DRY	M.A.R. 26°N T.A.G. 73-2 A	GALAPAGOS 424-3-5 (35-40)	FAMOUS CYP 74-23-12	ADEN 6243-3	N.E. PACIFIC BASIN Mn NODULES		
					Cx 2109	CP 2171	A 2249
SiO_2	0.4	0.93	19.7	6.91	15.25	16.97	19.41
Al_2O_3	0.91	1.01	2.0	1.51	5.51	5.79	6.46
FeO	0.15	0.36	15.83	4.21	9.32	6.06	16.64
MnO	90.24	92.25	41.15	69.63	60.84	61.24	47.73
MgO	4.22	4.15	4.4	3.12	4.16	3.94	3.59
CaO	3.05	1.78	2.7	2.78	2.84	3.14	3.26
K_2O	0.21	0.37	1.15	0.51	1.05	0.92	1.34
TiO_2	0.01	0.02	0.08	0.10	0.7	0.48	1.64
P_2O_5	0.04	0.12	–	0.19	0.36	0.41	0.6

deposits; 40-60 μm for the FAMOUS area; 100-400 μm for the T.A.G.; 5-20 μm for the Gulf of Aden). X-ray diffraction studies on the Fe-Mn concretions indicate the presence of abundant todorokite (9.7 Å and 4.8 Å peaks) and birnessite (7.2 Å and 3.6 Å), while in the Mn-nodules analysed only todorokite was found as the major Fe-Mn mineral constituent.

Chemical analyses of Fe-Mn concretions from the Galapagos and the Fe-Mn crust from the T.A.G. area show striking similarities. They are both enriched in MnO ($\simeq$90 %) and considerably depleted in FeO, SiO_2 and Al_2O_3 (< 1 %) (table 2). Similar types of material from the FAMOUS area and from the gulf of Aden are comparable. Indeed, both the Fe-Mn concretions from the FAMOUS area and those from the gulf of Aden (Cann *et al.*, 1977) have higher FeO (> 2 %) and SiO_2 (> 3 %) contents than do those from the Galapagos and the T.G.A. area (table 2). In this respect the gulf of Aden and FAMOUS samples are closer in composition to the Mn-nodules of the Pacific (SiO_2 = 15-19 %; FeO = 6-17 %, $Al_2O_3 \simeq 5$ %) from which they depart in their lower MnO content (< 45 %) (table 2).

CLAY-RICH MATERIAL.

The clay-rich material viewed by the electron microscope shows two distinct types of structure: flaky sheet-like polygonal forms and elongated tube-like agglutinated globules (fig. 4). A less common third structural feature is found in the Galapagos samples which show tiny fibers with no preferential orientation. The size of the tubular structures varies from 1 μm (Famous area, galapagos and gulf of Aden) to about 50 μm (Famous area) (fig. 4).

X-Ray diffraction studies on the clay-rich material

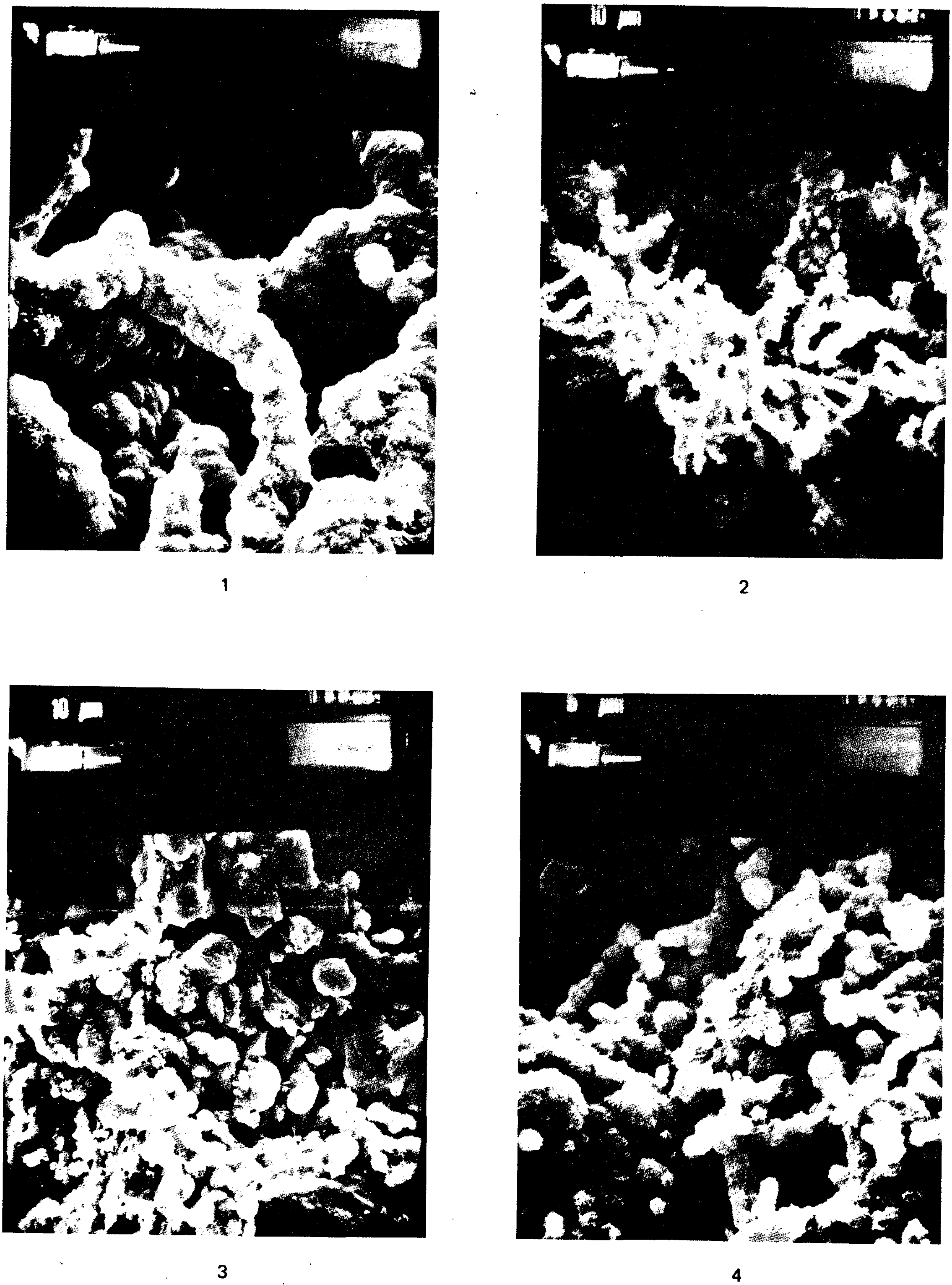


FIG. 4. – Clay-rich material viewed under a scanning electron microscope. (1) Green clay-rich material (CYP 74-26-15-1). From Transform Fault "A" in the FAMOUS area (magnification × 2 400). (2) Orange clay-rich material (CYP 74-26-15) from Transform Fault "A" in the FAMOUS area (magnification × 1 300). (3) Yellow clay-rich material (6243-12) from the gulf of Aden (magnification × 650). (4) Green clay-rich material (Leg 54-424-2 *c/c*) from the Galapagos area (magnification × 2 500).

TABLE 3

Partial microprobe analyses of secondary clay-rich and Fe-oxide (leg 54, Brown) material from ocean floor basement rocks.
Samples from Leg 37 are from Baragar et al. *(1977).*
The analyses from the Galapagos are from Hékinian et al. *(1978).*

Wt %	GALAPAGOS Leg 54 425-9-3 (88-90) green	GALAPAGOS Leg 54 425-9-3 (88-90) brown	M.A.R. 37°N Leg 37 332 B-35-2 (33-36) average of 5	M.A.R. 53°N CH 4-D 1 11	M.A.R. 53°N CH 4-D 2 5
SiO_2	33.6	11.45	28.35	42.31	39.84
Al_2O_3	1.19	–	2.95	6.15	15.07
FeO	38.73	69.13	8.36	10.40	13.47
MnO	0.06	0.24	0.26	0.09	–
MgO	4.52	2.13	26.22	17.29	15.56
CaO	0.09	0.16	0.76	1.51	0.71
Na_2O	–	–	<0.1	0.33	0.16
K_2O	2.52	0.11	0.79	1.06	0.33

has shown that the major clay mineral constituent consists of a smectite (12 Å peak) which upon glycolation expends up to about 17 Å peak. Other minor constituents include goethite (4.5 Å peak) and saponite. In addition there is also a 9 Å peak on most diffraction pattern which was tentatively attributed to a glauconite – celadonite composition (Hoffert *et al.*, 1978) for the FAMOUS area samples. However it is not excluded that such a peak could correspond to that of a zeolite.

The chemistry of the clay-rich material is the same for all the hydrothermal localities studied. The clay-rich material is made up essentially of SiO_2 (30-54 %) and FeO (25-40 %), and is depleted in Al_2O_3 (< 2 %) and MnO (< 1 %) (Table 1). The structural formula calculated for all the clay-rich material from the different localities is similar. As an example for the FAMOUS area deposits the structural formula :

$$Ca_{0.29}\,Na_{0.52}\,K_{0.58})\,Fe^{3+}_{3.3}\,Mg_{0.68})$$
$$(Si_{6.67}\,Al_{0.04}\,Fe^{3+}_{1.29}))_8\,O_{20}\,(OH)_4 \cdot H_2O$$

corresponds to a Fe-rich nontronitic clay.

Trace element studies of the clay-rich material published elsewhere (Cann *et al.*, 1977; Hoffert *et al.*, 1978; Hékinian *et al.*, 1978) show that it is depleted in its transitional metals content. The Fe-Mn concretions are also depleted in their transitional metals.

COMPARISON OF HYDROTHERMAL DEPOSITS WITH OTHER METALLIFEROUS PRODUCTS

In addition to their mode of emplacement and their geological settings (for further information see Cronan, 1975; Rona, 1977; 1978), the metalliferous sediments and the hydrogenous deposits including Fe-Mn crusts on ocean floor rocks are chemically different from the hydrothermal deposits in "*sensu stricto*". Indeed the later are considerably depleted in transitional metal contents (Hoffert *et al.*, 1978; Hékinian *et al.*, 1978) with respect to the other types of deposits. This is visualized by a binary Cu-Zn distribution diagram shown in figure 5. The Cu and Zn content of the hydrothermal deposits in general is less than 200 and 400 ppm respectively

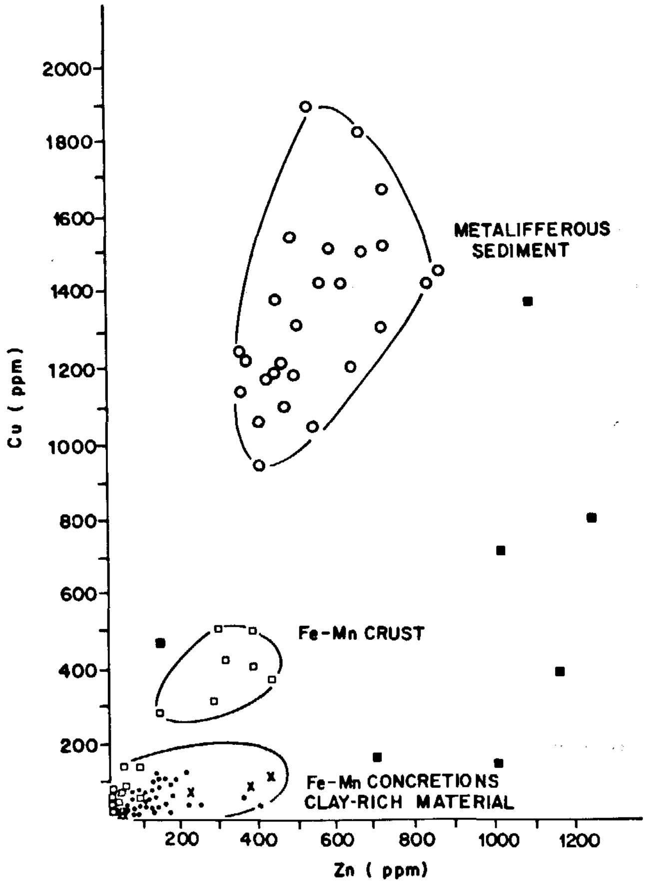


FIG. 5. – Cu-Zn (ppm) variation diagram showing the distribution of hydrothermal material from the FAMOUS area (□) (Hoffert *et al.*, 1978), from the Galapagos spreading center (·) (Hékinian *et al.*, 1978) and from the Gulf of Aden (×) Cann *et al.*, 1978). The Fe-Mn crusts are those covering the surface of pillow flows. The field of the metalliferous sediments are reported after the data from Sayles *et al.* (1972) and from Bischoff (1973).

(fig. 5), while the metalliferous sediments represented by those from the Bauer Deep (Bischoff, 1972; Sayles and Bischoff, 1973) and those from the Red Sea (Bischoff, 1969) have a Cu and Zn content higher than 400 ppm (fig. 5). Figure 5 also shows that the Fe-Mn crusts found to coat basement rocks have intermediate values of Cu (300-600 ppm) between those of the hydrothermal deposits in "*sensu stricto*" and the metalliferous sediment. The average Zn and Cu content of manganese nodules is about at least 5-10 folds higher than that of any hydrothermal deposits in *sensu stricto*.

BASEMENT ROCKS ASSOCIATED WITH THE HYDROTHERMAL DEPOSITS

We have gathered in the present study some data on basement rocks which were reported to be directly associated with hydrothermal material. Thus chemical analyses of rocks from the FAMOUS area, from the Galapagos Spreading Center DSDP drilling area, and from the Gulf of Aden are reported in Table 4. Major element analyses of these rocks showed that there is a difference in composition between the basement rocks from the Galapagos area which are essentially rich in TiO_2 ($\simeq 2$ %) and total iron oxide content ($\simeq 13$ %) when compared to both the Gulf of Aden and the FAMOUS area basalts (Table 4). The Galapagos rocks are typical ferrobasalts made up essentially of pyroxene and plagioclase while the rocks from the Gulf of Aden and the FAMOUS area are aphyric basalts composed of plagioclase, olivine, and clinopyroxene. This compositional difference is illustrated in figure 6 where the trend of the East Pacific Rise rocks appear to be even more differentiated towards a higher TiO_2 and higher FeO^t / MgO ratio than are those from the Atlantic Ocean. The degree of alteration of the rocks is variable from place to place. The FAMOUS area samples taken in the hydrothermal field (sample 26-15) and within a radius of less than 2 km are moderately fresh and only the olivine crystals are completely replaced by clay-rich material. In the Galapagos area underneath the hydrothermal material the basement rock is surprisingly fresh with only sporadic veins, veinlets and vesicles filled with green clay-rich material (Leg 54, Scientific Party, 1977). However further north of hole 424 a drilled hole (425) shows altered basement rock and a bleached zone was noticed (fig. 2). A vein containing a green clay-rich material and a reddish-brown amorphous material was analysed (Hékinian *et al.*, 1978) (Table 3). The green clay consists of smectite which is rich in FeO ($\simeq 39$ %) and in SiO_2 (33-36 %) and is somewhat similar to the hydrothermal material found in holes 424, 424 A and 424 B of the other Galapagos sites. The reddish-brown material consists mainly of FeO ($\simeq 7$ %) which has undergone various degrees of oxydation (Table 3).

Other secondary alteration products of basaltic rocks from the Mid-Atlantic Ridge near 53° N (Jehl, 1975), near 37° N (leg 37, hole 332 B, 335, Baragar *et al.*, 1977) and near 1° N (St Paul Rocks area, Melson and

TABLE 4

Basement rocks associated with hydrothermal deposits from various localities. The analyses from the Gulf of Aden were taken from Cann (1970). Analyses from the Galapagos are from Hékinian et al. *(1978).*

Wt %	FAMOUS				GULF OF ADEN		GALAPAGOS			
	26-5	19-5	19-6	20-8	6243-2	6243-4	424 5-1 (131-136)	424 A 4-1 (45-47)	424 B 5-1 44-48	4246 3-1 44-57
SiO_2	50.91	48.73	47.53	47.88	49.50	49.4	49.90	50.12	50.65	50.92
Al_2O_3	15.52	15.03	15.13	14.72	16.11	15.5	12.53	12.85	12.80	12.76
Fe_2O_3	1.75	5.11	4.92	1.84	2.41	1.6	5.20	3.76	4.73	4.41
FeO	7.29	4.80	3.91	7.28	6.44	7.7	8.54	9.95	9.19	9.57
MnO	0.2	–	0.17	–	0.25	0.40	0.21	0.21	0.21	0.22
MgO	5.78	7.92	8.20	10.38	8.33	8.5	6.67	5.57	5.70	5.89
CaO	12.60	10.73	11.55	12.47	12.42	12.3	10.39	10.65	10.68	10.65
Na_2O	–	2.51	2.16	2.05	2.27	2.4	2.0	2.31	2.37	2.37
K_2O	0.31	0.24	0.22	0.19	0.21	0.20	0.08	0.18	0.14	0.14
TiO_2	1.32	1.07	1.05	1.05	1.13	1.2	1.86	1.90	1.90	1.88
P_2O_5	0.16	0.12	0.11	0.16	0.10	0.20	0.19	0.15	0.16	0.15
H_2O	1.45	3.91	4.98	1.05	0.94	0.90	1.10	0.76	0.43	0.19
TOTAL	97.08	100.17	99.93	99.07	100.11	100.10	98.66	98.40	99.00	99.14
Co (ppm)	6	40.	–	44	–	–	–	–	–	–
Cr	–	–	–	–	–	–	82	91	112	102
Ni	10	–	87	–	105	115	63	48	46	43
V	–	175	235	207	–	–	433	447	443	427
Zr	–	–	–	–	–	–	110	–	114	126
Zn	–	85	94	68	100	110	–	–	–	–
Cu	0.5	78	83	75	170	240	–	–	–	–

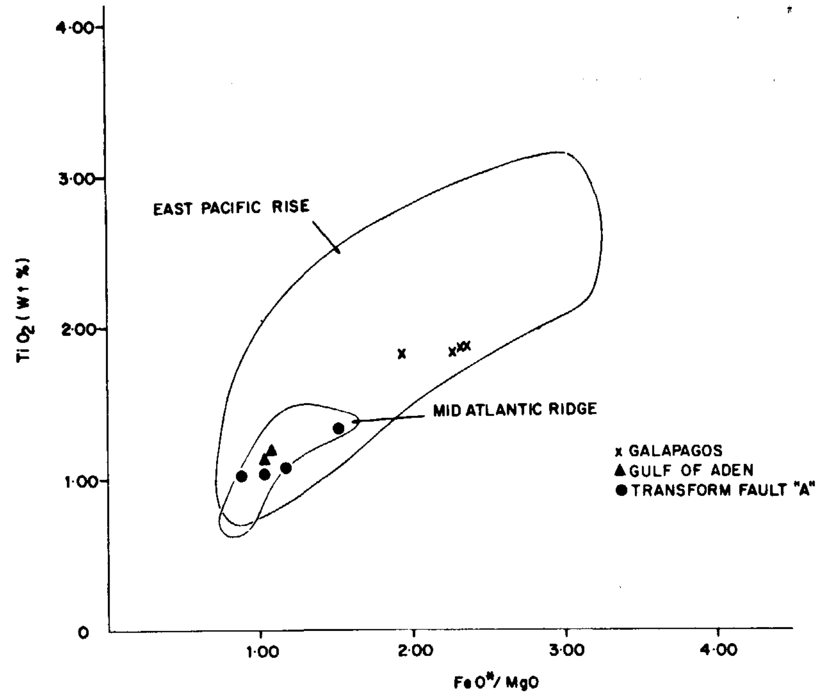


FIG. 6. – TiO_2 - FeO*/MgO (total Fe calculated as FeO) variation diagram of various types of basaltic rocks which were found to be associated with the hydrothermal deposits. The field of basaltic rocks from the Mid-Atlantic Ridge are those collected from the FAMOUS area (Arcyana, 1977). The field of the East Pacific Rise samples represent data taken from Melson (1977) and from Hékinian and Morel (in preparation). The data from the Gulf of Aden samples are from Cann *et al.* (1977).

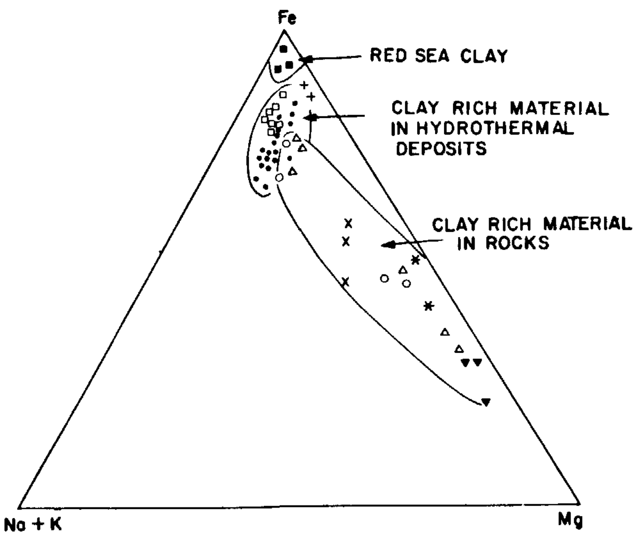


FIG. 7. – Mg-Fe-Na + K ternary diagram of clay material found in various geological environments. The Red Sea clay represents averages calculated from published analyses (Bischoff, 1969) (×) indicates samples of clay from St Paul's Fracture Zone (Melson and Thompson, 1973). Triangles are secondary clays from basalts drilled near 37° N (leg 37, Baragar et al., 1977). (*) Indicates the clays from basaltic rocks dredged from the M.A.R. near 53° N (Jehl, 1975). The circles are clay fractions in basaltic rocks from the Nazca plate, DSDP leg 34 (Scott and Swanson, 1976). The empty square and the full circles indicate the hydrothermal clays from the FAMOUS area and from the Galapagos area respectively (Hoffert et al., 1978). The crosses are the clay material filling veins of basement rock of the Galapagos area at site 425 (leg 54; Hékinian et al., 1978).

Thompson, 1973) consist mainly of a clay-rich material having a higher MgO content (> 15 %) and a slightly higher Al_2O_3 content (> 2 %) when compared to the hydrothermal deposits. The compositional variation of the clay rich material of both the ocean floor basement rocks and those of the hydrothermal deposits is shown in a ternary Mg – Fe – Na + K diagram (fig. 7). Thus the structural formula of the clay-rich material, found in the basement rocks of the Rift Mountain region near 37° N in the Mid-Atlantic Ridge (site 332 B, leg 37):
$(Ca_{0.19}\ Na_{0.03}\ K_{0.1})(Al_{0.07}\ Mg_{5.01}\ Fe^{2+}_{0.26})\ (Si_{6.9}\ Al_{1.1})\ O_{20}\ (OH)_4$
corresponds to that of a saponite.

It is likely that during the passage of hydrothermal fluids through basement rocks they must have undergone some degrees of alteration. It is uncertain whether the alteration through the deposition of secondary minerals is extensive or limited to interstitial pore fluids concentrated in veinlets, vesicles, and interconnecting cavities or small fissures between pillow flows. However it is interesting to notice that all the sizeable hydrothermal deposits are on top of and/or intermixed with sediment which might play an important role, as a buffer, for the discharge of hydrothermal fluid.

All the hydrothermal deposits in *"sensu stricto"* studied here are similar in composition despite the compositional differences of their associated basement rock and alteration products. This suggests that surface or near-surface environmental factors, such as the amount and type of sediment, the relationship of sediment to seawater, are determinant with respect to the type of hydrothermal discharge encountered (i.e. hydrothermal/deposits in *"sensu stricto"* as opposed to metalliferous sediments or hydrogenous material).

CONCLUSIONS

Hydrothermal deposits are here defined as heterogeneous material hydrated and forming isolated and relatively small edifices lying on a sediment-covered basement. These deposits are made up of Fe-Mn concretions overlying friable clay-size material which could be either interlayered with thin Fe-Mn laminae or forming irregular bands of variegated material.

The hydrothermal deposits in *"sensu stricto"* found in the accreting plate boundary regions of the Atlantic, Pacific and Indian Ocean (Gulf of Aden) are composed of a similar kind of material. They are all made up of Fe-Mn concretions which are depleted in their transitional metal content when compared to manganese nodules and metalliferous sediments. They all have comparable compositional variations of their clay-rich material which consists of an Fe-Si rich smectite.

No detectable intermixing of the hydrothermal material with the pelagic sediment were noticed. It is likely that discharge of hydrothermal solutions into seawater must happen relatively quickly. The presence of interlayering and irregular distribution of variegated products within each deposit suggests that fluid solutions have been differentiated during and/or after their discharge on the sedimented bottom. Up to now no evidence of vents or pathway for hydrothermal fluid to circulate within the sediment column and in basement rocks has been found.

The similarity of the hydrothermal deposits in *"sensu stricto'* from the various localities is accompanied by compositional differences of the associated basement rocks in the world show in general a distinctly different the Galapagos region and of Fe-Ti depleted basalts from both the Atlantic and the Gulf of Aden. Most secondary alteration products analysed from various basement rocks in the world show in genaral a distinctly different clay composition (enriched in Mg and Al) from that usually found in the hydrothermal deposits (enriched in Fe and Si). The formation of various secondary clay mineral in basement rocks could be dependent on the depth, the temperature and the pressure gradients existing within the crust. Further work on the secondary alteration products encountered in basement rocks directly related to hydrothermal deposits is necessary in order to have a more meaningful correlation between crustal circulation and the accumulation of hydrothermal material on the ocean floor.

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DISCUSSION

K. BOSTROM : What are the rates of accumulation of the crusts you described ? There are many crusts in the ocean, deposited slowly on seamounts that we hardly are prepared to call hydrothermal, since they also could form from sea water or biological matter. I think that without this 'rate-criterion' some of your crusts may not qualify as hydrothermal.

R. HÉKINIAN : The rate of accumulation of the Fe-Mn crusts was measured to be at least one order of magnitude greater than that of typical ferromanganese deposits : growth rates greater than 2 cm/10^6 years.

K. BOSTRÖM : Are there any alterations of the sediments below the Galapagos rise mounds ? Could some of the Mn or Fe in the hydrothermal crusts derive from the sediment ?

R. HÉKINIAN : The sediment associated with the hydrothermal deposits does not show any signs of alteration by hydrothermalism. In fact, no intermixing of both types of material was noticed.

M. HOFFERT : Dans les sites forés dans les sites hydrothermaux des Galapagos durant le leg 54, la limite entre les dépôts hydrothermaux et les autres sédiments est toujours tranchée. Il ne semble pas y avoir de relation entre les deux types de sédiments. Cependant, les vases carbonatées associées aux dépôts hydrothermaux diffèrent des autres vases carbonatées du bassin de Panama par la dissolution quasi-complète des organismes siliceux.

G. ARRHENIUS : What do you use as criteria for determining that a formation is hydrothermal ?

R. HÉKINIAN : Several criteria could be used to classify the material as being from hydrothermal origin :

1) the geological setting where they occur shows isolated small hills on tectonic lineations. The sediment surrounding these deposits is of a different nature.

2) the morphology of the deposits suggests a fluidal nature of the deposit. Cryptic laminations of different types of material such as clay-size products, Fe-Mn crusts and other amorphous Fe oxides are interlayered together.

3) the composition of the clay-size particles themselves which suggests the occurence of an unusual type of a nontronic clay rich in Fe, Si and depleted in Al ($\sim$ 1 %) content and in transitional metal content ($\sim$ 200 ppm). The average Pacific pelagic clay compared to these has a higher Al content, a lower Fe and high transitional metal content.

C. LATOUCHE : Did you find fibrous minerals (attapulgite or sepiolite) in clay rich sediments ?

M. HOFFERT : Non, aucun minéral de ce type n'a été décelé, ni dans les dépôts hydrothermaux des Galapagos, ni dans ceux de la zone FAMOUS.