

DIVISION OF ENTOMOLOGY
BOARD OF AGRICULTURE AND FORESTRY
HONOLULU, HAWAII

**SOME OF THE MINERAL RESOURCES
OF THE
HAWAIIAN ISLANDS**

By

G. DONALD SHERMAN

**SPECIAL PUBLICATION NO. 1
HAWAII AGRICULTURAL EXPERIMENT STATION
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Material presented in this paper was obtained from various projects of the Department of Soils and Agricultural Chemistry, College of Agriculture, University of Hawaii, which deal with fundamental properties of the soils and their formation. The department does not maintain a project for the development of natural resources. It is the purpose of this publication to make this data available to the public so that the maximum utilization of our resources may be attained.

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SOME OF THE MINERAL RESOURCES OF THE HAWAIIAN ISLANDS

By

G. DONALD SHERMAN

The mineral resources of the Hawaiian Islands have been considered to be very limited. In fact, they have been considered to be limited to coral sand, clay, and crushed lava rock. Any development of a mineral industry has been considered impossible in the Hawaiian Islands and has never been included in the planning of the research program for our development of natural resources. However, if one were to look into the mineral resources of other tropical and subtropical regions, one would soon observe that iron ore, bauxite, chromium, nickel, and manganese have been found in quantities to justify the development of a mining industry for the recovery of these valuable metals. They occur under the same weathering conditions found in Hawaii, and from lava rocks similar to those found in the Hawaiian Islands. Recent studies have shown that the weathering surface horizons are rich in the oxides of iron, aluminum, and titanium, and that the enrichment of our surface horizons with these oxides has been due to the tropical soil forming process, laterization.

WEATHERING PROCESSES OF HAWAIIAN GEOLOGICAL MATERIALS

Weathering of the earth's crust has two distinct aspects, *physical weathering or disintegration* and *chemical weathering or decomposition*. Physical weathering can be defined as changes of consolidated rock to an unconsolidated state without change in chemical composition. Chemical weathering involves a change in the chemical composition of either the consolidated or the unconsolidated materials. Under subtropical conditions which occur in the Hawaiian Islands, chemical decomposition will be the dominant weathering process. In chemical weathering there will be a cycle of weathering in which the primary minerals are decomposed to form new secondary minerals of greater stability. As weathering progresses, a successive series of minerals will form, each having a greater stability than its predecessor.

The Hawaiian Islands have a subtropical climate. The temperatures are relatively uniform with only small difference in mean temperature existing between summer and winter. Annual precipitation varies greatly in the islands, ranging from approximately 5 inches to over 500 inches per year. The volcanic lavas which built up the islands consisted of basalts, andesites and their related rocks, and trachytes. All of these are rocks having a very low quartz content. Likewise, the volcanic ash found in the islands has a mineral and chemical composition similar to the volcanic lavas. Thus, the parent geological materials have a uniform mineral and chemical composition. Weathering is very rapid, due to warm climate the year around and due to the lack of quartz, a mineral resistant to weathering, in the geological parent material. Vegetation also plays a very active role in determining the rate and type of weathering. In the dry areas, the vegetation has a higher content of bases in the leaves, giving rise to an organic matter which is near neutral in reaction and has a high content of calcium. In contrast are the tree ferns and staghorn ferns which grow in areas having a heavy annual rainfall. These ferns have a low calcium content. They produce an organic matter which is strongly acid and which has a very low content of bases. The strongly-acid organic matter produces a weathering media in which the aluminosilicates are not stable, thus favoring the formation of hydrated sesquioxides.

The time during which the geological materials have been exposed to weathering varies greatly in different islands. The two active volcanoes, Mauna Loa and Kilauea, are actively depositing fresh lavas on the earth's surface. The island of Hawaii except for its Kohala area, and the island of Maui except for its West Maui area are of recent origin, while Kauai is very old geologically. On Kauai, the surface rocks have decomposed and lost all of their silicate minerals. All stages of weathering, from the earliest stages to the latest, very advanced stages, are represented in various parts of the Hawaiian Islands. It is possible to find weathered materials rich in the following minerals: (a) 2:1 layered aluminosilicates, (b) 1:1 layered aluminosilicates, (c) hydrated free oxides, and (d) dehydrated free oxides. The above minerals represent a progressive desilication of the weathering horizon.

The fundamental weathering processes in the Hawaiian surface horizon are the type which leads to the development of laterite and lateritic soils. In the development of these soils, the hydrated and dehydrated sesquioxides

have accumulated through the decomposition of silicates and through the leaching of bases and soluble silica. The time sequence of weathering is influenced by climate (temperature and rainfall). The sequence of mineral formation due to progressive weathering is as follows:

1. **Arid conditions** (at least 10 very dry months per year):
primary minerals \rightsquigarrow 2:1 layered silicates \rightsquigarrow kaolin
2. **Semiarid conditions** (same as above).
3. **Pronounced wet and dry seasons** (at least 8 dry months):
primary minerals \rightsquigarrow kaolin \rightsquigarrow hydrated sesquioxides
4. **Approximately even dry and wet seasons:**
primary minerals \rightsquigarrow kaolin \rightsquigarrow ferruginous oxides and kaolin
 \rightsquigarrow ferruginous oxides \rightsquigarrow titaniferous-ferruginous oxides
 \rightsquigarrow titanium oxide and kaolin \rightsquigarrow kaolin
5. **Sufficient rainfall to keep surface moist at all times:**
primary minerals \rightsquigarrow kaolin \rightsquigarrow goethite and gibbsite
6. **Very wet (over 8 inches rainfall per month):**
primary minerals \rightsquigarrow {allophane \rightsquigarrow {gibbsite \rightsquigarrow bauxite
goethite
gibbsite

Under conditions 3 to 6, the oxides which are accumulating in the weathering horizon are iron oxide, aluminum oxide, and titanium oxide. Theoretically, it is possible, under certain tropical weathering conditions, that the end product of weathering could be dominantly any one of these oxides. However, in nature we obtain various combinations of these oxides. Usually, titanium oxide is the least likely to accumulate, because of a much lower level of this constituent in the general run of parent rocks. The triangle of percentage of the three oxides can be used to show the various types of combination which can occur (see figure 1). It is possible to group the products of tropical weathering as follows:

1. Ferruginous laterites
2. Aluminous-ferruginous laterite
3. Ferruginous bauxite
4. Bauxite
5. Titaniferous-ferruginous laterite
6. Titaniferous bauxite
7. Ferruginous-titaniferous laterite
8. Aluminous-titaniferous laterite
9. Titaniferous laterite

Specimens representing each of these types, except numbers 7, 8, and 9, have been found in the world. It is likely that numbers 7 and 8 will be found, but a titaniferous laterite would be very rare, indeed. The composition of different types of laterites is given in table 1. The nature of the end product of weathering will be determined, primarily, by climate; secondarily, by the composition of the weathering matrix and the time of exposure. In the Hawaiian Islands, the evidence obtained from the mineral composition of the weathered products supports the above hypothesis. Thus, weathered products containing aluminum iron and titanium oxides can be found in the Hawaiian Islands.

TABLE 1. THE CHEMICAL COMPOSITION OF VARIOUS HIGHLY-WEATHERED SOILS OCCURRING IN THE TROPICAL REGIONS.

COUNTRY	WORKER	DESCRIPTION OF FORMATION	OXIDES IN PER CENT		
			Al ₂ O ₃	Fe ₂ O ₃	TiO ₂
Portugal	Abreu (1)	Bauxite	60.0	2.5	trace
Haiti	Goldich and Bergquist (6)	Ferruginous bauxite	46.8	21.9	2.8
Portugal	Gumaraes (7)	Bauxite	36.8-42.3	1.7-9.7	0.5-2.2
India	Krishnan (16)	Ferruginous bauxite	55	25	—
New South Wales, Australia	Hanlon (8)	Ferruginous bauxite	39.5	30.5	4.0
Brazil	Setzer (18)	Laterite soils	17.5-21.0	22.5-27.0	5.5-10.0
India	Chhibber and Misra (3)	Bauxite and titaniferous bauxite	49.7-67.0	2.5-8.7	5.9-17.2
India	Harassowitz (9)	Ferruginous laterite	14.2	68.7	—
Cuba	Bennett and Allison (2)	Ferruginous laterite	12.4	71.1	0.8
Hawaii	Sherman (20)	Titaniferous-ferruginous laterite	12.0	48.6	20.0
Hawaii	Sherman (20)	Titaniferous-ferruginous laterite	8.1	53.5	25.2
Hawaii	Sherman (19)	Ferruginous laterite	7.0	78.5	7.0
Hawaii	Sherman (19)	Aluminous clay	48.5	9.8	4.5
Hawaii	Sherman (20)	Titaniferous-ferruginous laterite	5.8	60.8	26.0
Hawaii	Sherman (20)	Titaniferous-ferruginous laterite	3.6	60.4	24.0
Hawaii	Sherman (21)	Titaniferous-kaolin	25.8	9.9	24.4
Siam	Sherman (20)	Ferruginous laterite	30.0	46.2	1.8
Siam	Sherman (20)	Ferruginous laterite	24.8	51.2	2.4
Palau Island	Sherman (unpublished data)	Ferruginous bauxite	47.7	20.0	0.6

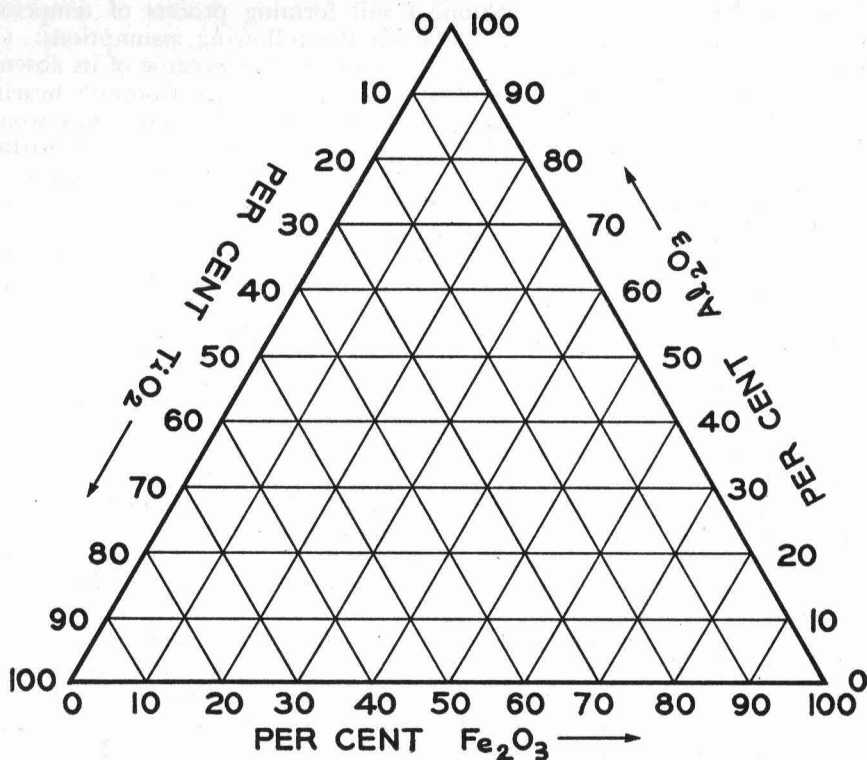


FIG. 1. Possible combinations of oxides in the end product of tropical weathering.

TITANIUM DEPOSITS

Hawaiian soils rich in titanium oxide were first described by McGeorge (17) in 1917. He reported soil analyses which showed a high titanium content. In his report, he pointed out that the average titanium oxide content of Hawaiian soils was found to be 5 per cent. He further pointed out that he had found soils containing more than 30 per cent. Kelley *et al.* (15) described two peculiar soils: one rich in manganese and the other rich in titanium.

In the middle 1930's, the U. S. Department of Agriculture made a soil survey of the Hawaiian Islands. The entry of this organization into the islands led to an interest in the chemical composition of the island soils. Hough and Byers (10) made a very complete study of the chemical and physical properties of seven Hawaiian soil profiles. Some of these profiles were soils having a very high titanium content. They reported that if the titanium-rich soils were dispersed, black minerals of a high specific gravity would settle out rapidly. These black minerals were identified by them as ilmenite and the magnetic iron oxide, magnetite.

In 1941, Hough *et al.* (11) published another comprehensive report on the chemical composition of Hawaiian soils. They proposed a hypothesis that the soil weathering occurring in Hawaiian soils was the same as that

which occurred with podzolization, a soil forming process of temperate regions. Their hypothesis was based on the following assumptions: (1) Quartz could not accumulate in the Hawaiian Islands because of its absence in the parent rock, and (2) ilmenite was the primary titanium bearing mineral which was considered to be resistant to weathering and, thus, would accumulate. They considered the titanium oxide enrichment in the surface horizon analogous to the origin of quartz in the A₂ horizon of a podzol. Hough's work pointed out that the high titanium oxide soils were the product of advanced stages of weathering.

In 1947, Cline *et al.* (4) made a tentative classification of Hawaiian soils. He grouped the Hawaiian soils into groups which tended to reflect the dominant mineral composition of the soil. In his classification, the soils having a high titanium content were grouped together in the Humic Ferruginous Latosol group. The soils belonging to the Mahana, Naiwa, and Haiku families of this group have a very high titanium oxide content.

As a result of Cline's classification of Hawaiian soils, research was initiated to determine the genesis of these titanium-rich soils. In 1948, Sherman *et al.* (22) reported the general chemical and physical properties of the soils belonging to the Humic Ferruginous Latosol group. Fujimoto *et al.* (5) in the same year reported a detailed study of the chemical composition of the soil separates of a titaniferous-ferruginous laterite crust profile. Sherman (19), in 1949, reported the relative influence of soil forming factors involved in the formation of Hawaiian soils. In this study, the influence of age or time of exposure to soil forming factors was emphasized, and with its interaction with climate. Under a climate which has alternately wet and dry conditions, iron and titanium oxides have accumulated. As rainfall increased in such a situation, the accumulation of these oxides increased. However, this increased accumulation of iron oxides depended on the maintenance of good oxidative conditions in the soil. Under a continuously wet condition, aluminum oxide became the dominant oxide of the soil. The most important factors in the development of the deposits rich in titanium and iron oxides were the length of time of exposure to weathering processes and the intensity of climatic conditions in accelerating weathering processes.

In 1950, Sherman (20) described the genesis of the ferruginous laterite crust. In reality, the laterite crusts described were high in both iron and titanium oxides. The enrichment of these crusts with these oxides has resulted from oxide deposition by oxidation and dehydration after ascending to the surface in the capillary waters. The importance of the role of dehydration in the formation of these crusts has been recently shown (24). As long as the soil has a protective vegetative cover there is little evidence of an accumulation of titanium and iron oxide in the surface horizon. The exposure of the soil to the sun causes *rapid* dehydration and formation of a crust. Concretions of iron oxide are also formed near the surface of the soil (23).

The studies of the distribution of titanium oxide in Hawaiian soils and surface formation reveal that there are two distinct types of titanium-rich deposits (21). The most common type, which is represented by titaniferous-ferruginous laterite soils, has been described in a number of publications (19, 20, 21, 22, 24). This type is contained in the relatively shallow, surface

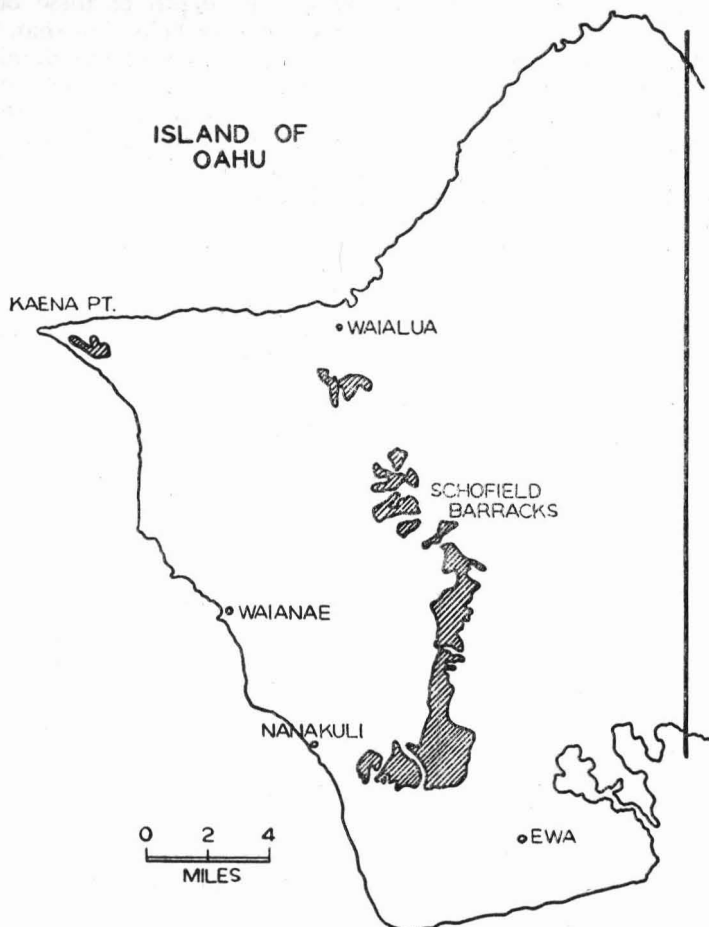


FIG. 2. Distribution of titanium deposits on Oahu.

formation which ranges from 1 foot to 6 feet. Near the surface, it is much richer in titanium oxide. The titanium oxide content of these soils ranges from 8 to 35 per cent. The second type occurs in locations where internal drainage is sufficiently sluggish for poor aeration to develop. The poor aeration causes the differential reduction of the iron oxide and its removal to an area where conditions for its oxidation are more favorable. In these locations the following sequence of mineral formation in the weathered surface horizons will occur: gibbsite \rightarrow titanium oxide-kaolin \rightarrow concretions of iron oxide containing appreciable titanium oxide \rightarrow iron oxides \rightarrow iron oxide-kaolin \rightarrow kaolin.

This sequence suggests that the titanium oxide-kaolin material has formed by the degradation of former titaniferous-ferruginous laterite crust due to its position in the sequence. This type of titaniferous clay deposits

often occurs as continuous, deep deposits. The depth of these deposits ranges from 1 to 15 feet, with the average occurrence being less than 2 feet. The distribution of the soils rich in titanium oxide and the titaniferous clays is shown in the following map of the islands (figure 2). It is difficult to give a reasonable, accurate estimate of the tonnage of soil containing titanium oxide in each of these classes, because of the irregularity of the occurrence of the titaniferous-ferruginous laterite. The composition of Hawaiian soils having a high titanium oxide content is given in table 2.

TABLE 2. THE TYPICAL CHEMICAL COMPOSITION OF TITANIUM OXIDE DEPOSITS IN THE HAWAIIAN ISLANDS.

LOCATION OF DEPOSIT	OXIDE CONTENT IN PER CENT			
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂
Waimea Canyon, Kauai	3.3	8.1	58.0	21.0
Waihee Point, Maui	18.1	9.6	48.7	10.7
Haiku, Maui	14.0	13.2	48.1	18.9
Waimea Canyon, Kauai	12.5	7.8	58.0	14.4
Waimea Canyon, Kauai	3.8	9.9	47.5	25.0
Kilauea, Kauai	3.6	19.7	45.0	8.5
Anahola, Kauai	28.5	25.8	9.9	24.4
Anahola, Kauai	25.5	21.8	19.9	20.0
Lanai City, Lanai	12.1	16.2	45.0	10.8
Near Meyers Lake, Molokai	13.8	7.2	56.6	15.2
Hawi, Hawaii	14.2	16.2	46.8	19.5
Waikolu, Molokai	25.0	11.8	27.4	8.4
Waimea Canyon, Kauai	3.9	5.8	60.8	26.0
Lower Forest Reserve, Molokai	7.8	3.6	60.4	24.0
Waimea Canyon, Kauai	7.4	12.8	60.2	16.4
Koolau Mountains, Oahu	39.0	29.6	9.9	17.6
Koloa Junction, Kauai	28.0	22.8	9.4	12.6
Lower Waimea Canyon, Kauai	1.8	2.8	58.8	34.9

DESCRIPTION OF TITANIFEROUS DEPOSITS

Titaniferous-ferruginous laterite. This type is always found on slopes where the existing climate has definite, alternating wet and dry seasons. Such a climate is conducive to rapid chemical weathering under conditions favoring the alternating reduction and oxidation conditions. In general, these areas occur just below the wet, tropical forest where weathering conditions favor the solution of iron and titanium through their reduction. Certain conditions are apparently necessary before titanium oxide can accumulate in these deposits, and they are as follows:

1. Conditions favoring intense chemical weathering under both reducing and oxidizing conditions. (Under such conditions titanium is released from its normally weathering-resistant minerals and will become soluble in the acid, and probably very reducing, environment.)
2. Conditions favoring the movement of titanium in the percolating water to an area of accumulation. (This hypothesis would have the dissolved titanium moving in the near-surface percolating waters which would carry the titanium to a dryer and more oxidizing environment, where it would be deposited.)

3. Number 2, above, requires the movement of titanium in percolating waters near the surface; and, in order to have this condition, it is necessary to have an impervious layer near the surface. (This impervious layer may be unweathered parent rock, but more commonly it is the point of contact with the subsoil plastic kaolin clay. The impervious layer at the top of the kaolin clay is developed by the deposition of iron oxide, often as a hard concretionary layer.)
4. A definite dry period is essential to cause the ascending movement of titanium toward the surface, where it is precipitated and dehydrated to the oxide called anatase.

The composition of the titaniferous-ferruginous laterite is determined by the vegetative cover, topography, and age. Vegetative cover is the protective cover of these areas against dehydration of the hydrated oxides. When the protective cover of vegetation is removed, the hydrated oxides are dehydrated. Prior to dehydration, the titanium oxide content is uniform in deposit above the impervious subsoil layer. After dehydration, there is an accumulation of titanium oxide at the surface, usually the upper 2 feet of the deposit. Topography influences the nature and composition of these deposits. They always occur on slopes. The greatest development of titanium oxide deposits occurs on benches or small plateaus of the slope. The deposit is likely to be a foot deep on a steep slope and as much as 10 feet deep on the more level benches. On gentle slopes, the deposit will average close to 4 feet in thickness. The influence of age is reflected in high contents of iron and titanium oxide and in the almost complete desilication of the deposit. Appreciable kaolin is found in the youthful deposits of this type.

There are other physical characteristics to be associated with these deposits. A dehydrated titaniferous-ferruginous laterite crust will have a bulk density in excess of 2.2. The bulk density of the surfaces of most of these deposits is higher than that found in the average soil. The bulk density of the deposits decreases with depth, because of the hydration of the minerals. The crusts are very hard and have a typical purple color.

Titaniferous clays. Wentworth *et al.* (26) described a Hawaiian pottery clay which had a high content of titanium oxide. These clays were found at high and inaccessible elevations of the Koolau Mountain Range on the island of Oahu. In 1947 and 1952 the author found sizeable areas of these titaniferous clays in the Waipuhi and Knudtson Gap areas of Kauai. These deposits are relatively low in iron oxide, being less than 10 per cent, with many less than 5 per cent.

The titaniferous clays are divided tentatively into two types. The difference lies in the nature of the formation of the deposits. The titaniferous clays from the Koolau mountains of Oahu and the Waipuhi area of Kauai can be described as a halloysite clay containing the mineral anatase. The deposit found in the Knudtson Gap on Kauai can be described as clay in which the dominant mineral is illite containing some halloysite and anatase. The former will have a titanium oxide content ranging from 10 to 25 per cent, and the latter will range from 6 to 12 per cent.

Sherman (21) described the anatase-halloysite clay as being formed by the probable degradation of a former titaniferous-ferruginous laterite crust. The degradation processes result from the poor internal aeration and drain-

age associated to the formation of the peneplain-like condition developed in a land area in the advanced stages of weathering. There is evidence that these deposits can be developed by differential deposition of iron and titanium oxides. The titaniferous-illite clays are developed in deeper sub-soil conditions, usually by seepage waters or, probably, perched water tables in or near to other titaniferous deposits. The exact explanation of the occurrence of these deposits has not yet been ascertained. The anatase-halloysite clays are nonplastic, while anatase-illite clays are weakly plastic.

MINERAL COMPOSITION AND USE

The mineral composition has been determined by utilizing the data obtained from chemical analysis, differential thermal analysis, dehydration curves, X-ray diffraction analysis, and the use of the electron microscope in making the mineral identification and allocations. Representative mineral composition of profiles is given in tables 3, 4, and 5.

TABLE 3. THE MINERAL COMPOSITION OF TYPICAL TITANIFEROUS-FERRUGINOUS LATERITE CRUST PROFILE.

DEPTH IN FEET	MINERAL COMPOSITION IN PER CENT						
	Quartz	Kaolin	Gibbsite	Hematite	Goethite	Anatase*	Accessory minerals
0-3	5	5	—	50	10	20	ilmenite <2.0 chromite >1.0 maghemite
3-18 CRUST	3	0	0	55	—	30	maghemite 2-5 chromite >1.0 ilmenite <2.0
18-30	2	0	10	30	30	10	ilmenite chromite
30-36	5	5	20	20	45	5	chromite
36†	5	60	15	15†	—	—	—

*The identification of anatase is tentative. Mineralogists have made conflicting identification of samples from laterite crusts. Several mineralogists insist on the ilmenite identification, while others feel that TiO_2 exists as the independent oxide, anatase, based on a 4.3 \AA line on X-ray diffraction patterns.

† Magnetite.

The potential possibility of mining Hawaiian titanium ores will have to wait for the development of techniques for their processing. The amount of titanium oxide in these ores is sufficient to justify their development as a source of titanium. The demand for titanium ores will increase as the unrestricted development of titanium metals continues. At present the cost of processing the ore into the metal is extremely high, thus preventing the fullest development of a titanium metal industry. The development of new and cheaper methods of the manufacture of titanium metals would greatly increase its production. The decrease in the price of titanium metal would increase the uses to which this metal could be applied.

In order that the Hawaiian Islands may develop their titanium resources, it will be necessary to develop special ore dressing methods for ore handling.

TABLE 4. MINERAL ALLOCATION OF TITANIFEROUS-FERRUGINOUS HORIZON ACCORDING TO SIZE OF PARTICLES.

SIZE OF PARTICLE IN MICRONS	MINERAL CONTENT IN PER CENT										
	Quartz	Illite	Hydrous mica intermediate	Montmoril- lonite	Kaolinite	Gibbsite	Magnetite	Goethite	Hematite	Anatase	Amorph. silicate
50-20	5	0	0	0	0	4	0	0	74	17	0
20-5	22	0	0	0	0	8	0	0	60	10	0
5-2	20	0	0	0	0	15	0	0	52	9	4
2-0.2	12	0	5	0	10	10	0	10	35	6	12
0.2 and less	0	0	20	0	20	10	0	8	15	3	24

TABLE 5. THE MINERAL COMPOSITION OF A TITANIFEROUS CLAY DEPOSIT
FROM THE KNUDTSON GAP, KAUAI (TENTATIVE).

Dominant mineral	illite
Major minerals	halloysite, anatase
Minor minerals	goethite, magnetite, chromite, gibbsite

A million dollar plant today will produce a ton of titanium metal per day or 300 tons per year. It will require approximately 8 tons of Hawaiian titanium oxide ore to produce a ton of titanium metal, or 2,400 tons of ore for the plant per year. Approximately three-quarters of an acre of a titaniferous-ferruginous laterite crust to a depth of 3 feet would supply this smelting plant with its ore requirement for a year, provided that dressing methods are developed whereby the titanium oxide can be separated from the Hawaiian ores.

The greatest problem will be the complete separation of the titanium oxide from the iron oxide of these ores. The fine texture of Hawaiian ores will present a problem in their use. It means that research work, probably supported entirely by local funds, must be undertaken to solve the problem of titanium oxide separation from these ores. The titaniferous clay deposits at present offer the best possibilities for industrial development. This is because the iron oxide content of these clays is low. Thus, in these clay deposits the problem of separating per unit of titanium oxide would be less, and preliminary evidence indicates that this separation in the titaniferous clays is feasible.

The titanium oxide deposits of the Hawaiian Islands have their advantages and their disadvantages for industrial development. Some advantages are as follows:

1. The TiO_2 content of the deposits is high, ranging from 6 to 35 per cent.
2. The Hawaiian titanium deposits occur as a shallow surface deposit over a large acreage, as shown in the accompanying maps of the islands (see figures 2-7). The occurrence of these deposits at or near the surface will permit strip mining. The tonnage of ore is very large.
3. The further confirmation of the tentative identification of the titanium oxide mineral, anatase, as the dominant mineral in the titaniferous-ferruginous laterite will enhance the value of these deposits. Anatase has been positively identified as the titanium mineral in the titaniferous clays; and, tentatively, in the titaniferous-ferruginous laterite.
4. The Hawaiian deposits would be available to the West Coast states where cheap water power exists and where many airplane manufacturers are located. Hawaiian titanium ores would compete with foreign ores from India and Australia for this titanium market.
5. The western part of the United States does not have a titanium pigment plant. The fast growing population on the West Coast will soon require a pigment plant. This will enhance the value of the Hawaiian ores.
6. On the island of Kauai there is ample supply of water for concentrating the ores.

7. Much of the titanium oxide ores occur on territorial lands, and in most of the privately owned lands the mineral rights have been reserved by the Territory. The Territory can exercise control over the mining operations and would be justified in spending public moneys for their development.

Some disadvantages in the industrial development of the Hawaiian titanium oxide ores are as follows:

1. The surface deposits are very shallow; thus, the damage from mining operations would be very great and might not meet with public approval. However, a mining permit law could be enacted which would require revegetation of the exposed subsoil, which in most cases is a kaolin clay. The scattered locations would not justify the installation of expensive and efficient ore dressing equipment.
2. The deposits of the titaniferous-ferruginous laterite occur on slopes which will require special types of equipment in order to develop these deposits. The equipment would need to be very mobile.
3. The fine texture of the material will require the development of special ore dressing methods for these deposits. Preliminary work indicates that the successful development of ore dressing methods will not require great expenditures of research funds.
4. The intimate mixture of iron oxides and anatase will require the development of special ore dressing methods for their separation. If titanium exists in the mineral ilmenite, essentially the same problem will exist. The cost of separation and concentration may prove to be too expensive to permit the economical development of these deposits.
5. The potential high damages to crop lands would make operations too expensive.

IRON ORE DEPOSITS

The preceding section on titanium oxide deposits has indicated and described deposits which can also be classified as acceptable iron ores. They would be classified as titaniferous iron ores. The distribution of these ores is too shallow to be considered an adequate source of iron oxide, but they still are large enough to be considered as a source of titanium.

The chemical composition and the mineral composition of these ores have been given in the preceding section on titanium deposits. The highest iron oxide occurs in the subsoil (friable) layer of the Humic Ferruginous Latosols, where it may be as high as 80 per cent Fe_2O_3 . The iron oxide minerals which are found in greatest amount are hematite and goethite. On Kauai, there are large and deep deposits of friable iron oxide ores which probably have a titanium oxide content of 5 per cent or less. The dominant iron oxide in these ores is goethite. Some kaolin will be found mixed into some of these deposits.

MANGANIFEROUS SOILS

Many of the Hawaiian soils have a very high manganese oxide content for soils. Kelley (13) was first to point out the high content of manganese in Hawaiian soils: as high as 9.7 per cent. This, however, is still too low for commercial development.

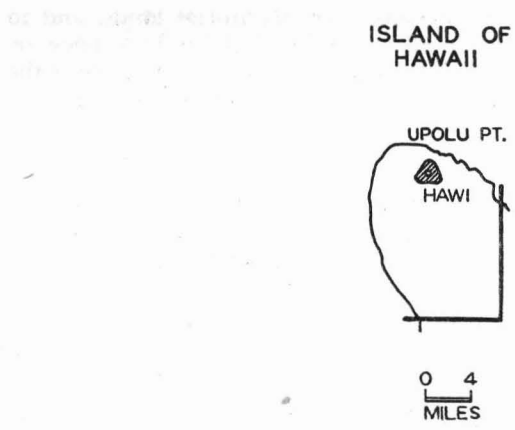


FIG. 3. Location of titanium deposit on Hawaii.



FIG. 4. Distribution of titanium deposits on Molokai.

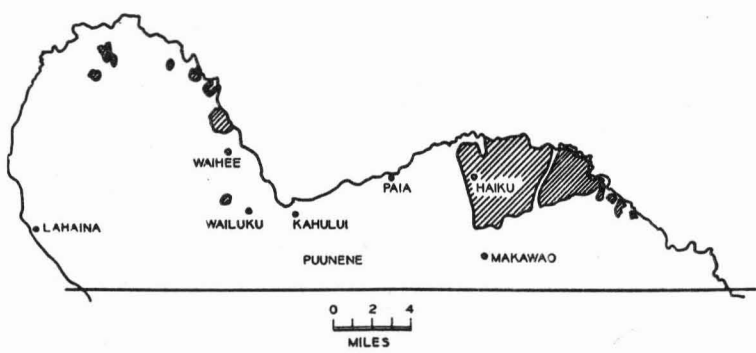


FIG. 5. Distribution of titanium deposits on Maui.

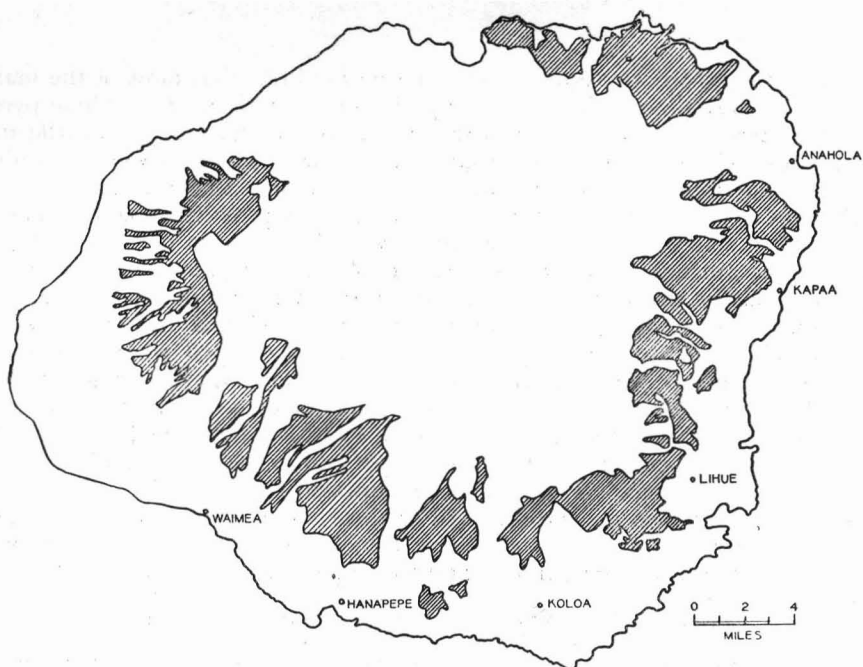


FIG. 6. Distribution of titanium deposits on Kauai.



FIG. 7. Distribution of titanium deposits on Lanai.

For general information it should be pointed out that most of the manganese in Hawaiian soils occurs as pyrolusite concretions (25). These pyrolusite concretions have developed in certain soils as a product of weathering processes. The concretions are found in soils which have developed under climate having an alternating wet and dry season. The rainfall must be sufficient to cause rapid leaching of bases and thus provide conditions favorable for the development of kaolin clays. The alternating wet and dry conditions are necessary for the solution of the manganous ion, in which form it may be precipitated, on oxidation and dehydration, to form a concretion. The manganiferous concretions are developed in several ways. They are as follows: (1) Spherical types are developed where the manganese dioxide is precipitated around a small nuclei; (2) irregular and angular shapes occur where precipitation has taken place in soil pores or small openings in the soil; (3) aggregate types are developed where manganese dioxide is precipitated on the surface and in the pores of a soil aggregate; and (4) manganese dioxide is precipitated on the surface of roots to form tubular-shaped concretions. All of these concretions have a high content of manganese, but they also have a high content of sesquioxides and silica. Table 6 gives the MnO_2 content of typical concretions.

TABLE 6. THE AVERAGE CHEMICAL COMPOSITION OF DIFFERENT TYPES OF PYROLUSITE CONCRETIONS.

TYPE OF MANGANIFEROUS CONCRETION	AVERAGE CHEMICAL ANALYSIS				RANGE OF MnO_2 CONTENT
	SiO_2	Al_2O_3	Fe_2O_3	MnO_2	
Spherical	16.7	32.7	8.5	33.1	29.4-39.8
Tubular	13.6	28.6	14.7	27.0	23.1-31.4
Irregular	15.6	26.0	9.6	31.6	25.1-44.2

The MnO_2 content ranges from 23.1 to 44.2 per cent. Deposits which approach ore possibilities are found in small areas only. These are so small that they have no commercial possibilities at this time. However, these locations can be considered to be low-grade manganese deposits.

OTHER MINERAL POSSIBILITIES

There may be other mineral possibilities in Hawaii, some of which may be unknown to us today. Of those known but today insignificant in value, some may become valuable in future economic changes or other increased need for such mineral element. Appreciable amounts of nickel, chromium, vanadium, zirconium, and cobalt have been found, but none have been found in quantities approaching commercial possibilities under present day standards. Most of the soils of the islands contain about 0.1 per cent of columbium, a very scarce chemical element. The columbium content is too low to be considered a source unless it can be concentrated during the processing of another mineral.

INDUSTRIAL CLAYS

The parent rock of the Hawaiian Islands was formed from lavas having very little, if any, quartz. Under a warm tropical environment, the surface

rocks weathered rapidly to form clays. A variety of clays were formed, largely because of different weathering environments in different places. Since the annual rainfall in Hawaii ranges from 5 to 500 inches per year, a wide range of weathering environment can be found, even though temperatures of the islands are relatively uniform. Thus, the characteristics of the climate, drainage, vegetation, and age or time of exposure play the dominant roles in clay formation in these islands. As the influence of the intensity factors is increased, a progressive desilication of minerals occurs as long as drainage conditions are not impeded. The various advanced stages of mineral weathering can thus be found in the Hawaiian Islands, as proposed by Jackson *et al.* (12) as sequence of weathering of the clay-sized minerals. The stages of their sequence of weathering are: stage 7, illite; stage 8, 2:1 intermediate; stage 9, montmorin; stage 10, kaolin; stage 11, gibbsite; stage 12, hematite; and stage 13, anatase.

The clays developed in the islands are generally not pure clays. They usually are a mixture of two or more types of clay minerals. Aside from a small, clay-pot industry, practically no effort has been made to develop the local clays for industrial uses. Given in table 7 are the types of clays in the Hawaiian Islands.

In table 8 are given the typical chemical and mineral composition of typical Hawaiian clays. In general, as weathering continues, the complexity of the minerals occurring in these clays increases. The few tests of Hawaiian clays made for ceramic purposes indicate that their greatest handicap to their use is shrinkage. It is difficult to build up the body of these clays because of the hydration of these clays.

DESCRIPTION OF CLAYS

Montmorin type. The clays of this group are believed to be montmorillonite or beidellite. The former is found in the Dark Magnesium clays and the latter in the black soils of the "Red and Black" complex. These clays are sticky plastic clays when wet and become hard and cloddy when drying. The soils having these clays crack during dry periods. The montmorin minerals making up the clay fraction of these soils usually run from 40 to 50 per cent of the soil. These clays have a high cation exchange capacity, ranging from 80 to 130 milliequivalents per 100 grams of clay or 50 to 75 milliequivalents per 100 grams of soil. Investigations have shown that the internal surface area of these clays is comparable to bentonite.

Kaolin. All kaolin clays found so far in the Hawaiian Islands have a high iron oxide content. In spite of this impurity, the kaolin content of many soils is as high as 85 per cent. The type of kaolin minerals has not been well established, but the data to date indicate kaolinite and halloysite. The kaolin clays have a low cation exchange capacity. The high iron oxide content limits the use of these clays. A pure white kaolin clay has been found in a fairly large deposit on Hanalei Heights, Kauai.

Goethite clays. The goethite clays are found as the friable subsoils of the soils belonging to the Humic Ferruginous group and as deep, smooth, red ferruginous clays found in deep deposits. The latter was probably used as the coloring material in the Hawaiian salt and was also used by Hawaiians for various therapeutic purposes in correcting their various ailments.

TABLE 7. THE TYPES OF CLAYS FOUND IN THE HAWAIIAN ISLANDS.

CLIMATIC ENVIRONMENT	TYPE OF CLAY MINERALS	CHARACTERISTICS
Semi-arid: Annual rainfall 10 to 25 inches	Montmorin	Plastic sticky clays amounting to from 40 to 50 per cent of soil. High adsorption.
Alternating wet and dry season with strong dry season: Annual rainfall 25 to 75 inches	Kaolin	Granular non-plastic clay containing iron oxides.
Alternating wet and dry season: Annual rainfall 35 to 75 inches	Goethite clays	Subsurface friable ferruginous clays. Floury texture.
Alternating wet and dry season: Annual rainfall 35 to 75 inches	Dehydrated anatase-hematite clays	Massive indurate clays which break down to graphite-like material.
Alternating wet and dry condition with poor internal drainage: Annual rainfall 45 to 90 inches	Anatase-halloysite clays	Purplish-gray, granular clay. Massive but not indurate.
Alternating wet and dry condition with poor drainage: Annual rainfall 35 to 100 inches	Anatase-halloysite-illite clays	Gray massive, non-plastic clay. Impervious in nature.
Continuous wet condition: Annual rainfall 65 to 125 inches	Plastic-goethite-gibbsite-kaolin clay	Plastic, red clay. Very compact, impervious.
Very wet condition: Annual rainfall 120 to 300 inches	Allophane-gibbsite-goethite clay	A greasy, smeary clay having a very low bulk density. Irreversible shrinking on drying.

TABLE 8. CHEMICAL AND APPROXIMATE MINERAL COMPOSITION OF TYPICAL HAWAIIAN CLAYS.*

HAWAIIAN CLAYS:	MONTMORILLONITE	KAOLINITE	ANATASE-HALLOYSITE	ANATASE-HALLOYSITE-ILLITE	GOETHITE	ALLOPHANE-GIBBSITE-GOETHITE	PLASTIC GOETHITE-KAOLINITE-GIBBSITE	DEHYDRATED ANATASE-HEMATITE
Chemical analysis:								
SiO ₂	42.7	35.5	28.5	39.0	5.5	12.9	21.3	3.8
Al ₂ O ₃	15.3	26.1	25.8	27.0	7.6	26.8	23.9	9.9
Fe ₂ O ₃	13.0	19.1	9.9	3.8	78.5	26.7	37.1	47.5
TiO ₂	1.3	2.7	24.4	8.0	7.2	6.4	4.7	25.0
CaO	1.5							
MgO	2.2							
Cation exchange capacity, m.e./100 gm.	80	25	20	45	20	130	45	3
Mineral analysis:								
Quartz	5	0	0	5	3	4	1	1
Illite	5	0	10	50	0	2	1	-
Montmorillonite	75	8	0	-	0	-	10	-
Vermiculite	0	0	0	-	0	0	1	-
Kaolin	12	72	45	25	0	0	19	-
Allophane	0	8	0	-	0	0	0	-
Gibbsite	0	4	0	-	7	23	16	10
Goethite + hematite	0	6	10	3	80	29	39	50
Anatase	0	2	25	8	7	7	4	25

* All analyses, except on montmorillonite, are on whole clay without any separation of the clay fraction.

Anatase-illite-halloysite clays. A gray to grayish-purple clay can be found at the surface or in the subsoil of the soils occurring on old, weathered peninsulas. These clays are developed where seepage waters from higher elevations enter the level plain. These seepage waters apparently carry appreciable amounts of soluble silica and potassium. The entrance of these waters into the poor drainage conditions of the plain causes the resilication of gibbsite. Since illite should not occur in a geologically old area, it is suggested that it has formed by resilication of gibbsite in the presence of potassium. This genesis is considered only as speculative hypothesis.

These clays are of considerable interest because they have excellent ceramic properties. Pots made from them have a very smooth surface. While the shrinkage is greater than desired, cracking during firing does not occur.

Anatase-halloysite clays. These are similar in every respect to the anatase-illite-halloysite clays. Their kaolin fraction is a mixture of kaolinite and halloysite. They have been used for pottery work (26).

Allophane-gibbsite-goethite clays. Clays rich in allophane occur in the tropical rain forest areas of the islands of Hawaii and Maui. These clays are characterized by a very low bulk density of from 0.1 to 0.5. Their mechanical analysis reveals that 70 per cent of the clay fraction consists of particles smaller than 0.2 microns in diameter. These clays are unusual in their properties in that they exhibit little plasticity or body. In their moist condition the cation adsorption capacity of these clays is extremely high, being over 120 milliequivalents per 100 grams. The high adsorption is attributed to allophane. On drying, these clays shrink from one-tenth to one-half their volume. This is an irreversible shrinkage. The properties of the dry clay are entirely different than those of the original clay.

Plastic-goethite-gibbsite-kaolin clay. In the soils of the heavy rainfall of the older islands, geologically, a deep red, plastic clay occurs in the subsoil. This clay is sufficiently plastic to mold easily. It is a dense, uniform clay, which is being used to make flower pots at the present time. It is the most manageable clay for ceramic purposes found in the islands. In poorly drained areas, the iron content of these clays is greatly reduced and the kaolin content is increased. The goethite-kaolin clay with a low gibbsite content was used by the Hawaiians for medicinal purposes.

Dehydrated titaniferous-ferruginous clays. These clays occur as dehydrated laterite crusts. They may be an excellent source of titanium and iron for the metal industry. Otherwise, they are of little value as industrial clays.

RECOVERY OF SALTS FROM OCEAN WATER

The Hawaiians have recovered salt by evaporation of sea water in shallow evaporating beds built near the ocean. The sea water enters the beds at high tide, and it is evaporated to dryness by solar radiation. The crystalline salt which they recover is red or rust colored, due to the addition of clay to the evaporating mixture. The clay which was added is, to our best knowledge, either a colloidal goethite clay or an amorphous goethite-allophane or goethite-kaolin clay. It is likely that both clays contained varying amounts of gibbsite. This Hawaiian salt is still produced and sold on the local markets. It is considered an excellent salt in certain Oriental, pickled foods.

The recovery of salts from ocean water has been accomplished by several processes. A number of these processes require expensive equipment. How-

ever, the successful recovery of certain ocean-water salts has been made by evaporation beds in the San Francisco Bay area. Magnesium is one of the elements which can be recovered. The Hawaiian Islands need magnesium in their fertilizer mixtures and also need it for other industrial purposes. The imported magnesium salts of fertilizer or industrial grades are very expensive. For instance, the dolomite, which a mainland farmer buys to lime his soil or to add magnesium to his soil, will cost him 15 dollars or less a ton. In the Hawaiian Islands, farmers pay more than 50 dollars a ton for the same material. Thus, it is feasible for a small business of recovering magnesium salts from ocean water to develop for the purpose of supplying the local trade requirements.

The island of Maui has a very desirable location for evaporation beds to recover salt from ocean water. This location is at Kihei. Near sea level, the location has easy access to ocean water. It is located in the flat valley where temperatures are very high. It has the highest percentage of cloud-free days, plus days with little cloudiness. The trade winds sweep over the area, because there are no mountains in this valley to divert their course. All of the factors which favor evaporation are thus found in this location. In the recovery of magnesium compounds, an adequate source of calcium is required. The island of Maui also has abundant supplies of calcium in its coral rock and sand deposits. Thus, an efficient salt recovery plant could be built at Kihei, Maui.

DISCUSSION

The object of this paper is to acquaint the public with the information which has been obtained regarding the mineral resources of the Hawaiian Islands. The data presented indicates that the two mineral resources of titanium-rich soils and clay materials should be considered in any research program fostering an expanded industrial development in these islands.

The potential expansion of the titanium metal industry should enhance the possible development of the Hawaiian deposits. The present volume of titanium metal production is very small due to lack of production facilities, and production with the presently used Kroll Process is costly. The U.S. Bureau of Mines developed the Kroll Process in 1946. Much of the success of the development of titanium metal has been due to the persistence of the Bureau of Mines and the enthusiasm of the various branches of our armed services. Only recently has the interest of the metal industry been aroused, and it is now working in close co-operation with the Bureau of Mines to develop titanium metal. In spite of the relatively slow progress which is being made in the development of this metal, the scientists actively engaged in the development of research are optimistic about their final success. This view is reflected in the following statement from an industrial company (27): "Certainly, the production problems are even now being mastered with such rapidity as to suggest that within a few years titanium metal will overrun magnesium in tonnage output. Titanium likely will compete primarily with aluminum, and to a lesser extent with various alloy steels and some of the more complex nonferrous alloys." The success of the titanium metal industry depends upon the development of a cheaper method of production, and there is confidence that the industrial technology of the American industry will solve this problem.

With these considerations in mind, it will be some time before an increase in demand for titanium ore will occur. The predicted production for 1953 will be between 2,200 and 2,500 tons of metal. The present industrial program calls for the production of 22,000 tons. The industrial users are asking for 200,000 tons annual production of this metal. Such expansion will increase the demand accordingly for ore in the future.

The development of industrial uses of Hawaiian clays depends on deposits having a uniform composition. The titaniferous clays do possess the uniformity necessary for them to be a good industrial clay. The shrinkage factor is still the limiting factor in their use for the manufacture of structural products. Very little effort has been made to develop the clays of the Hawaiian Islands, even though similar clays are being used extensively in other parts of the world. This development should be a part of any future industrial development program.

SUMMARY

A description of mineral resources present in Hawaiian soils and a description of their environment have been presented. The data presented in this paper indicate that the following conclusions are justified:

1. The soils of the Hawaiian Islands have a very high titanium oxide content. The titanium oxide content averages 5 per cent. In individual types of soils there has been an accumulation of titanium oxide content to as much as 35 per cent.
2. The soils having from 8 to 35 per cent titanium oxide can be considered as a source of titanium ore for industrial purposes. These rich deposits are of two types. They are, namely, titaniferous-ferruginous laterite, which has an iron oxide content in excess of 40 per cent, and titaniferous clays, which have a low iron oxide content. The possibility of developing ore dressing methods for the separation of titanium oxide appears to be more feasible for the latter than the former. The development of special ore dressing methods for these ores is absolutely necessary before these deposits can be developed.
3. The titanium oxide probably occurs as anatase-leucoxene in the titaniferous clays; and, while anatase has been identified in the titaniferous-ferruginous laterite, it is being questioned. There is a need for additional mineralogical studies in this type of deposits.
4. The ferruginous laterites have a very high iron oxide content, but due to their high titanium oxide content they are not suitable for industrial development.
5. The manganiferous soils of the Hawaiian Islands can only be considered as a source of manganese in cases of dire need in a national emergency. The manganese oxide does occur in concretions from which it is possible to separate it if cost is not a factor.
6. The Hawaiian Islands have a great variety of clays. These clays vary greatly in their properties, depending on their mineral composition. Kaolin, kaolin free oxide mixtures, montmorin, allophane-gibbsite, and free oxide mixture clays occur in deposits in the islands. The shrinkage factor will limit the industrial utilization of these clays.
7. It is possible to recover a variety of salts from ocean water by solar evaporation in Hawaii.

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