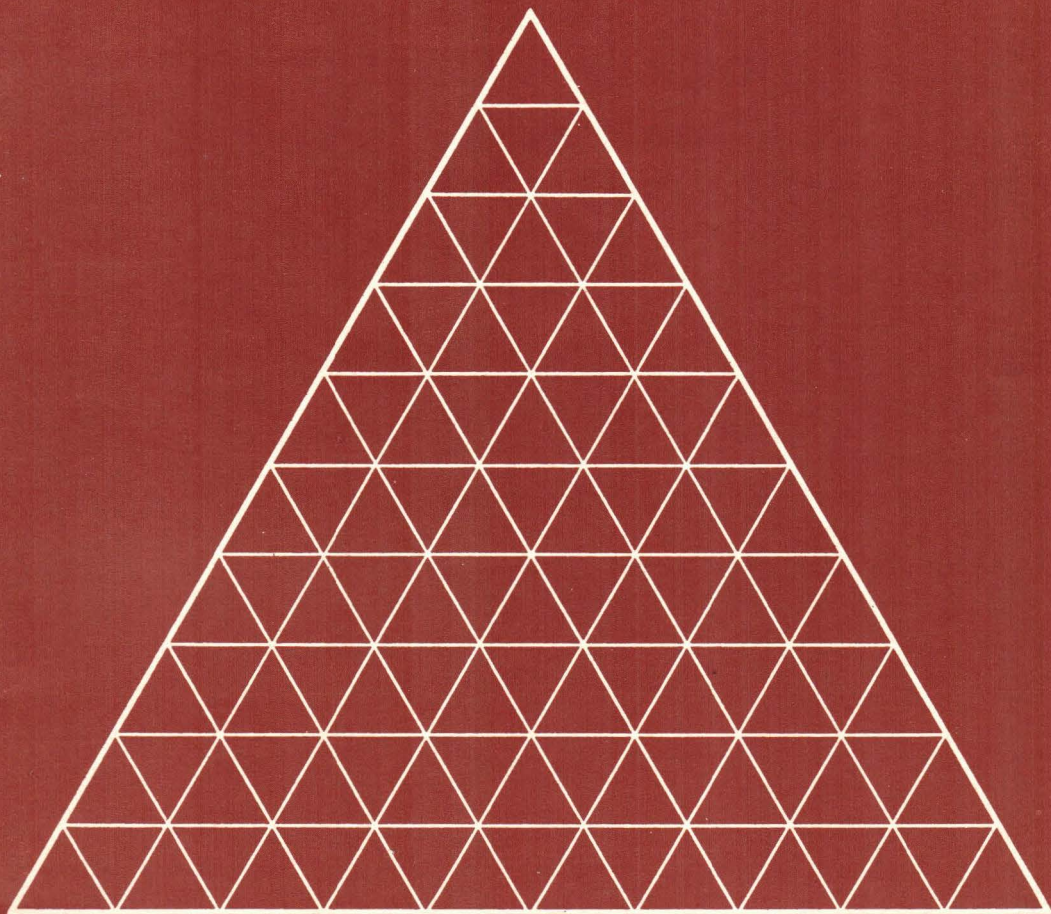
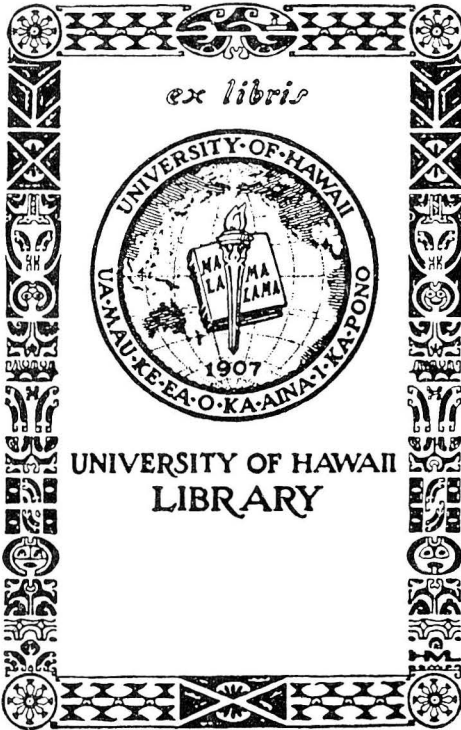


Some of the Mineral Resources of the Hawaiian Islands



G. Donald Sherman, James L. Walker, and Haruyoshi Ikawa

Bulletin No. 138
Hawaii Agricultural Experiment Station
University of Hawaii
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Some of the Mineral Resources of the Hawaiian Islands¹

G. DONALD SHERMAN, JAMES L. WALKER,

and

HARUYOSHI IKAWA

Mineral resources in the Hawaiian Islands were considered to be very limited in 1954 when the first report on this subject was published (27). At that time these resources were confined to titanium-rich soils, coral sand, clay, and volcanic rock materials. There also were suggestions of other possibilities, one of which—bauxite—has since materialized into a potential mineral resource. The discovery of extensive bauxite deposits in the Islands by soil scientists of the Hawaii Agricultural Experiment Station has led to a real interest in the potential of possible Hawaiian mineral resources. The Hawaiian bauxite deposits have been subject to extensive field explorations by aluminum metal-producing firms during 1956 to 1960, and by the U.S. Geological Survey, which exploration has just been completed (22).

The Hawaiian mineral deposits are, with few exceptions, the product of intense chemical weathering and leaching under the warm humid climate of the Islands. Under these environmental conditions iron oxide, bauxite, nickel, manganese, titanium oxides, and others will be concentrated either as residuum or by enrichment due to redeposition of materials solubilized at other sites and subsequently precipitated, or by a combination of the two processes. In Hawaii, the surface enrichment appears to be limited to the oxides of aluminum, iron, and titanium which are the characteristic products of lateritic weathering.

¹This bulletin is a revision of *Some of the Mineral Resources of the Hawaiian Islands*, by G. Donald Sherman, 1954, Hawaii Agricultural Experiment Station, Special Publication No. 1. 28 pp.

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 the changing of consolidated rock to an unconsolidated state without change in chemical composition. Chemical weathering involves a change in the chemical composition of either consolidated or unconsolidated material. Under subtropical conditions which occur in the Hawaiian Islands, chemical decomposition will be the dominant weathering process. Chemical weathering is a cycle 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 a small difference in mean temperature existing between summer and winter. Annual precipitation varies greatly in the Islands, ranging from as little as 5 inches to more than 500 inches per year. The volcanic lavas which built up the Islands consist of basalts, andesites and related rocks, and trachytes. All of these rocks have either no or 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 limited variation in mineral and chemical composition. Weathering is very rapid, due to warm climate the year around and 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 organic matter which is near neutral in reaction with 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, and they produce organic matter which is strongly acid and which has a very low content of bases. The strongly-acid organic matter produces a weathering medium in which the alumino-silicates are not stable, thus favoring the formation of hydrated sesquioxides. The weathering processes are enhanced by the high-infiltration capacity of surface which facilitates leaching.

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, whereas Kauai is very old geologically. On Kauai, the surface rocks have decomposed and have lost all of their silicate minerals. All stages of weathering, from the earliest to the most recent, very advanced stages, are represented in various parts of the Hawaiian Islands. It is possible to find weathered materials rich in the following minerals: (1) 2:1 layered alumino-silicates, (2) 1:1 layered alumino-silicates, (3) hydrated free oxides, and (4) dehydrated

free oxides. The above minerals represent a progressive desilication of the weathering horizon.

The fundamental weathering processes in the Hawaiian surface horizon are of 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 titaniferous and ferruginous
 oxides and kaolin \rightsquigarrow ferruginous oxides, titanium oxide, and
 kaolin \rightsquigarrow kaolin, bauxite, and laterite
5. Sufficient rainfall to keep surface moist at all times:
 primary minerals \rightsquigarrow kaolin \rightsquigarrow goethite, gibbsite, and laterite
6. Very wet (more than 8 inches rainfall per month):
 primary minerals \rightsquigarrow

allophane	\rightsquigarrow	gibbsite	\rightsquigarrow	<table style="border: none;"> <tr> <td style="border-left: 1px solid black; padding-left: 5px;">bauxite</td> </tr> <tr> <td style="border-left: 1px solid black; padding-left: 5px;">goethite</td> </tr> <tr> <td style="border-left: 1px solid black; padding-left: 5px;">hematite</td> </tr> </table>	bauxite	goethite	hematite
bauxite							
goethite							
hematite							
goethite		goethite		laterite			
gibbsite		hematite					
maghemite							

Under conditions 3 to 6, the oxides which are accumulating in the weathering horizon are iron oxide, aluminum oxide, and titanium oxide. It is theoretically possible that under certain tropical weathering conditions the end product of weathering could dominantly be 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 laterite
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

TABLE 1. The chemical composition of various highly-weathered soils occurring in the tropical regions

COUNTRY	WORKER	DESCRIPTION OF FORMATION	OXIDES IN PERCENT		
			Al ₂ O ₃	Fe ₂ O ₃	TiO ₂
Haiti	Goldich and Bergquist (8)	Ferruginous bauxite	46.8	21.9	2.8
Portugal	Gumaraes (9)	Bauxite	36.8-42.3	1.7-9.7	0.5-2.2
India	Krishman (19)	Ferruginous bauxite	55	25	—
New South Wales, Australia	Hanlon (10)	Ferruginous bauxite	39.5	30.5	4.0
Brazil	Setzer (23)	Laterite soils	17.5-21.0	22.5-27.0	5.5-10.0
India	Chhibber and Misra (5)	Bauxite and titaniferous bauxite	49.7-67.0	2.5-8.7	5.9-17.2
India	Harrasowitz (11)	Ferruginous laterite	14.2	68.7	—
Cuba	Bennett and Allison (3)	Ferruginous laterite	12.4	71.1	0.8
Hawaii	Sherman (25)	Titaniferous-ferruginous laterite	12.0	48.6	20.0
Hawaii	Sherman (25)	Titaniferous-ferruginous laterite	8.1	53.5	25.2
Hawaii	Sherman (24)	Ferruginous laterite	7.0	78.5	7.0
Hawaii	Sherman (24)	Aluminous clay	48.5	9.8	4.5
Hawaii	Sherman (25)	Titaniferous-ferruginous laterite	5.8	60.8	26.0
Hawaii	Sherman (25)	Titaniferous-ferruginous laterite	3.6	60.4	24.0
Hawaii	Sherman (26)	Titaniferous kaolin	25.8	9.9	24.4
Siam	Sherman (25)	Ferruginous laterite	30.0	46.2	1.8
Siam	Sherman (25)	Ferruginous laterite	24.8	51.2	2.4
Palau Islands	Sherman (unpublished data)*	Ferruginous bauxite	47.7	20.0	0.6
Hawaii	Sherman (unpublished data)*	Saprolitic bauxite	62.0	1.2	1.1
Hawaii	Walker (35)	Saprolitic bauxite	62.0	5.2	0.9
Hawaii	Walker (35)	Titaniferous-ferruginous laterite	5.8	55.9	26.8

*Sherman, G. Donald. 1960. Hawaii Agricultural Experiment Station, Honolulu.

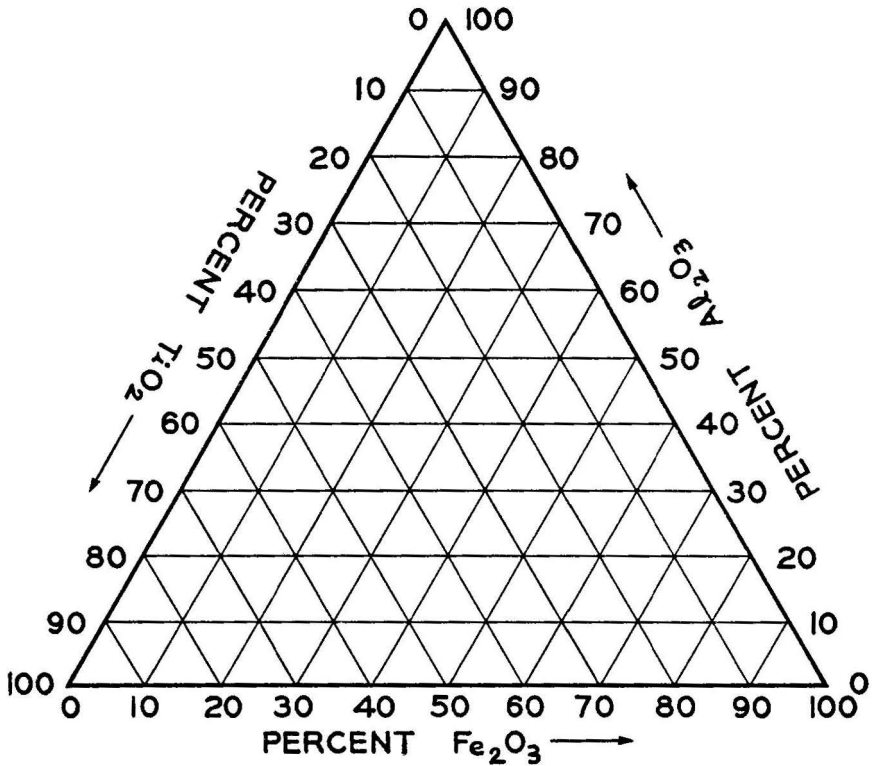


FIGURE 1. Possible combinations of oxides in the end product of tropical weathering.

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 product of weathering will be determined, primarily, by climate and 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.

BAUXITE DEPOSITS

Bauxite-rich soils and near-surface weathered rock were discovered in 1955. The chemical analysis of aggregates from the Princeville Ranch on Kauai and similar aggregates from the Haiku area of Maui showed

almost 60 percent alumina. These findings created an interest in these areas by the aluminum metal companies. In the period between 1956 and 1960, geologists from as many as six major aluminum metal-producing firms had conducted explorations of bauxite-rich areas. While no mining has occurred, many of these firms have an interest in these deposits. However, the mineral rights are clouded by rights of surface owners and former mineral right reservations. Procedures for permit to mine even on State lands need review and clarification before an economic environment favoring development of these deposits can be attained. These deposits, while undeveloped, still remain a potential mineral resource which is an asset to our State and Nation.

The State of Hawaii has supported field studies and research to accomplish the following objectives: (1) to establish an accurate tonnage estimate on each island; (2) to establish the quality of each deposit with respect to its suitability to established aluminum extraction procedures; and (3) to determine methods of beneficiation of the areas which would improve the economic chances of development of the deposit. The Department of Agronomy and Soil Science, the discoverer of the deposits, has never ceased in its efforts to establish the nature and genesis of each deposit, and in addition, also, to evaluate the quality and tonnage of each deposit. It has researched the basic properties of each deposit in order to develop new procedures for the beneficiation of the ores and the subsequent extraction of the alumina from them.

Three important reports have been published. The first report, by Sherman (29), described the geographical distribution of the deposits, their general mineralogical composition, their general quality characteristics, and a crude estimate of tonnage of ore. The second report, by Patterson (22) of the U.S. Geological Survey, was based on a field study of the Kauai deposits in detail. Patterson's tonnage estimates were higher and quality determination lower than those presented in Sherman's report (29).

The third report, by Calhoun and Hill (4) of the U.S. Bureau of Mines, is based on a detailed study of the processing characteristics of the Hawaiian bauxitic deposits. Their report notes that they submitted the ores to certain types of beneficiation procedures and extractions and the results were considered encouraging. The most promising results were obtained from the deposits on Maui.

The Hawaiian bauxite deposits can be separated into four types based on their mineral and weathering characteristics. The four types of deposits are as follows: (1) ferruginous bauxites formed on Koloa flows on the eastern half of Kauai; (2) Maui deposits which are developed from andesitic or mugearite flows having a low iron content and higher silica content; (3) deposits along the Hamakua Coast of the island of Hawaii developed by the rapid weathering of volcanic ash under very heavy rainfall characteristic of tropical rain forest regions; and (4) saprolitic bauxite developed in rock weathering below the soil formation zone under high rainfall. A short description of the characteristics and development potential of each deposit follows.

Ferruginous Bauxites of Kauai

The ferruginous bauxite deposits of Kauai have received most of the exploratory attention of the aluminum firms. Some of the areas of these deposits have been surveyed in great detail by different firms. The low silica content, the accessibility to good roads, and the nearness to seaports capable of handling ocean-ships make these deposits attractive to commercial development even though they are marginal commercial deposits.

The ferruginous bauxite deposits of Kauai have formed under a warm humid tropical climate on the Koloa volcanic flows and pyroclastic materials. These flows are from late post-erosional volcanic eruptions and are ultrabasic rocks—melilite and nepheline basalts and basanite. The drainage and climate have provided an ideal environment for the rapid decomposition of these rocks. The desilication has favored the formation and accumulation of the hydrous amorphous as crystalline forms of free oxides of aluminum, iron, and titanium. The mineral assemblages of the weathering rocks favor the overall accumulation of aluminum and iron oxides—ferruginous bauxite.

The free oxides appear to segregate into zones of accumulation with time of exposure to the weathering processes. While the entire deposit is rich in iron oxides, there is moderate evidence of the accumulation of each oxide in different zones of the weathering geologic formation. The greatest concentration of titanium oxide is found in a very shallow surface layer of 6 inches or less. This titaniferous surface layer is underlain by a layer of nodular iron oxide and ferruginous bauxitic nodules. These nodules are found in the intensely weathered Halii soils. The thickness of this layer ranges from 4 to 12 inches. The main ferruginous bauxite lies below the nodular material. This material occurs as both clastic material and as firm saprolitic material retaining the original rock structure. There is evidence of segregation of the aluminum and iron oxides, as evidenced by the black metallic iron oxide sheets, pans, and aggregates, and, likewise, white to yellowish sheets, nodules, and aggregates of gibbsite. The bauxitic layer is underlain by weathered rock which is rich in kaolin clay. The beginning of the occurrence of appreciable kaolin clay in the weathered rocks can be readily identified by the occurrence of black coatings of manganous oxides having a metallic lustre in the pores and channels between rocks.

The data presented in table 2 are the chemical composition of samples taken from three pits dug on the slopes of Kilohana Crater. These locations are from one of the richer areas of this type of deposit. The data presented in table 3 show the range of variation within the entire area of the deposit. These data are somewhat higher in bauxite concentration than those presented by Patterson (22), which may be due to methods used in preparation and analysis of samples. However, it should be pointed out that this difference does not affect the quality of the evaluation of the ore body.

The commercial exploration of this type of ore deposit awaits the development of a satisfactory beneficiation process. In its present state, the alumina content is on the low side for its economic extraction by the

TABLE 2. The chemical composition of samples from pits on the slopes of Kilohana Crater, island of Kauai (Analysis is average of several samples.)

DEPTH	PIT NO. 1 NORTHERN SLOPE			PIT NO. 2 NORTHWEST SLOPE			PIT NO. 3 SOUTHWEST SLOPE		
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃
	%	%	%	%	%	%	%	%	%
Surface									
N*	1.0	14.2	62.7	1.1	57.0	14.0	0.5	9.2	69.7
C†	4.2	17.6	51.1	1.5	26.4	46.9	3.0	11.8	61.8
1 to 6 Feet									
N	0.9	53.2	15.2	1.1	53.9	16.7	0.8	50.2	20.4
C	1.8	28.9	46.0	2.3	33.8	39.8	0.9	30.6	44.0
6 to 12 Feet									
N	1.0	53.6	16.7	2.7	50.9	20.7			
C	2.5	32.9	40.7	5.4	30.9	42.5			
Below 12 Feet									
N				4.1	54.2	16.4			
C				10.2	31.8	38.1			

*N = Nodule.

†C = Clay.

TABLE 3. The chemical composition of ferruginous bauxites weathered directly from melilite-nepheline basalt from the Wailua Game Refuge, Kauai

SAMPLE	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	H ₂ O (110°C)
	%	%	%	%	%
1	4.0	48.5	26.0	3.1	17.3
2	4.7	47.0	25.1	3.3	17.5
3	5.5	46.3	28.7	3.6	17.9
4	4.4	45.8	28.0	4.1	17.6
5	2.1	41.2	36.1	5.0	16.8
6	1.9	43.1	36.0	5.8	16.7
7	2.0	39.3	37.0	5.5	16.3
8	2.4	39.3	36.5	6.5	16.7
9	2.1	19.2	60.8	5.5	14.1
10	0.0	36.2	38.6	6.0	16.8
11	0.0	44.3	28.7	4.5	19.7
12	0.0	43.7	31.0	5.0	22.2
13	0.4	41.7	32.5	4.1	18.9

caustic soda method. In addition, the high iron oxide content presents a disposal problem for the large quantities of "red mud," the waste product which is a product of the conventional method of extraction. This waste could not be dumped into the ocean without polluting the beaches and ruining them for recreational purposes. The "red mud" could be spread over the lowlands having thin soils and rocky surfaces to make additional crop land. There is no question but that this would be profitable; however, some method of removing sodium from the "red mud" would be essential.

This ore body weighs roughly 1400 tons per acre-foot. Conservatively, it contains 30 percent alumina, which is 420 tons of alumina per acre-foot. If one assumes a 75 percent recovery in the extraction (which is low) the extraction yield would be 315 tons of alumina per acre-foot. If the enriched bauxite zone is 10 feet in thickness, then the commercial yield of alumina will be 3150 tons per acre. These figures are conservatively low and assume no beneficiation before the caustic soda extraction. However, an estimated 5600 tons of "red mud" would have to be disposed of in a manner satisfactory to public welfare. It is the cost of this operation which limits the commercial development of these deposits.

It is essential that beneficiation procedures be developed to economically handle this material. Several methods of beneficiation have been examined by public-supported research at the U.S. Bureau of Mines (4) and the Hawaii Agricultural Experiment Station. The results have been encouraging. The methods which have given promising results are: (1) magnetic separation of iron oxide after air-drying; (2) screening after air-drying; (3) calcining and then extraction; and (4) acid digestion and recovery of oxides of aluminum, iron, and titanium, separately. An example of the possible results is indicated in the magnetic separation where 50 percent reduction of iron oxide is accomplished with 5 to 10 percent loss of alumina. There is a need for basic research in order to fully understand the basic properties and mineralogical transformations which can occur in materials of these deposits.

The reclamation of these areas after mining has been developed by the Hawaii Agricultural Experiment Station. The area can be returned either to crop production or to a vegetative cover in 40 days after mining at a cost of \$175.00 to \$250.00 per acre. Several reports (29, 30, 37) of this work have been published.

Bauxites Formed on Andesitic and Mugearite Flows

Bauxites which have formed on andesitic and mugearite flows have a low iron oxide content and appreciable silica content. They occur on West Maui in the Honolua Formation and on East Maui on the easterly slopes of Haleakala. The best exposures of the deposits occur at Nakalele Point and on both sides of the Haleaku Gulch and towards the ocean from the Hana Road. The alumina content ranges from 37 to 46 percent with areas of enrichment as high as 55 percent. The silica content ranges from 4 to 16 percent. Inasmuch as the material has a low content of iron oxide, the

standard Bayer Process may be used. Without question, these deposits are the most attractive for commercial development except for their locations. The deposits on West Maui lack roads and those on East Maui are held by many small land owners. The senior author's tonnage estimate is 16,000,000 tons of alumina in each area, which is barely sufficient to support a small plant. The estimate on East Maui is based on very fragmentary data as to depth and extent of area. It is entirely possible that our present estimates may be entirely too low, in which case the development possibilities would be much brighter.

The bauxite has developed in a mugearite flow on West Maui. This flow formation was a massive flow of rock having a fine texture. It is sufficiently porous to the entry of water to permit the rapid weathering by chemical processes. The mugearite weathers first to kaolin clay and on further desilication the clay decomposes to gibbsite. The gibbsite occurs as excellent crystalline aggregates and subcrystalline amorphous materials. The quality of the deposit is related to degree of decomposition of the kaolin clay. In much of this deposit, the bauxite is overlain by a windblown soil varying in depth from 1 to 12 feet. This soil has a weak development of bauxite in it.

The bauxitic areas of East Maui present a very complex situation as far as their evaluation. The geological formation consists of alternating dense lava flows with beds of volcanic clinkers between them. The occurrence of bauxite is found in the surface horizon where it exists in a recent volcanic material of andesite. The formation is underlain in most cases by an iron oxide pan or waxy dark red ferruginous clay which is very conspicuous in the profile. The bauxite has developed by two processes; first, by the weathering of the andesitic rock to halloysite and then to gibbsite and, second, by enrichment from the precipitation of colloidal alumina carried down the slope in the gravitational water moving above the iron oxide pan—but here its occurrence is restricted to zones in which water percolated freely. Thus, one often finds islands of unweathered rocks surrounded by weathered materials at different stages of weathering, kaolinitic or gibbsitic. The quality of this ore in areas is excellent. The complex occurrence makes it difficult to evaluate the ore body for commercial purposes.

Based on the best information available, an acre-foot of these deposits will yield 580 tons of alumina based on a 33 percent content and density of 80 pounds per cubic foot. The extraction of alumina will be more efficient in this bauxite and a yield of 500 tons of alumina per acre-foot can be expected. If the deposit contains 7 feet of commercial bauxite, then a yield of 3500 tons of bauxite per acre can be expected.

The data presented in table 4 give the typical chemical composition of bauxites from East and West Maui deposits. The lower iron oxide content is very striking.

The development of an alumina extraction plant is a definite possibility in the future. However, if this development is to materialize, it will be necessary to gain a better estimate of the tonnage on the East Maui area.

TABLE 4. Chemical composition of typical bauxite deposits on the island of Maui (Data from Calhoun and Hill (4).)

LOCATION	DEPTH OF SAMPLING, FEET	CHEMICAL ANALYSIS IN PERCENT				
		SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	
Honokala Gulch	E *	11.8	14.1	34.8	24.4	6.4
Nakalele Point	W †	7.0	13.4	42.6	16.6	4.0
Wailena Gulch	W	5.0	20.5	38.4	16.7	3.4
Opana Point	E	17.0	12.0	33.2	27.2	7.8
Hanehoi Stream	E	9.0	12.4	36.6	22.5	6.7
Hoalua Stream	E	5.0	13.9	36.4	21.9	6.8
Waipio Stream	E	4.3	10.2	35.0	24.7	7.6
Hoolawa Stream	E	7.0	6.9	32.4	31.1	9.0
1.5 Mile West Road 17	E	5.3	9.7	39.6	22.5	4.7
1.5 Mile South Opana Point	E	11.2	7.8	38.0	24.4	5.9
Pauwela	E	10.5	7.1	36.4	25.0	7.2
Kahakuloa	W	5.0	3.5	44.9	21.0	3.2

*East Maui.

†West Maui.

The public does not have this data at this time. An alumina extraction requires large amounts of water, hence the water resources available for this industrial development must be known and be available. Lastly, since the two deposits are divided, adequate roads for transporting the materials must be developed, especially for the West Maui deposits.

Hamakua Coast

The largest area of bauxite is located in the high-rainfall regions of this area, north and west of Hilo. The bauxite has formed in the beds of successive volcanic ash which blankets the surface of this area. The weathering of these volcanic ash deposits under a warm humid climate has produced an amorphous hydrous aluminous oxide clay containing about 28 percent of alumina. The material contains large quantities of water and presents problems which are very unusual as far as the extraction of bauxite is concerned. The typical composition is given in table 5. The material contains appreciable silica and iron oxide. A completely new method of extraction would have to be developed before commercial development could be contemplated.

A method of beneficiation is suggested by an unusual property of these bauxitic materials. Sherman (28) has shown that by air-drying, almost pure aggregates of gibbsite will form. The iron oxide becomes magnetic in air-drying, providing a method of separation. The data in table 6 give the chemical composition of this gibbsite aggregate. The cost of drying and the subsequent separation make this procedure unprofitable.

From the public point of view, these deposits should not be developed as the removal of the bauxite will uncover an unweathered rock surface on which reclamation will be difficult.

TABLE 5. The chemical composition of the amorphous ferruginous bauxitic clays of the Hamakua Coast, of the island of Hawaii

DEPTH, INCHES	SiO ₂ %	Al ₂ O ₃ %	Fe ₂ O ₃ %	L.O.I. %
0-15	10.6	26.8	26.0	32.9
15-38	10.1	34.5	27.3	28.3
38-60	13.6	29.6	29.0	24.2
60-62	7.2	39.9	22.7	27.2
62-65	8.0	33.9	27.7	26.7
65-72	3.4	36.3	27.7	25.4
72-77	9.4	30.4	30.8	24.0
77-83	8.1	32.8	29.5	25.8
83-85	2.4	40.3	26.8	26.6
85-90	10.9	27.5	33.6	23.5
90-93	14.7	33.4	26.5	22.9
93-102	18.6	28.1	28.9	20.3
102-116	19.9	19.8	38.0	14.5

TABLE 6. Chemical composition of the light-colored aggregates of gibbsite formed on dehydration of soils of the Hydrol Humic Latosol group

LOCATION	SiO ₂ %	Al ₂ O ₃ %	Fe ₂ O ₃ %	TiO ₂ %	H ₂ O %
Onomea	0.89	61.88	0.88	2.76	31.88
Kaiwika	0.72	63.03	1.20	3.02	33.09
Hilo Sugar Company	0.62	62.22	2.28	1.28	33.40
Hakalau	0.90	61.60	2.08	4.52	31.52
Pepecko	0.69	62.81	0.88	2.22	32.60
Hilo Forest Reserve	0.58	63.30	0.90	1.22	32.89
Average	0.72	62.46	1.37	2.50	32.55

Saprolitic Bauxite

A recent discovery has been made of bauxite deposits in the saprolitic weathered rocks in the Koolau Mountains of Oahu and in the Kokee area of Kauai. The former deposit is limited to the Kahuku end of the Koolau Range, and the latter, to the westerly end of the Alakai Swamp. The saprolitic bauxites occur usually under a ferruginous surface soil which will indurate and become a laterite crust on exposure. Some of the surfaces may be rich in titanium oxide. The bauxite occurs in the weathered rocks below this surface. These weathered rocks retain their rock structure and give little evidence of the extent of their weathering. The alumina content of these weathered rocks ranges from 55 to 62 percent. Their density is much higher than other ores, being 130 pounds per cubic foot or 2840 tons per acre-foot. A recovery of 2500 tons of alumina can be expected from an acre-foot of this deposit. There is a lack of

information as to the tonnage of this ore body. Present exposures suggest thickness of 3 to 5 feet. This ore is commercial by any standard and, therefore, efforts should be made to have these deposits surveyed for potential tonnage. Commercial firms are interested but, under present laws, the right to explore entails the public acquisition of the results by a subsequent public auction of mining leases. In table 7 are given the available analyses of the saprolitic bauxites.

TABLE 7. The chemical composition of a limited number of saprolitic bauxites on the islands of Kauai and Oahu

LOCATION	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃
	%	%	%
Kokee, Kauai under laterite crust	0.5	57.7	3.4
Waimea Canyon, Kauai	1.2	58.9	1.2
Kahuku No. 1, Oahu	0.8	62.0	2.0
Kahuku No. 2, Oahu	3.8	57.7	2.8

TITANIUM DEPOSITS

Hawaiian soils rich in titanium oxide were first described by McGeorge (20) 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 percent. He further pointed out that he had found some soils contained more than 30 percent. Kelley *et al.* (17) 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 (12) 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 when the titanium-rich soils were dispersed, black minerals of a high specific gravity settled out rapidly. These black minerals were identified by them as ilmenite and the magnetic iron oxide, magnetite.

In 1941, Hough *et al.* (13) 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.* (6) 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.* (31) reported the general chemical and physical properties of the soils belonging to the Humic Ferruginous Latosol group. Fujimoto *et al.* (7) in the same year reported a detailed study of the chemical composition of the soil separates of the titaniferous-ferruginous laterite crust profile. In 1949, Sherman (24) 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 and its interaction with climate was emphasized. 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 (25) 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 capillary waters. The importance of the role of dehydration in the formation of these crusts has recently been shown (33). As long as the soil has a protective vegetative cover there is little evidence of an accumulation of titanium and iron oxides 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 (32). Walker (35) has substantiated these findings in his recent work.

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 (26). The most common type, which is represented by titaniferous-ferruginous laterite soils, has been described in a number of

TABLE 8. The typical chemical composition of titanium oxide deposits in the Hawaiian Islands

LOCATION OF DEPOSIT	OXIDE CONTENT IN PERCENT			
	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

publications (24, 25, 26, 31, 33). This type is contained in the relatively shallow surface 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 5 to 35 percent. 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 \rightsquigarrow titanium oxide-kaolin \rightsquigarrow concretions of iron oxide containing appreciable titanium oxide \rightsquigarrow iron oxides \rightsquigarrow iron oxide-kaolin \rightsquigarrow kaolin. The chemical composition of titanium-rich soil is given in table 8.

Katsura *et al.* (18) and other unpublished work have shown that most of the titanium in soils occurs as titaniferous ferruginous minerals, such as titanomagnetite, titanomaghemite, pseudobrookite, etc. This fact lowers the value of these deposits for commercial development except for special purposes.

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 of minerals under conditions favoring alternating reduction and oxidation processes. In general, these areas occur just below the wet tropical forest. Weathering conditions in these areas

favor the solution of iron and titanium by the reduction of the higher valence compounds to their lower valence state. Certain conditions are apparently necessary before titanium oxide can accumulate in these deposits, and these conditions 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 becomes soluble in the acidic 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 drier and more oxidizing environment, where it would be deposited.)
3. Condition 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 permit the movement of titanium toward the surface, where it is precipitated and dehydrated to the oxide called anatase and as titanomaghemite and other titaniferous-ferruginous minerals.

The characteristics of the titaniferous-ferruginous laterite are determined by the vegetative cover, topography, and intensity of weathering of the soil. Vegetative cover protects these areas against dehydration of the hydrated oxides. When the protective cover of vegetation is removed, the hydrated oxides undergo dehydration. Prior to dehydration, the hydrated titanium oxides are deposited uniformly 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, which always occur on slopes. The greatest development of titanium oxide deposits occurs on benches or small plateaus of a slope. The deposits are likely to be a foot deep on steep slopes and as much as 10 feet deep on the more level benches. On gentle slopes, the deposits will average close to 4 feet in thickness. The influence of weathering intensity is reflected in high contents of iron and titanium oxide minerals and in the almost complete desilication of a deposit. Appreciable kaolin is found in less intensely weathered 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. These soils are frequently underlain by deposits of saprolitic bauxite (35).

Titaniferous Clays

Wentworth *et al.* (18) 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 senior author found sizeable areas of these titaniferous clays in the Waipuhi and Knudsen Gap areas of Kauai. These deposits are relatively low in iron oxide, all contain less than 10 percent and many less than 5 percent Fe_2O_3 .

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 Knudsen 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 percent, and the latter, from 6 to 12 percent.

MINERAL COMPOSITION AND USE

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 9 and 10.

TABLE 9. The mineral composition of a typical titaniferous-ferruginous laterite crust profile

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

*The identification of anatase is tentative. Mineralogists have made conflicting identifications 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 Å line on X-ray diffraction patterns.

†Magnetite.

TABLE 10. Mineral allocation of a titaniferous-ferruginous horizon according to size of particles

SIZE OF PARTICLE IN MICRONS	MINERAL CONTENT IN PERCENT										
	Quartz	Illite	Hydrous mica intermediate	Montmoril- lonite	Kaolinite	Gibbsite	Magnetite	Goethite	Hematite	Anatase	Amorphous silicate
50 to 20	5	0	0	0	0	4	0	0	74	17	0
20 to 5	22	0	0	0	0	8	0	0	60	10	0
5 to 2	20	0	0	0	0	15	0	0	52	9	4
2 to 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

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 advantages and disadvantages for industrial development. Some advantages are as follows:

1. The TiO_2 content of the deposits is high, ranging from 5 to 35 percent.
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 stripmining. 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. Titanium oxides are often associated with bauxite and, in development of beneficiation processes for these ores, titanium may become a valuable by-product.
5. Much of the titanium oxide ores occur on State lands, and in most of the privately owned lands the mineral rights have been reserved by the State. The State 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 has been 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 would necessitate special types of equipment in order to develop these deposits. The equipment would need to be very mobile.

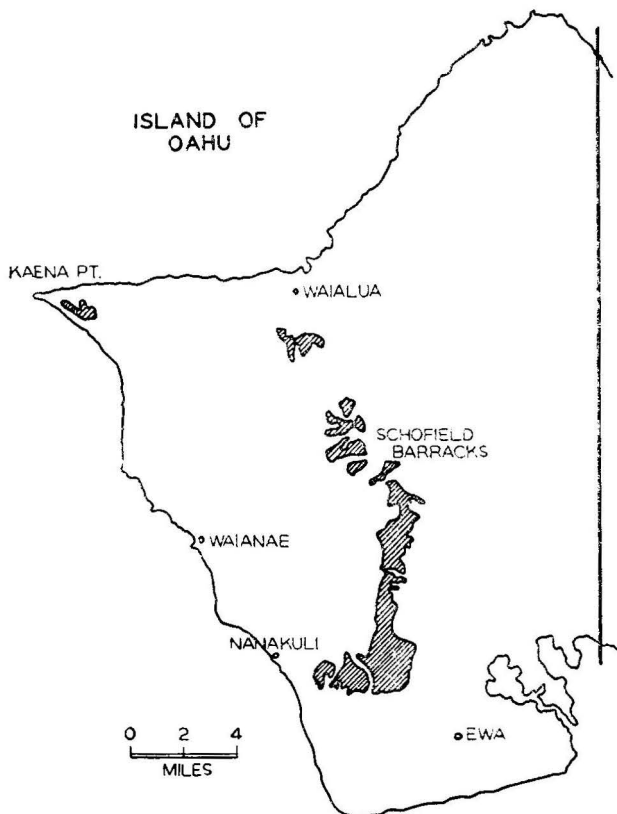
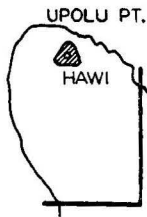


FIGURE 2. Distribution of titanium deposits on Oahu.

3. The intimate mixture of iron oxides and anatase will require the development of special ore-dressing methods for their separation. The cost of separation and concentration may prove too expensive to permit the economical development of these deposits.

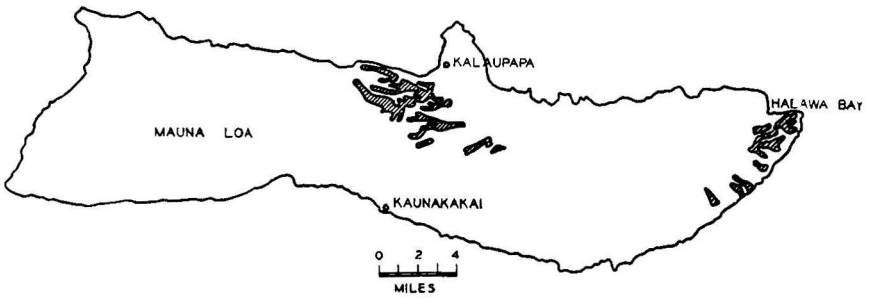
One of the potential commercial uses of titanium oxide from the Hawaiian titaniferous soils would be the local development of titania gem stones which are developed synthetically by a patented procedure of controlled recrystallization of TiO_2 from solution. The Hawaiian titaniferous earths could be extracted for TiO_2 and used in this process. The titania gem stones are attractive stones resembling diamonds in appearance, but are much lower in hardness as they can be scratched by glass. The value of such a development would be a gem for the jewelry trade which could be known as Hawaiian "gems," especially if unique native designs could be developed. The development would provide employment for many people, especially for craftsmen and artistically talented people. A very small amount of ore would be required for this industrial development.

ISLAND OF HAWAII



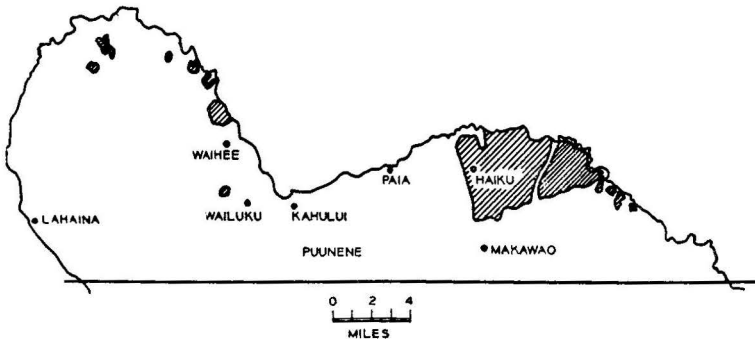
0 4
MILES

FIGURE 3. Location of titanium deposit on Hawaii.



0 2 4
MILES

FIGURE 4. Distribution of titanium deposits on Molokai.



0 2 4
MILES

FIGURE 5. Distribution of titanium deposits on Maui.



FIGURE 6. Distribution of titanium deposits on Kauai.



FIGURE 7. Distribution of titanium deposits on Lanai.

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 limited to consider them an adequate source of iron oxide, but they are still extensive 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 content occurs in the subsoil (friable) layer of the Humic Ferruginous Latosols, where it may be as high as 80 percent 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 percent 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 (15, 16) was first to point out the high content of manganese in Hawaiian soils, as high as 9.7 percent. This, however, is still too low for commercial development.

For general information it should be pointed out that most of the manganese in Hawaiian soils occurs as manganiferous concretions (34). These pyrolusite concretions have developed in certain soils as a product of weathering processes. The concretions are found in soils which have developed under a 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 nucleus; (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 11 gives the MnO_2 content of typical concretions.

The MnO_2 content ranges from 23 to 44 percent. Deposits which approach ore possibilities are found in small areas only, but 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.

TABLE 11. The average chemical composition of different types of manganiferous concretions

TYPE OF MANGANIFEROUS CONCRETION	AVERAGE CHEMICAL ANALYSIS				RANGE OF MnO ₂ CONTENT
	SiO ₂	Al ₂ O ₃	Fe ₂ O 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

OTHER MINERAL POSSIBILITIES

Recent soil fertility research has shown that the application of simple silicates such as calcium silicate has given remarkable increase in yield of sugar cane and Sudan grass. Other experiments have indicated a need for magnesium. Baver *et al.* (2) and Monteith and Sherman (21) have shown very beneficial effects on growth, and the former have reported a yield increase of three tons of sugar per acre due to the application of calcium silicate. Extensive experimentation is in progress and there is ample evidence of a need for both silicate and magnesium carriers as soil amendments and fertilizers. Such materials are not available at reasonable prices to the Islands. The need for a magnesium carrier can be obtained by grinding picrite basalt (oceanite) to a 200-mesh size. Picrite basalt contains approximately 15 percent magnesium oxide in the form of olivine. On the basis of this magnesium concentration it is worth more than \$50 per ton based on its cheapest competing carrier.

A boulder and an outcropping of picrite basalt (oceanite) occur on Oahu Sugar Company's land along the Kunia Road on Oahu. Nearby cement plants have the equipment to grind this material to a proper size.

The olivine is not a good silicate carrier due to its high magnesium content. At rates of application as soil amendment, the magnesium will depress both the calcium and potassium uptake by the plant and lower yields. A calcium silicate source will have to be located or mixed applications of coral and olivine-rich material be applied. A natural mixture occurs at Kekaha, Kauai, along the beaches.

There may be other mineral possibilities in Hawaii, some of which may be unknown to us today. Of those known but today still insignificant in value, some may become valuable in future economic changes or other increased need for such mineral elements. Appreciable amounts of nickel, chromium, vanadium, zirconium, and cobalt have been found, but none found in quantities approaching commercial possibilities under present-day standards. Most of the soils of the Islands contain about 0.1 percent 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.* (14), as a sequence of weathering of the clay-sized minerals. The stages in the sequence of their 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. Usually, they are a mixture of two or more types of clay minerals. An effort is being made to develop industrial clay products in the Islands, with some success. The development of fine ceramic products must wait until clays with lower shrinkage properties are found. Clays of better qualities are being found each year and a special report will be made in this area at a later date.

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 is recovered 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. However, 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 a 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 at 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 AND SUMMARY

The object of this report is to acquaint the public with up-to-date information of the mineral resources of the Islands. The mineral resources of the Islands are largely composed of those materials which can be concentrated by the processes of chemical decomposition of rocks under a warm humid tropical climate. The products of such weathering processes are the free oxides of metals and clays. Bauxite and oxides of titanium and iron are concentrated by this process in Hawaii. Bauxite appears to have the best potential for ultimate development.

However, it must be pointed out that there can be no development of mineral resources in the Islands until a favorable economic climate can be developed. Mining laws must be enacted which foster the development of the industry but which at the same time protect the public from abuses of mining practices that give no consideration to conservation.

Other mineral resources are described with their development potential. The possibility of a ceramic industry is improving with time. Clays with lower shrinkage properties are being found each year.

The titanium metal has improved its industrial position considerably in the jet era. On the other hand, research has demonstrated that the close relation between iron and titanium in the mineral assemblage provides little hope for a titanium industry in the Islands except for special uses.

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