Reprinted from
"Progress in Oceanography" Volume 3
PERGAMON PRESS
OXFORD · LONDON · EDINBURGH · NEW YORK
PARIS · FRANKFURT
1965

PETROLOGY OF SUBMARINE VOLCANICS AND SEDIMENTS IN THE VICINITY OF THE MENDOCINO FRACTURE ZONE

Y. Rammohanroy Nayudu*

Department of Oceanography, University of Washington, Seattle, Washington

Abstract. Pyroxene-rich basalts, glassy basalts, olivine basalts and paloganite tuff breccias of various sizes were dredged from the top and in the vicinity of the Mendocino Fracture Zone. Some of these rocks have encrustations of ferro-manganese oxide minerals. In addition, manganese nodules of different sizes were recovered which contain a nucleus of palagonite tuff.

Several sediment cores collected to the north and south of the Mendocino Fracture Zone contain mostly medium yellowish brown clay, commonly known as red clay. Study of the cores revealed two areally restricted bio-lithologic units: (1) Radiolaria–Foraminifera-rich silty clay, and (2) Radiolaria-rich silty clay. The above units grade down into Foraminifera-rich silty clay and silty clay barren of Radiolaria respectively. Red clay is characteristically confined to Radiolaria-rich silty clay, silty clay barren of Radiolaria and contains abundant ferro-manganese micronodules. Greater concentrations of ferromanganese micronodules occur below the sediment surface and are associated with palagonite grains. The sediments to the north of the Mendocino Fracture Zone are rich in zircon, rutile? and zeolites.

The petrography and petrology of the dredged basalts, manganese nodules and sediments are discussed. It is suggested that the sediments, especially in the Radiolaria-rich clay, are dominantly volcanic in origin and locally derived. It is concluded that manganese nodules and red clay containing manganese micro-nodules (manganese grains) are genetically associated with palagonite complexes formed by submarine volcanism which was related to the development of the Mendocino Fracture Zone.

INTRODUCTION

Murray (1939), first reported the existence of a submarine scarp off Cape Mendocino and showed that it extends 70 miles from the shore. Shepard and Emery (1941), suggested that the scarp could be traced at least 400 miles west of the coast and called the near-shore scarp the Gorda Escarpment. On the basis of the *Horizon* survey and from all the available data Menard and Dietz (1952) described the topography in detail and showed that the Gorda Escarpment extends west from Cape Mendocino for at least 1200 miles and

* The research was completed at Scripps Institution of Oceanography and the final manuscript at the University of Washington. Contribution No. 326 of the Department of Oceanography, University of Washington.

suggested the name Mendocino Submarine Escarpment for this large scale feature.

Since the discovery of this feature, several expeditions to the area were undertaken by the Scripps Institution of Oceanography which included geophysical and geomagnetic surveys. Results of these surveys have been treated in the publications of MENARD (1955), MASON (1958), MENARD and VACQUIER (1958), MENARD (1959, 1960b), VACQUIER *et al.* (1961), MASON and RAFF (1961), and RAITT (1963). However, these reports do not include the study of either rocks dredged or the sediment cores taken in the area. REVELLE (1944), discussed Carnegie Sample no. 62, which is located north of the Mendocino fracture zone. MENARD (1953), studied two cores taken in the Tufts Abyssal Plain near the northwestern margin of the Mendocino Fracture Zone. NAYUDU (1959a, b) and NAYUDU and ENBYSK (in press), presented the general nature of the sediment distribution. Recently, ENGEL and ENGEL (1963) in their study of basalts from the northeastern Pacific Ocean, included two basalt samples dredged from the Mendocino Ridge.

During the expeditions "Fan Fare" (1959), and "Mendocino" (1960), dredged rock samples and sediment cores were collected in the vicinity of the Mendocino Fracture Zone. This report concentrates on the petrography and petrology of the samples dredged and sediment cores collected in the area.

In this report, the name Mendocino Fracture Zone is used as a general term which includes the main ridge and the Mendocino Escarpment.

TOPOGRAPHY

Figure 1 is a physiographic diagram of the area under investigation, taken from the physiographic map of the northeastern Pacific prepared by MENARD (1964). It shows that the Mendocino Fracture Zone extends approximately 1500 miles west from Cape Mendocino. Its height close to the shore is about 10,500 ft, which gradually decreases towards the west; about 1000 miles from shore it is approximately 8420 ft. The average slope from the top to the bottom varies from 7° to 10°. However, some portions of the scarp have much steeper slopes. The topography on the north side 200–400 miles from the continental margin is more complex and is characterized by several north, northeast trending ridges which form the southern margin of the Ridge and Trough Province (MENARD and DIETZ, 1951). The southern margin of the smooth Tufts Abyssal Plain (HURLEY, 1960), is north of the Mendocino Fracture Zone. The Pioneer Ridge on the south is a prominent feature which almost parallels the eastern margin of the fracture zone. A detailed description of the topography, including the tectonic interpretation of these remarkable features, is fully discussed by MENARD (1959, 1964).

PETROGRAPHY OF ROCK SAMPLES

Four successful dredge hauls were made during the expedition "Fan Fare". The location and depth are shown in Table 1. These samples are from the eastern margin of the Mendocino Fracture Zone and less than 150 miles off Cape Mendocino; their distribution is shown in Fig. 1. The samples can be separated into three major groups: (1) manganese nodules, (2) palagonite tuff breccias with ferromanganese oxide encrustations, (3) basalts. The petrographic descriptions of selected samples from these groups are given below.

A detailed discussion on the problem of submarine eruption of basalts

TABLE 1. LOCATION AND LENGTH OF CORES
MENDOCINO EXPEDITION, 1960

Core No.	Length (cm)	Depth (m)	Latitude (north)	Longitude (west)
1	95	1920	32° 36′	118° 07′
2b	88		33° 45′	119° 31′
3	180	4250	33° 58′	122° 34′
4	158	4640	34° 02′	125° 15′
5	164	4460	36° 04′	125° 04′
6	175	4280	38° 25′	126° 09′
7	101	4150	39° 47′	126° 21′
8	30	3140	40° 33′	126° 31′
9	108	3120	40° 56′	126° 31′
10b	35	2830	40° 37′	125° 17′
11	135	2950	41° 30′	126° 32′
12	172	3260	40° 36′	127° 25′
13	135	4510	40° 07′	128° 10′
14	124	3190	40° 40′	129° 13′
15	140	4520	40° 00′	131° 00′
16	174	3870	40° 02′	133° 07′
17	93	4140	40° 25′	133° 06′
18	142	4740	39° 30′	133° 05′
20	172	4080	41° 06′	135° 32′
21	168	5150	41° 07′	151° 22′
22	76	5560	39° 21′	149° 56′
23	156	4810	40° 38′	149° 01′
24	142	4720	40° 47′	146° 00′
25	156	4700	40° 41′	142° 52′
26	152	4540	40° 44′	139° 22′
27	150	5290	39° 05′	139° 26′
28	158	5270	38° 40′	142° 36′
29	147	5380	38° 02′	137° 58′
30a	72	4810	38° 00′	134° 00′
32	140	4510	39° 30′	131° 47′
33	128	3640	40° 44′	131° 45′
34	88	1240	32° 32′	117° 31′

TABLE 1.—*continued*
FANFARE EXPEDITION, 1959
Location of Dredge Samples

Dredge No.	Depth (m)	Latitude (north)	Longitude (west)
20	4500	40° 15′ to 40° 18′	128° 27′ to 128° 29′
25	1260	40° 23′	128° 16′
33	3925	40° 19′	127° 39′
36	1820 to 2390	40° 24′ to 40° 19′	125° 32′ to 125° 43′

and a review of the origin, mode of formation and meaning of the term "palagonite" have been described by NAYUDU (1962a, b, 1964); accordingly, the term "palagonite" is used in this report.

Manganese Nodules

Dredge sample no. 20, obtained from the eastern margin (Mendocino Ridge) of the Mendocino Fracture Zone at a water depth of 4500 m, consists predominantly of manganese nodules. They vary in shape from almost spherical, ovoid and irregular shapes to flattened slabs. The nodules range in size; the spherical type vary from 3 to 12 cm in diameter, and the largest flattened type reaches 20 cm across. The surfaces are irregular and frequently reniform in appearance. When broken the majority of the manganese nodules show that they consist of a series of concentric dark gray layers alternating with yellowish material and sometimes with a light gray material which shows the concretionary nature of the nodules (Pl. 1A). The dark gray material is ferromanganese oxide minerals, the yellow layer is palagonite and the light gray material is probably a decomposition product (an admixture of montmorillonite, zeolites, mineral grains originally associated with the primary palagonite, and occasionally carbonate) of the palagonite. In addition to concentric structure, several nodules show radial structures which essentially consist of dark gray ferromanganese oxides. Generally, the nodules contain a nucleus of yellowish palagonite or its decomposition products. Some of the samples containing a palagonite nucleus show dendritic growths of ferromanganese oxides. The shapes and internal structures of the nodules bear a close resemblance to the nodules described by MURRAY and RENARD (1891),

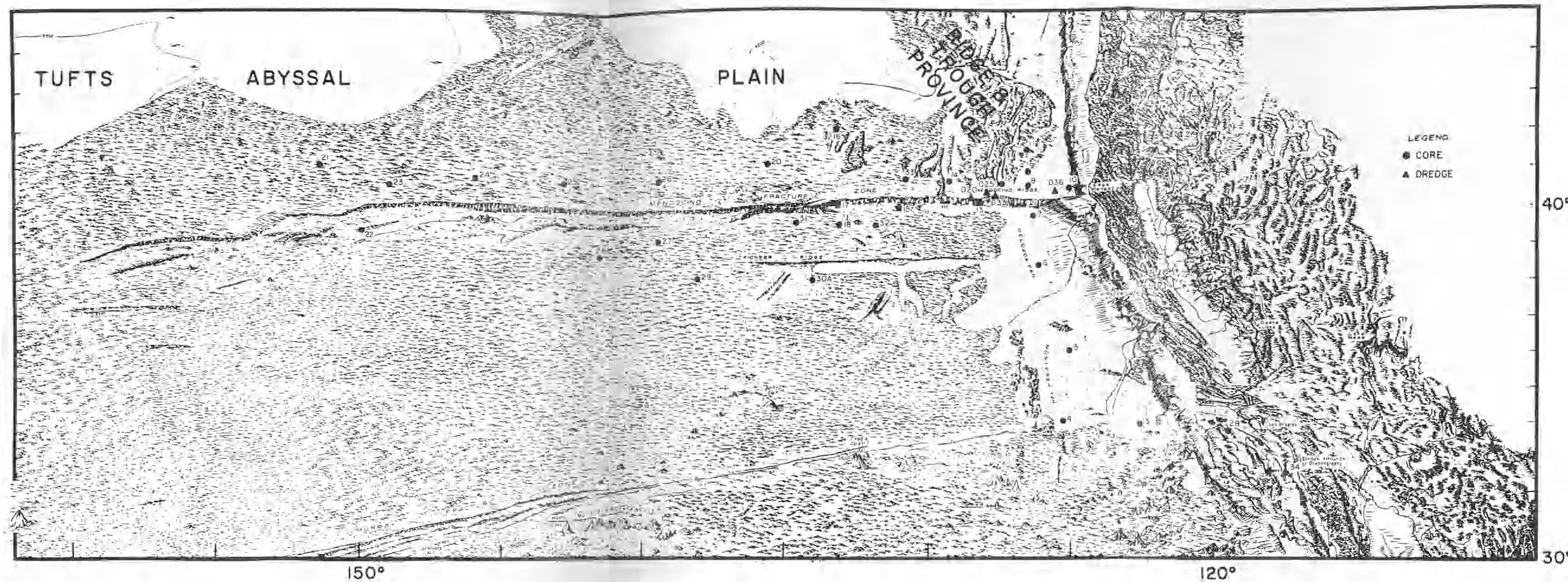


FIG. 1. The physiographic diagram showing the Mendocino Fracture Zone and adjacent area (after MENARD, Copyright 1964. By permission of McGraw-Hill Book Co.)

MENARD (1960a), and MERO (1962), and some of the samples are similar to manganese nodules discussed by NAYUDU (1964) and BONATTI and NAYUDU (1965).

Palagonite Tuff Breccias with Ferromanganese Encrustations

Many manganese encrusted cobbles and pebbles were recovered in dredge hauls. The largest number of these were obtained from the top of the Mendocino Fracture Zone, at a water depth of 1260 m. These rocks have a dark brown crust of ferromanganese oxides and in several specimens yellowish brown patches are visible in the crust (Pl. 2A). The sawed sections of these samples show that the nucleus of the manganese encrusted rocks is palagonite tuff breccia. Two samples of palagonite tuff breccias with manganese encrustation are shown in Plates 1B and 2A. In these samples basaltic fragments of different shapes and sizes are set in a matrix of palagonite with its typical yellowish color. The sample in Plate 1B contains a light yellowish gray matrix which surrounds yellowish brown palagonite containing vitreous basaltic glass fragments. These fragments occupy approximately 20–30 per cent of palagonite. The outer yellowish gray matrix may be a decomposition product of the palagonite.

In thin sections the basaltic fragments consist of pyroxene-rich basalts. The tachylytic glass of the ground mass of basaltic fragments shows different stages of devitrification, and it contains needles and rods of opaques which have a tendency to concentrate along the margins of the fragments. Chlorite, zeolites, montmorillonite, fragments of plagioclase, pyroxene and olivine are some of the main constituents of the yellowish gray matrix. Partially altered very fine fragments of basaltic glass (sideromelane), some containing pyroxene or olivine are present. Occasionally sideromelane fragments with rims of partially altered palagonite also occur. Hence the yellowish gray matrix is considered to be the decomposition product of the palagonite. The mineral fragments: plagioclase, pyroxenes, and olivine are believed to be the original minerals present in the primary palagonite matrix. In thin sections the palagonite is deep golden yellow and forms a margin around larger sideromelane fragments. Concentrations of dark opaques are noticed along the margin of sideromelane. Within the palagonite, segregations of black or reddish brown patches, concentric rings and needle-like structures, probably ferromanganese oxides, are characteristically visible (Pls. 1C, 2B). These features suggest that the processes of migration and segregation of metallic elements take place on a microscale, probably during and after the palagonitization.

Basalts

Basaltic rocks constitute most of the specimens which are of various shapes

Plate I

1A. Photograph showing manganese nodules dredged from the Mendocino Fracture Zone. Note the nucleus of yellowish palagonite and concretionary structure in the broken nodules; layers of ferromanganese oxides, palagonite (partly altered) and light yellowish gray material (altered palagonite) are seen.

1B. Photograph of slab cut from manganese encrusted rock, which shows the nucleus consisting of palagonite tuff breccia; the yellowish gray matrix with fragments of basalt surrounds the yellowish brown palagonite containing basaltic glass fragments. The outer yellowish gray matrix is a decomposition product of the palagonite.

1C. Photomicrograph of thin section of palagonite tuff breccia shown in 1B. Within the deep golden yellow palagonite note segregations and concentrations of ferromanganese oxides in the form of specks, hair-like and circular structures. Plane light ×120.

FIG. 1A

FIG. 1B

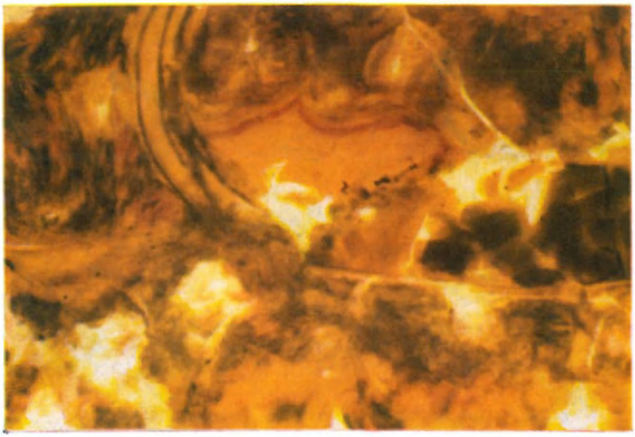


FIG. 1C

FIG. 2A

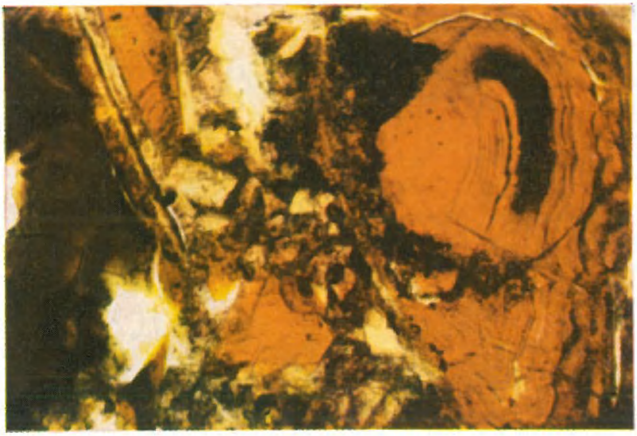


FIG. 2B

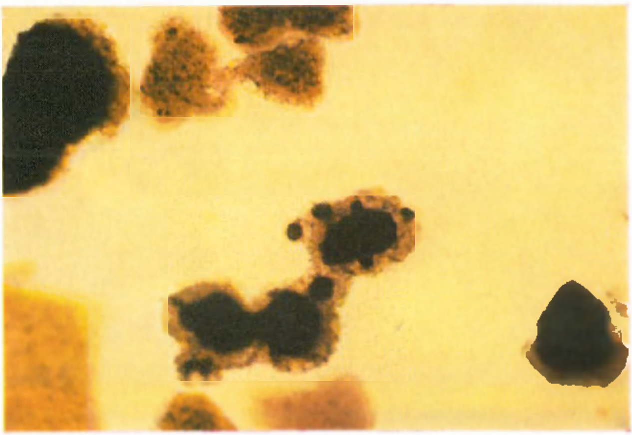


FIG. 2C

PLATE II

2A. Ferromanganese oxide encrusted rock from the Mendocino Fracture Zone. Slab cut from the nodule shows the nucleus of typical yellowish palagonite tuff breccia. Note yellowish brown patches in the crust.

2B. Photomicrograph of thin section of palagonite tuff breccia shown in 2A. Note excellent development of concentric rings and patches of ferromanganese oxides within the golden yellow palagonite; on the left a dark brown fragment of sideromelane can be seen. Plane light $\times 120$.

2C. Palagonite grains from the sediments (Core 15) showing typical color; concentration and replacement by opaque ferromanganese oxides; also note the dark specks and different shapes of the replaced ferromanganese oxides. Plane light $\times 65$.

and range in size from boulder to pebble. Some of the samples have thin encrustations of hydrated ferromanganese oxides. A few broken or cut samples reveal the presence of dark gray glassy margins. In general basalts show no visible weathering or alteration. Most of the specimens are compact and fine-grained basalt and a few of them are vesicular.

In thin sections most of these rocks are pyroxene-rich basalts. Pyroxene is essentially monoclinic and consists of augite which occurs as subhedral crystals, grains and aggregates. Some grains of the augite are slightly purplish, probably titaniferous augite, and occasionally hour-glass structures are observed. Pyroxenes show little or no alteration and vary approximately from 30 to 50 per cent by volume of the rocks.

A few thin sections of basalt contain olivine in variable amounts and are grouped as olivine basalts. Olivine is present as subhedral crystals and shows different degrees of alteration, leading to iddingsite, fibrous serpentine or chlorite.

In thin sections, these basalts show the presence of needles, fine laths and tabular plates of plagioclase, which occur as phenocrysts and also are found in the ground mass. Plagioclase, which is mostly labradorite, has a tendency to form glomeroporphyritic aggregates. Some laths locally develop subophitic texture and are covered by glass or enveloped by pyroxene (Pl. 3A).

Some fragments of basalt contain dark gray basaltic glass margins which grade into light gray basalt. In thin section these margins are dark gray tachylyte with hair-like needles of dark opaques and thin needles of plagioclase. Occasionally plagioclase and pyroxene occur together as phenocrysts. Subradiating laths of plagioclase often enclose aggregates of pyroxene. In thin sections the light gray basalt is a porphyritic, glassy basalt with glomeroporphyritic aggregates of plagioclase (labradorite). Subhedral crystals of clinopyroxene are also present as phenocrysts and fine grained aggregates are partly enclosed by the plagioclase laths (Pl. 3B). As a rule, both the pyroxenes and the plagioclase are fresh and a few grains of the pyroxene show minor alteration. The devitrification and decomposition of the glass of the ground mass result in concentrations of black opaques (secondary magnetite or ferromanganese oxides?) and reddish brown stains. The texture of these rocks varies from vitrophyric to intersertal.

DESCRIPTION AND DISTRIBUTION OF SEDIMENTS

During the "Mendocino" expedition, 1960, several deep-sea cores were collected. The location, depth and length of these cores are shown in Table 1, and their distribution in Fig. 1. A study of the sediment cores shows a Radiolaria-rich clay horizon of variable thickness is present in the top part of cores nos. 15, 17, 18, 20 to 31, and its distribution is shown in Fig. 2. The

PLATE III

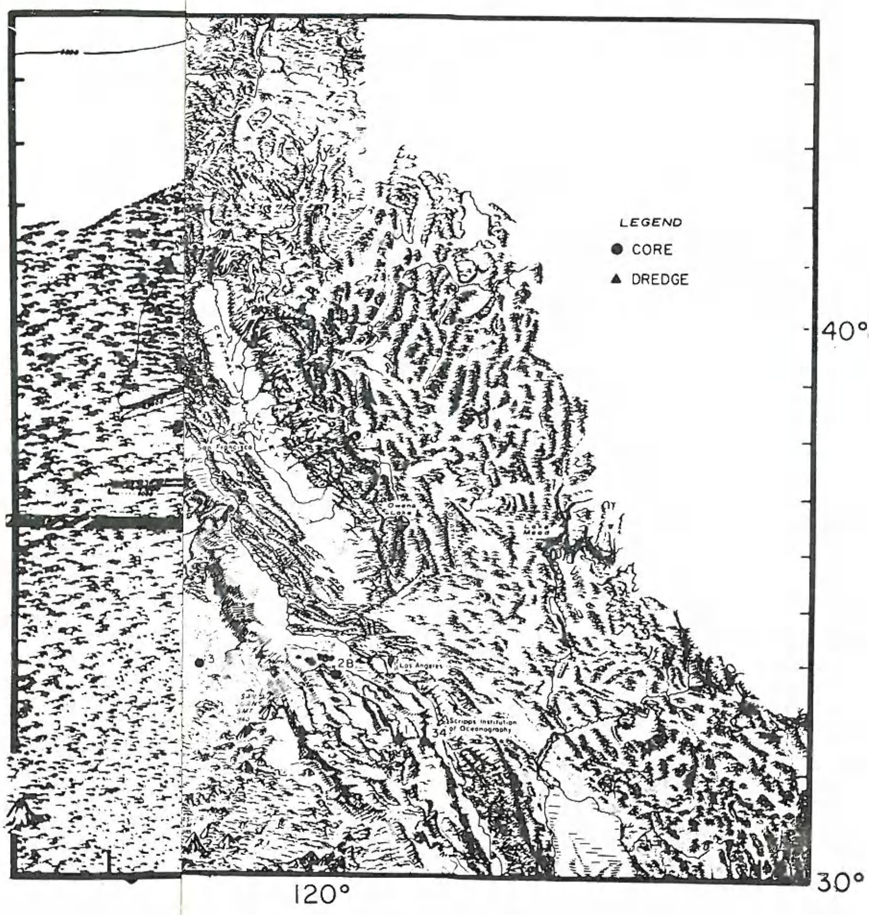
3A. Photomicrograph of pyroxene-rich basalt showing phenocrysts of plagioclase and pyroxene in the glassy ground mass. Plane light ×120.

3B. Photomicrograph of glassy basalt showing glomerporphyritic aggregates of plagioclase and granular pyroxene; fine laths of plagioclase are also prominent in the glassy ground mass. Plane light ×120.

thickness of this horizon increases seawards and reaches a maximum of 25 cm in core no. 21, which is the westernmost core north of the Mendocino Fracture Zone. Radiolaria predominate, are rich in variety and most of them are well preserved. Sediments of the surface horizon are essentially silty clay. Silt-size plagioclase feldspar (andesine-labradorite) is the dominant mineral. Fresh and partly altered pyroxenes, palagonite and basaltic glass, quartz, micronodules (manganese grains), zeolites and zircon are some of the other important components of the sediments. Colorless glass shards of andesitic? composition are common in this horizon and they increase in amount in the westernmost cores (Cores 21–23).

The Radiolaria-rich clay surface horizon gradually grades into sediments barren of Radiolaria. A petrographic study of the sediment barren of Radiolaria shows that silt size plagioclase (andesine-labradorite and oligoclase?) is the prominent mineral. Other inorganic components of the sediment include quartz, pyroxenes (fresh and partly altered), basaltic hornblende and occasionally green hornblende, basaltic glass, palagonite grains and micronodules. Yellowish brown aggregates (probably altered palagonite grains) predominate in the sand size fraction of the sediment. These aggregates consist of microcrystalline, birefringent minerals probably cryptocrystalline silica and zeolites. In addition, palagonite spherulites often contain segregations of black opaques (ferromanganese oxides) as specks, globulites and concentric rings. Some of the palagonite grains are almost completely replaced by ferromanganese oxides of different shapes and sizes (Pl. 2C). Furthermore, the relatively high concentrations of these spherulites of palagonite and manganese oxides are characteristic of the south side of the Mendocino Fracture Zone. Zeolites (phillipsite with its characteristic twins, and other zeolites with tabular plates, sheaf-like aggregates and radiating clusters) occur in the sediments and their concentration increases with depth. Zircon, rutile and goethite or hematite ? were observed in these sediments. Zircon, occasionally epidote, biotite altered to chlorite and green hornblende appear to be more prominent north of the Mendocino Fracture Zone (Cores 20, 21).

In Cores 8, 9, 11, 12, 13, 14, 16 and 33, the surface layer of Radiolaria-rich clay is associated with large numbers of Foraminifera, and is designated as Radiolaria–Foraminifera-rich sediments (mixed horizon). Its distribution is also shown in Fig. 2. The thickness of this mixed horizon is quite variable and reaches a maximum of 30 cm in core no. 12. Considerable mixing of sediments has been observed in this area, probably due to the activity of the mud-feeding animals at the bottom. The above mixed horizon passes into Foraminifera-rich sediments in which planktonic Foraminifera are predominant in number and variety. Coccoliths are present. The total carbonate content of this Foraminifera-rich sediment horizon varies from about 60 to 80 per cent of the total sample. The inorganic constituents of the sediments



clay is shown by dotted line pattern.

consist of plagioclase, quartz, fresh and partly altered pyroxene, brown and green hornblende, partly altered palagonite, basaltic glass and biotite altered to chlorite.

DISCUSSION AND CONCLUSIONS

The description of sediments presented above reveals that the area under investigation consists chiefly of two bio-lithologic units in the surface: (1) Radiolaria–Foraminifera-rich silty clay (mixed horizon), (2) Radiolaria-rich silty clay. The areal distribution of these units is shown in Fig. 2. The mixed horizon is located in the Ridge and Trough Province and is close to the continental margin. The Radiolaria-rich clay is the largest unit present north and south of the Mendocino Fracture Zone.

The predominant color of the sediments is medium yellowish brown (10YR5/2), based on the National Bureau of Standards color chart, distributed by the National Research Council. Cores 16, 20 and 21 located on the northernmost part are much lighter whereas cores located close to the Mendocino Fracture Zone are much darker. However, for general description and discussion purposes, the entire area covering Radiolaria-rich silty clay is commonly described as red clay (REVELLE, 1944; MENARD, 1953).

The Radiolaria–Foraminifera-rich silty clay surface unit merges in depth with a carbonate-rich sediment horizon. Foraminifera and coccolith content in this horizon in some intervals reaches 60–80 per cent. The inorganic constituents are derived from both local volcanics and continental rock types (Cores 14, 16 and 33). Plagioclase feldspar and quartz predominate and basaltic glass, green and basaltic hornblende, feebly birefringent microcrystalline aggregates and mica (partly altered to chlorite) are common. The carbonate-rich section in depth contains intervals rich in zeolites which are present as tabular plates, aggregates and phillipsite (cross twinned). Micronodules (manganese grains) are scattered throughout the sediment. The zeolites and manganese grains are associated with palagonite and suggest a genetic relationship.

In Core 14, the top 9 cm is medium dusky brown (10YR3/2) and consists of large amounts of manganese grains, basaltic glass and pyroxene. This section grades into medium greenish gray to greenish gray which in general is of similar composition. Such a change in color at depth might possibly be the result of solution and upward migration of iron and manganese from the deeper sediments due to reducing conditions and diagenetic processes peculiar to the vicinity of the core. It might also be due to changes in the rates of deposition.

The Radiolaria-rich silty clay surface unit gradually grades into silty clay barren of Radiolaria. Petrographic studies of the sediments in both the

Radiolaria-rich and barren clays show that sand-size inorganic components of the region investigated consist mainly of volcanic material of basaltic composition, although some amount of terrigeneous material from the continental margin is present. The sand-size fraction of the sediment consists largely of microcrystalline aggregates of birefringent minerals (zeolites? and cryptocrystalline silica?), probably altered palagonite and grains of palagonite which have been replaced by opaques (ferromanganese oxides) of different forms and shapes (Pl. 2C). In addition, manganese grains are important constituents of the sediments. The high concentration of manganese grains and microcrystalline aggregates (altered palagonite?) increases with depth in the sediments and are commonly found south of the fracture zone (Cores 15, 17, 18, 22, 27, 28, 30). In some intervals nearly 60–80 per cent of the sand fraction consists only of manganese grains. In general, sediments (sand to silt size) of the area consist predominantly of plagioclase feldspar, fresh and partly altered pyroxene, basaltic glass (both sideromelane and mostly altered tachylyte). The amount and sizes of the above minerals also increase with depth.

The sediments of the northernmost part of the Radiolaria-rich clay area suggest that there is a greater dilution by terrigeneous sediments of continental origin. It has been already pointed out that the color of these sediments is lighter than the sediments that were found south of but very close to the Mendocino Fracture Zone.

The north–south trending ridges of the Ridge and Trough Province effectively inhibit the movement of the sediments from the continental margin, except through deep-sea channels. The only channel of such importance is the Cascadia Channel to the north, which debouches sediments from the Cascadia Abyssal Plain bordering the continental margin, to the smooth Tufts Abyssal Plain. Its southern margin is shown in Figs. 1, 2. The present writer (1962c) has shown that in the southeastern margin of the Tufts Abyssal Plain there is mixing of sediments from a different provenance. Minerals such as biotite, basaltic hornblende, zircon, epidote and rutile found in the Cascadia Abyssal Plain predominate in the sediments which are probably transported by the Cascadia Channel.

The influence of mineral assemblage described above has been observed to a great degree in Cores 16, 20 and 21, which are located close to the southern and southeastern margin of the Tufts Abyssal Plain and to a lesser degree in other cores located very close to the Mendocino Fracture Zone. Moreover, the micronodule concentrations in the northernmost cores are also considerably less. Furthermore, the sediments north of the fracture zone are rich in zircon and rutile? in the fine fraction.

REVELLE (1944) reported that Carnegie sample no. 62 (40° 37′ N. and 132° 23′ W.), which is located slightly north of Core 17, contained 0.10% ZrO_2, 0.79 % TiO_2 and 1.40 % MnO_2. He further stated that sample 62 located close to the land is similar to normal red clay whereas, sample 61 located in the Tufts Abyssal Plain, approximately 650 miles from shore and about 250 miles farther northwest of sample 62, is gray clay with terrigeneous influence. MURRAY (1877), and MURRAY and RENARD (1891) were the first to suggest that red clay was derived from the decomposition of volcanic ejecta, although Murray admitted the possibility that colloidal clay material carried in suspension from land also contributed some part to the red clay. On the other hand, REVELLE (1944) strongly favored the idea that a considerable amount of red clay was derived from soils transported from land. BRAMLETTE (1961, p. 360) recognized the importance of the decomposed pyroclastic material in the formation of pelagic clay and stated, "The pelagic (red) clay still poses many problems, such as the proportion derived from pyroclastics and the various other sources."

However, the writer is inclined to believe that the normal red clay (Carnegie sample no. 62) which is equivalent to the dark medium yellowish brown clay described in the area, is probably due to the dominant influence of decomposed submarine volcanic material (mainly palagonites, basaltic glass, and mafics) which is derived locally.

NAYUDU (1959a, b), NAYUDU and ENBYSK (in press), defined seven biolithologic units in the northeast Pacific, immediately north of the Mendocino Fracture Zone (north of 40° N.). These units include Radiolaria-rich clay in the Tufts Abyssal Plain and a *Globigerina*-rich silty clay band. The Radiolaria-rich clay horizon of 7–10 cm thick grades into sediment barren of Radiolaria. The *Globigerina*-rich silty clay contains a considerable number of Radiolaria in the top section (10–15 cm) which grades down into *Globigerina*-rich sediment or ooze, with few or no Radiolaria.

The present study reveals, as previously mentioned, that a large area north and south of the Mendocino Fracture Zone consists of Radiolaria-rich silty clay which increases in thickness seaward, and grades down into sediments barren of Radiolaria. Hence, both these horizons are tentatively correlated with similar horizons from the Tufts Abyssal Plain in the north. The surface of the mixed horizon of Radiolaria–Foraminifera-rich silty clay and the Foraminifera-rich horizon in the northeastern region of the area under study are also tentatively correlated with the *Globigerina*-rich silty clay band in the north described in the earlier study.

From the radiocarbon dates in the *Globigerina*-rich band in the north, it has been suggested (NAYUDU, 1964) that the upper Radiolaria-rich clays represent post-glacial sediments. The seaward increase of the rather thick Radiolaria-rich clay horizon immediately north and south of the Mendocino Fracture Zone suggests a highly favorable environment for Radiolaria and also probably less dilution by the terrigenous sediments.

MURRAY and RENARD (1891) were the first to propose that the manganese of nodules is derived from volcanics. PETTERSSON (1943, 1945, 1955, 1959) strongly favors the idea that manganese is derived from pyroclastics decomposing on the ocean floor. NAYUDU (1962a, b, 1964) emphasized that palagonitization is a primary phenomenon associated with the submarine eruption of basalts and that the basaltic magma builds piles of palagonite tuff breccia in the initial phase of submarine eruptions. In the later phase, massive lava intrudes the palagonite tuff breccia and develops pillows, sills and laccolith-like structures, resulting in heterogeneous rock complexes. Nayudu further suggested that the alteration and decomposition of palagonite results in the concentration of ferromanganese oxide minerals, zeolites, montmorillonite and/or carbonate, and that palagonitization is probably an important first step in the concentration of manganese and iron in the nodules. BONATTI and NAYUDU (1965) presented a brief review of the various theories on the origin of manganese nodules on the ocean floor and suggested that submarine volcanism is a major source of manganese.

Petrographic studies of the dredged samples, on and around the Mendocino Fracture Zone, show that pyroxene-rich basalts, palagonite tuff breccias and glassy basalts predominate. Manganese nodules and manganese oxide mineral encrusted rocks are associated with palagonite tuff breccia. In thin sections it is seen that segregation, concentration and much migration of ferromanganese oxides take place in palagonite (Pls. 1C, 2B). Moreover, it was pointed out earlier that a considerable number of palagonite grains in the sediment were replaced by variously shaped ferro-manganese oxides (Pl. 2C). The shapes of these oxides are strikingly similar to the shapes of several of the micronodules present in the sediment, thus suggesting their genetic relationship to palagonite. Hence, it appears that the major components of the sediments are derived from basic volcanics, mainly pyroxene-rich basalts, palagonite tuffs and glassy basalts.

From the petrology of the dredged samples of the manganese nodules, palagonite tuff breccias, basalts and sediments, it appears that most of the red clay and the manganese micronodules of the area have a direct genetic relationship to palagonite tuffs and basalts, which are associated with the formation of the main ridge and any subsequent volcanism in the area.

ACKNOWLEDGEMENTS

This paper has been prepared as a token of my respect and admiration and is presented as a tribute to Professor Hans Pettersson on his 75th birthday.

The writer expresses his special thanks to M. N. Bramlette, H. A. Coombs, E. L. Hamilton, and F. P. Shepard for their valuable suggestions, comments and critical reading of the manuscript. The author takes the responsibility for the interpretations. Thanks are due to my colleague W. R. Riedel, who supplied the samples, for helpful information and discussions; to Roy Wadge for preparing the thin sections; to John P. Harris, Thomas J. Walsh and Jo Laird for their assistance in the laboratory.

The research on which the results of this paper are based was sponsored by the National Science Foundation Grant (G-21518) and in part supported by the Office of Naval Research Contract Nonr-477(10) project NR083-012, and the writer is indebted for these contributions.

REFERENCES

BONATTI, ENRICO and NAYUDU, Y. R. (in press) The origin of manganese nodules on the ocean Floor. *Amer. J. Science*, **263** (1), 17–39

BRAMLETTE, M. N. (1961) Pelagic sediments. In: *Oceanography*, *Amer. Assoc. Advancement of Sci. Pub.*, No. 67, 345–366.

ENGEL, CELESTE O. and ENGEL, A. E. J. (1963) Basalts dredged from the northeastern Pacific Ocean. *Science*, **140**, (3573), 1321–1324.

HURLEY, ROBERT J. (1960) The geomorphology of abyssal plains in the northeast Pacific Ocean. Marine Physical Laboratory of the Scripps Institution of Oceanography, Ref. 60-70, 104 pp. (Unpublished manuscript).

MASON, R. G. (1958) A magnetic survey off the west coast of the United States. *Geophys. J.* **1**, 320–329.

MASON, R. G. and RAFF, ARTHUR D. (1961) Magnetic survey off the coast of North America, 32°N. Latitude to 42° N. Latitude. *Geol. Soc. Amer. Bull.*, 72, 1259-1265.

MENARD, H. W. (1953) Pleistocene and Recent sediments from the floor of the northeastern Pacific Ocean. *Geol. Soc. Amer. Bull.* **64**, 1279–1294.

MENARD, H. W. (1955) Deformation of the northeastern Pacific Basin and the west coast of North America. *Geol. Soc. Amer. Bull.* **66**, 1149–1198.

MENARD, H. W. (1959) Minor lineations in the Pacific Basin. *Geol. Soc. Amer. Bull.* **70**, 1491–1496.

MENARD, H. W. (1960a) Possible pre-Pleistocene deep-sea fans off central California. *Geol. Soc. Amer. Bull.* **71**, 1271–1278.

MENARD, H. W. (1960b) Consolidated slabs on the floor of the eastern Pacific. *Deep-Sea Res.* **7**, 35–41.

MENARD, H. W. (1964) *Marine Geology of the Pacific*. McGraw-Hill, New York, 271 pp.

MENARD, H. W. and DIETZ, R. S. (1951) Submarine geology of the Gulf of Alaska. *Geol. Soc. Amer. Bull.* **62**, 1263–1285.

MENARD, H. W. and DIETZ, R. S. (1952) Mendocino Submarine Escarpment. *J. Geol.* **60**, 266–278.

MENARD, H. W. and VACQUIER, V. (1958) Magnetic survey of part of the deep-sea floor off the Coast of California. Office of Naval Research, *Research Reviews*, June, 1–5, 1958.

MERO, J. L. (1962) Ocean-floor manganese nodules. *Econ. Geology*, **57**, 747–767.

MURRAY, H. W. (1939) Submarine scarp off Mendocino. *California. Field Engineers Bull.* **13**, 27–33.

MURRAY, JOHN (1877) On the distribution of volcanic debris over the floor of the ocean. *Proc. Roy. Soc., Edin.* **9**, 247.

MURRAY, JOHN and RENARD, A. F. (1891) Deep-sea deposits. *Rept. Challenger Exped.*, London, 525 pp.

NAYUDU, Y. R. (1959a) Recent sediments of the northeast Pacific. Preprints, Internat. Oceanogr. Cong., Amer. Assoc. Adv. Sci., 477–478.

NAYUDU, Y. R. (1959b) Recent sediments of the northeast Pacific. Univ. of Washington, Ph.D. dissertation, 53 pp.

NAYUDU, Y. R. (1962a) *A new hypothesis for origin of guyots and seamount terraces;* Crust of the Pacific basin. *Geophys. Monograph*, No. 6, 171–180.

NAYUDU, Y. R. (1962b) Submarine eruption of basalts and the problems of palagonitization (Abstract). *Internal. Sym. of Volcanology, Japan*, **47**.

NAYUDU, Y. R. (1962c) Origin and distribution of deep-sea sand-silt layers in northeast Pacific. (Abstract). *Amer. Assoc. Petr. Geol.* **46**, 2, 273–274.

NAYUDU, Y. R. (1964) Carbonate Deposits and Paleoclimatic implications in the northeast Pacific Ocean. *Science*, **146** (3643), 515–517.

NAYUDU, Y. R. (1964) Palagonite tuffs (Hyaloclastites) and the products of post-eruptive processes. *Bulletin Volcanologique*, 27 (in press).

NAYUDU, Y. R. and ENBYSK, B. J. (in press) Bio-Lithology of Northeast Pacific Surface Sediments. *Marine Geology*.

PETTERSSON, H. (1943) Manganese nodules and the chronology of the ocean floor. (*Medd. Oceanogr. Inst., Göteborg*). *Göteborgs Kungl. Vetenskaps- och Vitterhets-Sämhalles Handlinger*, (6), (B), **2**, (8), 1–43.

PETTERSSON, H. (1945) Iron and manganese on the ocean floor (*Medd. Oceanogr. Inst. Göteborg*, 7). *Göteborgs Kungl. Vetenskaps- och Vitterhets-Sämhalles Handlinger*, (6), (B), **3**, (8), 1–37.

PETTERSSON, H. (1955) Manganese nodules and oceanic radium. *Deep-Sea Res.*, supp. **3**, 335–345.

PETTERSSON, H. (1959) Manganese and nickel on the ocean floor. *Geochim. et Cosmochim. Acta*, **17**, 209–213.

RAITT, R. W. (1963) *Seismic refraction studies of the* Mendocino Fracture Zone (Abstract). Internat. Assoc. of Physical Oceanogr., XIII General Assembly, I.U.G.G., VI-71 (E21).

REVELLE, R. (1944) Marine bottom samples collected in the Pacific Ocean by the *Carnegie* on its seventh cruise. *Carnegie Inst. Washington, Pub.*, 556, 196 pp.

SHEPARD, F. P. and EMERY, K. O. (1941) Submarine topography off the California coast; canyons and tectonic interpretation. *Geol. Soc. Amer., Spec. Paper*, **31**, 171 pp.

VACQUIER, V., RAFF, ARTHUR D. and WARREN, R. E. (1961) Horizontal displacements of the floor of the northeastern Pacific Ocean. *Geol. Soc. Amer. Bull.* **72**, 1251–1258.