Contributions to the Geology of Mineral Deposits

Exploration for Porphyry Metal Deposits Based on
Rutile Distribution—a Test in Sumatera
Titanium Mineral Resources of the United States—
Definitions and Documentation

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A. Exploration for Porphyry Metal Deposits Based on Rutile Distribution—a Test in Sumatera, by Eric R. Force, Sukirno Djaswadi, and Theo van Leeuwen

B. Titanium Mineral Resources of the United States— Definitions and Documentation, by Eric R. Force and Langtry E. Lynd

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By ERIC R. FORCE, SUKIRNO DJASWADI, and THEO VAN LEEUWEN

CONTRIBUTIONS TO THE GEOLOGY OF MINERAL DEPOSITS

A new exploration tool for porphyry deposits in the tropics

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EXPLORATION FOR PORPHYRY METAL DEPOSITS BASED ON RUTILE DISTRIBUTION—A TEST IN SUMATERA

By ERIC R. FORCE,[1] SUKIRNO DJASWADI,[2]
and THEO VAN LEEUWEN[3]

ABSTRACT

At the Tangse porphyry-copper prospect, rutile in thick soil reflects the distribution of the quartz-sericite and biotite-chlorite zones of hydrothermal alteration at depth. Detection of rutile in the samples is not simple, but studies of rutile distribution may nevertheless be a cheap exploration method for tropical porphyries.

INTRODUCTION

A program of investigation is being undertaken cooperatively by the Indonesian Directorate-General of Mines and the U.S. Geological Survey (USGS), sponsored by the Government of Indonesia and the U.S. Agency for International Development; it includes this study.

Recent work has documented the presence of rutile in the most severely altered parts of porphyry alteration systems (Lawrence and Savage, 1975; Force, 1976a; Williams and Cesbron, 1977; Force and others, 1980; Force, 1980a; Llewellyn and Sullivan, 1980; Czamanske and others, 1981). Because this rutile has a related origin and similar distribution to the copper mineralization, knowledge of rutile distribution should be useful in exploration for porphyry copper, as suggested by Lawrence and Savage and by Williams and Cesbron. As rutile is resistant to weathering, determination of rutile distribution in soil could be an important part of an exploration method where porphyry deposits are concealed by thick soils leached of copper. We suspect, on the basis of knowledge of rutile occurrence summarized by Force (1976b, 1980b), that in the volcanotectonic arcs where many of these porphyries occur, the mere presence of

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rutile is an indication of porphyry-related alteration in the broad sense. This hypothesis needs further checking.

ACKNOWLEDGMENTS

RUTILE DISTRIBUTION IN PORPHYRIES

Czamanske and others (1981) provide the most comprehensive picture so far of the distribution and origin of rutile in porphyries. Rutile is a secondary mineral that mimics the distribution of original magmatic titanium minerals such as sphene, biotite, and ilmenite. It reaches its greatest abundance and grain size in the biotite potassium feldspar alteration zone of porphyries in the Western United States. There it averages 0.3 percent or more as crystals, averaging about 0.03 by 0.06 mm, locally in mosaics where it forms pseudomorphs of primary, magmatic titanium minerals. In peripheral alteration zones, rutile abundance and grain size progressively diminish. In some porphyries, the distribution of rutile and of copper ore is about the same.

APPLICABILITY TO EXPLORATION IN THE TROPICS

The correspondence of rutile distribution to certain alteration zones, coupled with its resistance to weathering in soils, suggests that an exploration method for porphyry deposits could be based on rutile distribution. In the deeply weathered tropical terranes where this approach would be most useful, however, many porphyries are of different compositions and have different types of alteration than the Western U.S. quartz monzonitic porphyries most intensively studied by Czamanske and others. A few data suggest that these differences do not detract from the potential usefulness of rutile. Lawrence and Savage (1975) and Cox and others (1973) described quartz dioritic porphyries that contain rutile. We find that advanced argillic alteration assemblages with andalusite (common except in Western United States) contain rutile.

Two types of exploration with rutile distribution seem possible: proximal exploration in soils and local streams, and distal exploration in sediments of large streams.

THE TANGSE PORPHYRY

The Tangse porphyry-copper prospect in Aceh province, northern Sumatera (fig. 1), has been briefly described by Young and Johari (1978), Page and others (1979), and Taylor and van Leeuwen (1980). Subsequent geological mapping, geochemical sampling, ground magnetics, induced polarization, and diamond drilling (1,600 m) by Rio Tinto Indonesia have resulted in a more comprehensive documentation of the deposit.

The prospect area is near the confluence of two major rivers, Krung (river) Tangse and Kr. Bale (fig. 2). It forms a topographic depression, occupied by alluvial flats and low, flat-topped hills within the Barisan Range, a rugged mountain range that runs along the entire western edge of the island of Sumatera. Following closely the crest of the Barisan Range is a continuous system of axial valleys, including the Kr. Tangse valley, which marks the outcrop of the main fault line of the Sumateran fault system. This is essentially a right lateral fracture system, although gravity faulting is also important (Katili and Hehuwat, 1967; Page and others, 1979). Several other occurrences of porphyry copper are found along this fault zone farther to the southeast (Taylor and van Leeuwen, 1980).

The topographic morphology of the Tangse area is subdued because the rocks here are strongly fractured and altered. Primary copper mineralization is largely confined to an elongated multiphase stock consisting of various quartz diorite and dacite porphyries and having plan dimensions of 6 1/2 km by 2 km (northwest part shown in fig. 2). This stock was intruded into a large composite pluton of granitic to dioritic composition, which was emplaced in a thick sequence of Mesozoic metavolcanic and metasedimentary rocks. The long axis of this intrusive complex is alined between two obliquely converging fault zones belonging to the Sumateran fault system. A major feature of the Tangse part of the fault system is the large mass of serpentinized ultramafic rocks. Numerous dikes (mostly postmineralization) cut the intrusive complex and adjacent wall rocks. Potassium-argon ages, determined on hornblende or biotite from five samples, indicate a middle Eocene age for the pluton and a middle to late Miocene age for the mineralized stock and late dikes.

Alteration at Tangse is multistage, and telescoping of alteration types has taken place. Fracture-controlled phyllic and advanced argillic alteration assemblages, the latter characterized by the presence of andalusite, have been superimposed on earlier biotite alteration, which has affected virtually the entire quartz diorite stock. The secondary biotite has also been selectively altered to

chlorite throughout the stock, although the conversion is only locally complete. An extensive propylitic halo surrounds the strongly altered stock, but otherwise the areal distribution of alteration types does not conform to a zonal sequence even though the temporal relations are clear.

Primary sulfide minerals are pyrite, chalcopyrite, and molybdenite, which are present as disseminations among rock-forming minerals and in veinlets. Rocks showing only early-stage alteration seldom have total sulfide contents of more than 1–2 volume percent; rocks affected by late-stage alteration usually have total sulfide contents of more than 3 volume percent. Primary copper mineralization is widespread, although generally of low tenor, and is found in association with all alteration types, except propylitic alteration. The best mineralization is found in fault-controlled zones of chlorite-sericite-quartz alteration. Chalcopyrite is nowhere observed at the surface owing to strong weathering. Some chalcocite is commonly present directly below the oxidation zone over a relatively short interval. Zinc and lead form a well-defined geochemical halo to the zone of copper-molybdenum mineralization, but gold is absent.

Secondary rutile had already been detected under the microscope in several core and weathered outcrop samples before the present study began. It forms both single tiny crystals and massive to skeletal finely granular clusters. Some clusters appear to form pseudomorphs of former Fe/Ti oxide crystals, but more commonly the rutile is intimately associated with masses of chlorite with or without secondary biotite; this rutile is probably the byproduct of chloritization (and secondary biotitization?) of titaniferous mafic minerals, such as magmatic biotite. The common occurrence of zircon crystals within the rutile clusters supports this interpretation. Rutile is also commonly present in alteration assemblages that contain little or no chlorite (quartz-sericite; quartz-sericite-andalusite). In these associations, it is usually enclosed in sericite masses. Whether the rutile survived overprinting of biotite-chlorite alteration by later phyllic and advanced argillic alterations, or whether it is directly related to these late hydrothermal processes, has not been determined.

Rutile was not observed in unaltered quartz diorite or in postmineral dikes. The propylitic zone has not been studied in detail, but the available data from thin-section study suggests that rutile is absent in this zone also, even where it overlaps the zone of secondary biotite alteration. Sphene, however, is very common in the propylitic zone. Though our knowledge of rutile distribution in unweathered rock is sketchy at Tangse, it is in accord with results of Czamanske and others (1981) and of Williams and Cesbron (1977),

who studied rutile from a large number of porphyry copper deposits. They observed that rutile may be present in the inner fringes of the propylitic zone, and is found throughout more intensely altered zones, but disappears outward in favor of the local titanium-bearing accessory in the host rocks.

EXPLANATION

Quaternary sediments

Quaternary volcanic rocks

Ultramafic complexes

Tertiary and Mesozoic intrusive rocks

Tertiary to Paleozoic undifferentiated rocks

Tangse porphyry stock
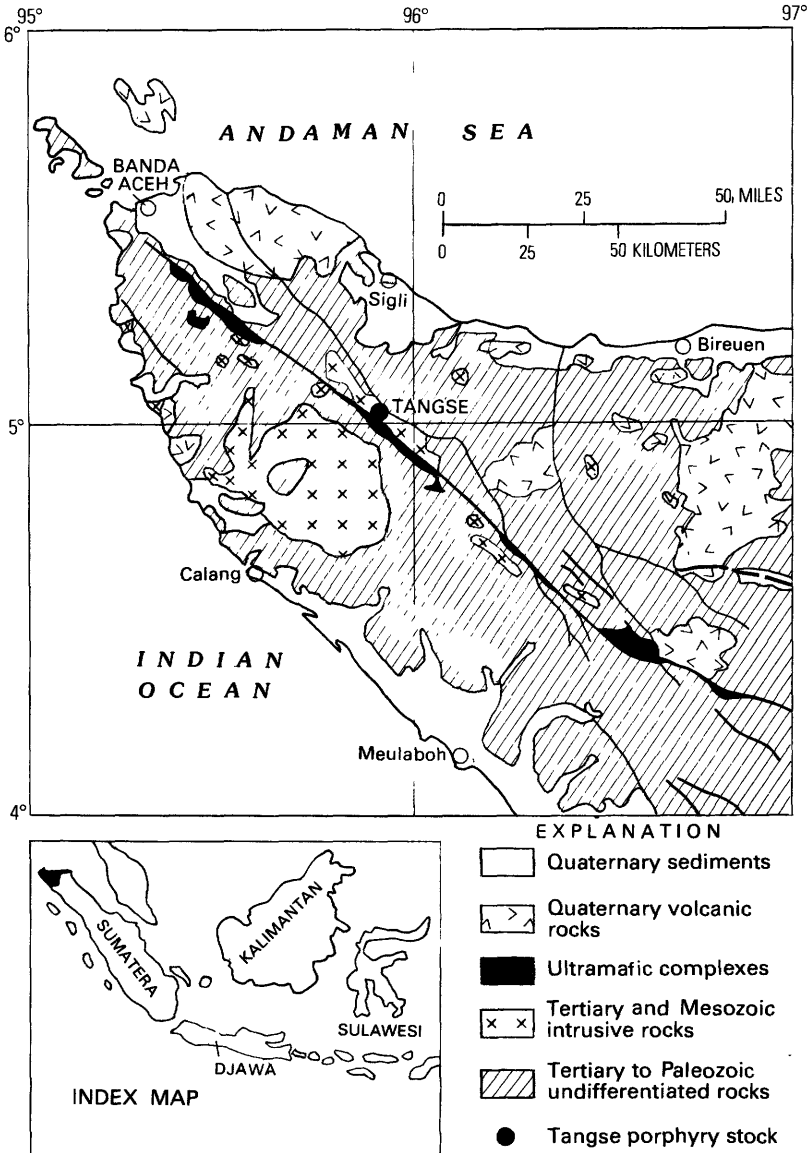
FIGURE 1.—Location and regional geologic map (modified from Young and Johari, 1978).

SAMPLING METHODS

Soil samples were collected from about the upper meter of exploration trenches. Stream sediments were from large active streams upstream and downstream from the deposit and small streams within the deposit. We found that most of the rutile was too fine to be concentrated in a pan. The best sample proved to be a –80 mesh screen fraction from which the clay-size material was decanted. Most of these fractions were prepared in the field. Bulk samples and +80 mesh pan concentrates were also collected for insurance.
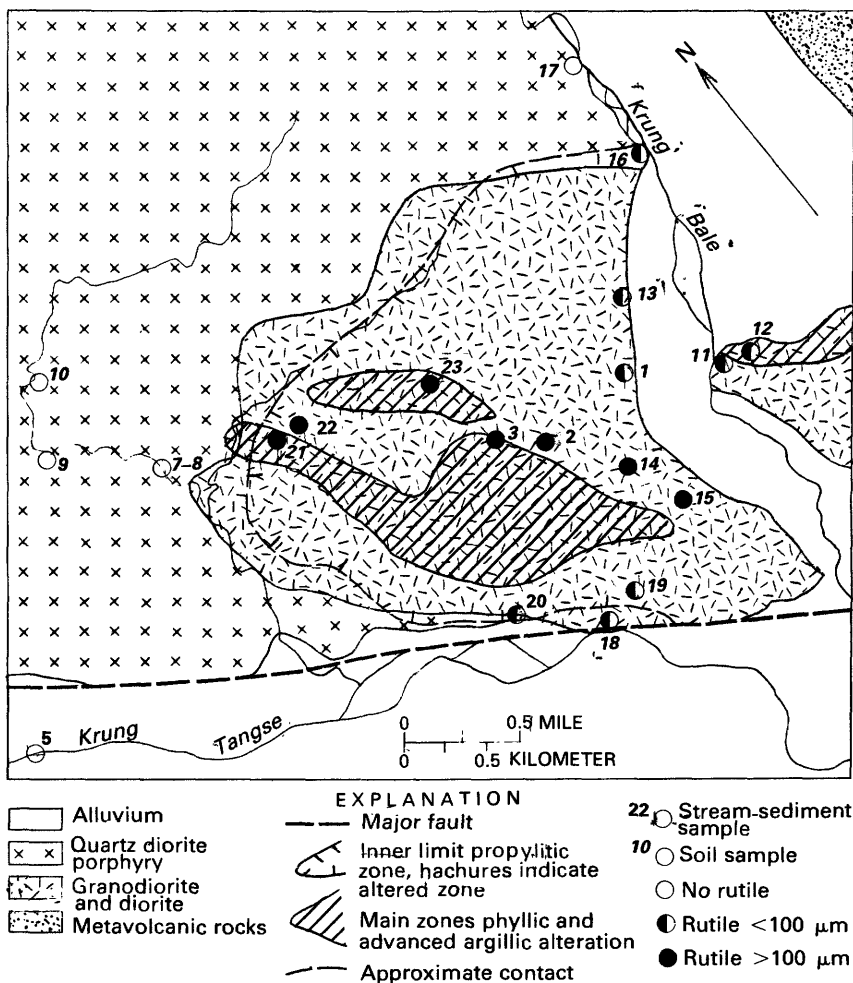
FIGURE 2.—Geologic and alteration map of the Tangse prospect showing distribution of rutile in proximal soil and stream-sediment samples.

LABORATORY METHODS

The rutile is too fine to be identified with confidence under a binocular microscope. In thin sections of weathered rock, we observed that goethite(?) and rutile crystallites were so similar that they were difficult to differentiate. Accordingly, we treated samples with acid to remove goethite, and examined them in grain mounts in oils under a petrographic microscope. Immersion in unheated but concentrated hydrochloric acid for 2 hours proved to be the least drastic treatment that worked. We identified rutile with condenser engaged under a high-power objective, using both plane and cross-polarized light. Some of the rutile was present as inclusions.

Presence or absence of rutile was determined in numbered, but otherwise unlabeled, samples by the first and second authors working independently. We examined pan concentrates also, and, though some rutile was identified, no information resulted beyond that obtained from –80 mesh fractions.

RECOMMENDED METHOD

A simple but effective method for rutile determination is (1) use an aliquot of a sample collected for soil geochemistry; (2) digest it in cold hydrochloric acid for 2 hours; (3) rinse, allowing the clay-sized material to escape; (4) remove the coarse fraction with an 80-mesh screen and dry the fines; (5) identify in grain mount with petrographic microscope, as explained above, and record rutile grain size. This should all be possible in a suitably equipped field office.

RESULTS OF PROXIMAL EXPLORATION

Soil samples.—The distribution of rutile in soil at Tangse correlates closely with the intensity of alteration of parent rock. Rutile is limited to soils over rock that has been altered to quartz-sericite (±andalusite) or biotite-chlorite assemblages. All soils over such rock contain rutile (fig. 2). In addition, the coarsest rutile is found in an axial belt of maximum alteration and sulfide concentration.

We were able to see postmineral dikes in trench bottoms and avoided taking soil samples over them. An exploration program based on rutile distribution without trench exposures, however, would have to allow for postmineral dikes that would yield samples without rutile in intensely altered and mineralized areas.

Stream sediments.—Three samples of sediments from short streams draining the deposit were analyzed (fig. 2). The fact that all contained rutile indicated that proximal alluvial sampling as

well as soil sampling for rutile could be useful in delineating a por-
phyry body.

RESULTS OF DISTAL EXPLORATION

Nine sediment samples from the two largest streams were col-
lected; six were downstream of the deposit (most are outside area
shown on fig. 2). Rutile was not observed in any of these samples.
Two problems are apparent: (1) Massive dilution with other debris
has taken place, making rutile hard to find; (2) vigorous winnowing
has removed most of the fine-grained rutile and transported it to
lower energy depositional sites downstream. Thus, reconnaissance
or distal exploration by means of rutile distribution may not be
useful.

COMPARISON WITH OTHER EXPLORATION
TECHNIQUES

At Tangse, rutile exploration worked best in proximal samples—
that is, in soil samples and in sediment samples from small streams
draining the deposit. Thus, exploration based on rutile distribution
is most appropriately compared with other proximal exploration
techniques such as soil geochemistry and trenching.

Rutile distribution is consistent with results of soil geochemistry
at Tangse (Young and Johari, 1978; Page and others, 1979) but can
be determined easier and faster. Rutile distribution, like gold dis-
tribution, gives information even where other diagnostic elements
have been leached from tropical soils. Where gold is absent over
mineralized rock, as it was at Tangse, prospecting with rutile may
be the only effective surface technique.

Our observations of the rutile in soil collected at the top of soil
profiles exposed in trenches corresponded well with our observations
of rock alteration made on weathered samples at the bottom of the
same trenches. Thus, to some extent, knowledge of rutile distribution
can make extensive trenching unnecessary.

An integrated technique using soil geochemistry, trenching, and
rutile distribution should provide more information at about the
same cost as that for present exploration techniques.

Tangse is the wrong place to test the use of rutile in distal or re-
connaissance exploration, as Kr. Tangse and Kr. Bale are powerful
braided streams carrying immensely more material than is sup-
plied by erosion of the subdued hills underlying the deposit. Our
initial results were discouraging as were those of stream-sediment
geochemistry for similar distal exploration. A better test could be
done where a deposit is nearer a drainage divide.

CONCLUSION

The distribution of rutile in soil over the deeply weathered Tangse porphyry is the same as the distribution of intensely altered rock at depth. With the methods we have described here, the distribution of rutile in soil is not difficult to establish. Thus, rutile studies could be a valuable part of comprehensive exploration programs for porphyry deposits in the tropics. Alluvial prospecting for distant porphyries by means of this technique appears to be inefficient in our somewhat atypical example. More detailed work and tests over other deposits are certainly warranted.

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Titanium Mineral Resources of the United States—Definitions and Documentation

By ERIC R. FORCE *and* LANGTRY E. LYND

CONTRIBUTIONS TO THE GEOLOGY OF MINERAL DEPOSITS

GEOLOGICAL SURVEY BULLETIN 1558-B

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CONTRIBUTIONS TO THE GEOLOGY OF MINERAL DEPOSITS

TITANIUM MINERAL RESOURCES OF THE UNITED STATES—DEFINITIONS AND DOCUMENTATION

By Eric R. Force[1] and Langtry E. Lynd[2]

ABSTRACT

A somewhat complicated definition of titanium mineral resources that is parallel to current industry evaluation practice is applied to all identified U.S. resources. The totals of these resources have been published jointly by the U.S. Bureau of Mines and the U.S. Geological Survey every year since 1977 without the documentation that this article provides. Those totals currently are as follows: rutile and its polymorphs 14.1×10^6 metric tons contained TiO_2, altered ilmenite 33.5×10^6 tons, low-TiO_2 ilmenite 46.8×10^6 tons, and perovskite 20×10^6 tons. The largest contributions to these resources for rutile (56 percent) are made by hydrothermally altered rocks (porphyries), for altered ilmenite (97 percent) by shoreline sand bodies, for low-TiO_2 ilmenite (68 percent) by gabbro-anorthosite complexes, and for perovskite (100 percent) by alkalic igneous complexes. Placer deposits contain 42 percent (by weight; more than 50 percent by value) of U.S. resources of titanium minerals. Individual placer deposits or districts approach the largest igneous deposits or districts in resource magnitude.

INTRODUCTION

This paper defines, documents, and updates our titanium mineral-resource figures published by the U.S. Bureau of Mines (Lynd, 1978, table 3, and Lynd, 1980, table 3, "derived in consultation with the U.S. Geological Survey"). Older compilations are by Klemic and others (1973) and Peterson (1966). Location information is given by Tooker and Force (1980) and Rogers and Jaster (1962); figure 1 shows the locations of deposits listed herein.

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[1]U.S. Geological Survey.
[2]U.S. Bureau of Mines.

GEOLOGY OF TITANIUM DEPOSITS

Economic deposits of titanium minerals occur in several distinct geologic settings; these are discussed in some detail in Force and others (1976). For the purposes of this paper, we will confine ourselves to observing that the titanium minerals of value are all oxides; in order of decreasing economic value these are rutile and its polymorphs, altered ilmenite[3] (known also as "leucoxene," arizonite, pseudorutile, and so forth), ilmenite, and possibly perovskite. These oxides occur in hard-rock deposits, in placer deposits, and in altered rock. Hard-rock deposits occur in igneous gabbro-anorthosite complexes (ig of table 1), in igneous alkalic complexes (ia), and in metamorphic aluminosilicate bodies (ma). Placer (p) deposits range from unindurated modern deposits to indurated old deposits and include shoreline sand bodies (ps), glacial lake delta sands (pg), and fluvial deposits (pf). Altered rocks (a) containing titanium oxides include those formed by hydrothermal alteration (ah), such as the porphyry deposits, and those formed by weathering (aw), such as the saprolite deposits.

DEPOSITS AND PROCEDURE

Our compilations of titanium resources list only those that pass certain tests, which indicate their economic relevance. These criteria follow; they constitute our definition of an identified resource of titanium minerals.

Only the titanium oxide minerals rutile and its polymorphs, altered ilmenite, ilmenite, and perovskite, which are known or thought to have some economic value, are included in these figures. Titaniferous magnetite, sphene, and other titanium minerals whose economic value has not been demonstrated are not included in this report except in special circumstances listed below.

Also excluded from resources listed here are titanium minerals of finer grain size than 20 μm (0.02 mm), on the grounds that they cannot presently be separated. Where ilmenite is known to be present as separable grains intergrown with magnetite, resources of the ilmenite are included. Where inseparable intergrowths of magnetite and ilmenite together contain 25 percent or more of TiO_2, resource figures are also included on the grounds that this material could be smelted into high-TiO_2 slag.

We have also used a grade cutoff in calculating resources. Our

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[3]Ilmenite that has been upgraded by oxidation and leaching during weathering, typically to 55-65 percent TiO_2 compared with 45-50 percent in unaltered ilmenite.

figures include only deposits containing at least 1 percent ilmenite or 0.1 percent rutile or linear combinations thereof in unconsolidated deposits or 10 percent ilmenite or perovskite or 1 percent rutile in hard rocks. Lower grade resources are included if titanium minerals could be produced as byproducts of other minerals already being mined in the same deposits; the byproduct resource listed is based on recovery for 20 years unless otherwise stated.

Resource figures given in table 1 include reserves (see Lynd, 1978, 1980, and 1983, for separate reserve listing). Resources of less than 100,000 metric tons of TiO_2 are omitted.

Resources of dipping deposits were calculated to a depth of 50 m, unless otherwise stated or unless the references cited have demonstrated resources to another depth.

RESOURCE DOCUMENTATION

The following brief descriptions of titanium mineral deposits are keyed to table 1. Some documentation herein consists of reasons why resources listed by others have been omitted from our list.

Alabama.—Sullivan and Browning (1970) gave figures for recoverability of altered ilmenite from sand and gravel operations, mostly in Cretaceous sands. The figure in table 1 is based on 10 years of potential recovery.

Alaska.—The large resources listed by Klemic and others (1973) are believed not to fit the definitions of this report. Most of the TiO_2 in the large mafic igneous deposits and a derived alluvial fan is present in magnetite and sphene (Wells and Thorne, 1953), although some ilmenite is present (Rossman, 1963; C. L. Sainsbury, written commun., 1952). The black sand beach deposits contain TiO_2 as sphene, augite, hornblende, and magnetite in addition to ilmenite (Thomas and Berryhill, 1962; Cook, 1969). Tonnage figures for the beach deposits are not available.

Arizona.—At least three Arizona porphyry copper deposits (San Manuel, Bagdad, Ajo) contain rutile. Resource figures are from Force (1981) and Czamanske and others (1981). Recoverability of the rutile is discussed by Llewellyn and Sullivan (1980) and Sullivan and Llewellyn (1981).

A kyanite-quartz rock in Yuma County contains rutile (Marsh and Sheridan, 1976). Resource figures are based on an approximate average rutile content of 1 percent.

Arkansas.—Alkalic igneous rocks in the Magnet Cove district contain rutile and its polymorphs (Fryklund and Holbrook, 1950). Our resource figures are for the Magnet Cove rutile deposit (E. C. Toewe and others, written commun., 1971) and the Christy brookite deposit (Reed, 1949).
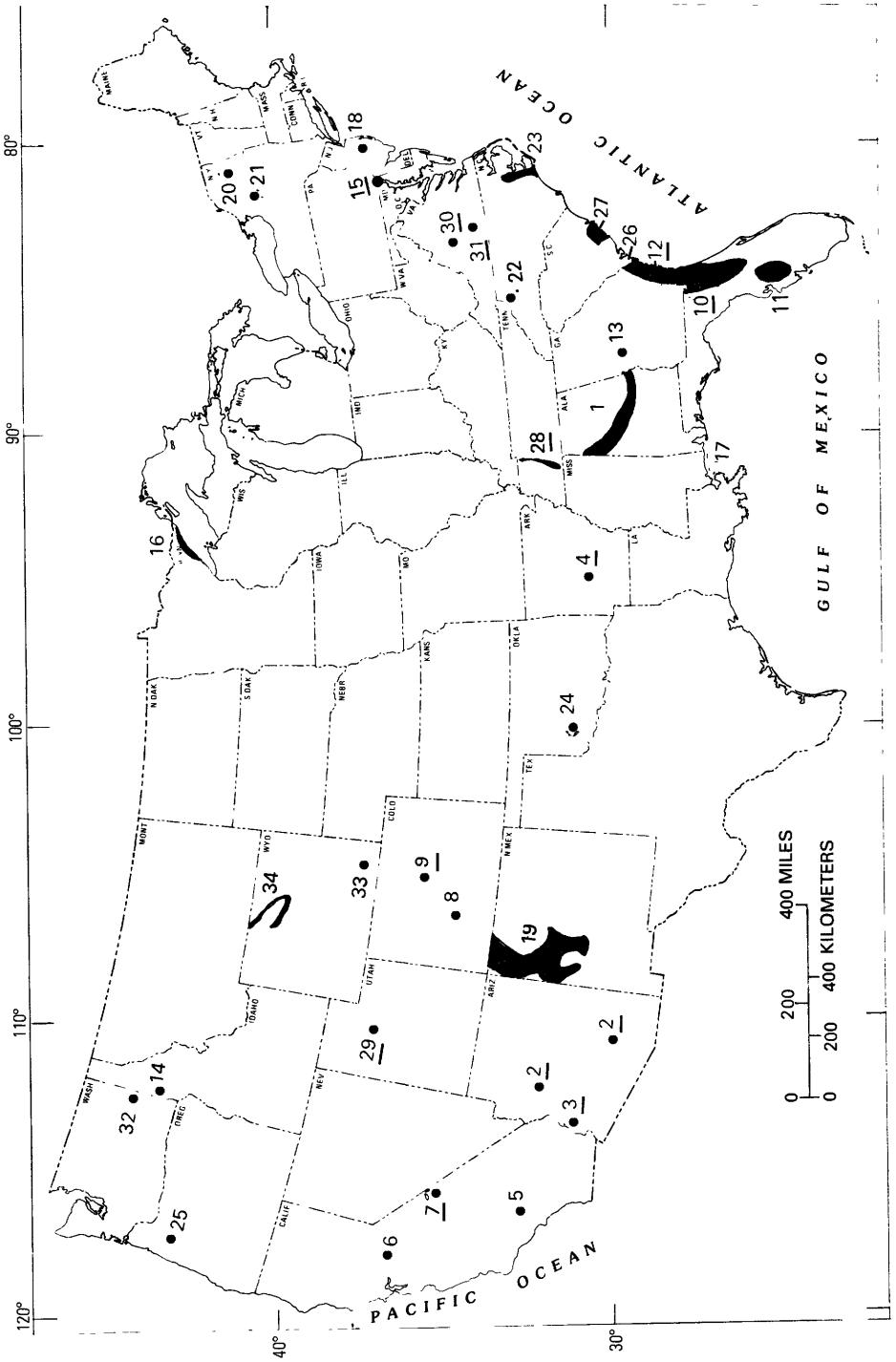
California—Ilmenite-magnetite deposits of the San Gabriel Mountains could be upgraded by smelting and are therefore included. The listed resource figure is from an aggregate of sources, including Oakeschott (1948).

A silica sand operation at Ione discards heavy minerals with 20 percent altered ilmenite (Gomes and others, 1979, and written commun.).

Unpublished work by Force and Sherman Marsh with Scott Werschky indicates that andalusite-topaz-rutile rock in the White Mountains (Gross and Parwel, 1969) contains an average of 2.5 percent rutile in about 10^7 metric tons of rock.

Colorado.—Alkalic igneous rocks near Powderhorn (Temple and Grogan, 1965) contain large disseminated perovskite resources (Wall Street Journal, 1976) as veins with magnetite in pyroxenite. The average perovskite content of ore is about 8 percent. Elger and others (1980) have shown that this perovskite can be used to make titanium products.

A topaz-sillimanite gneiss near Evergreen contains rutile (Marsh and Sheridan, 1976).

Florida.—The aggregate resource figure in table 1 includes deposits at Trail Ridge, Green Cove Springs, and elsewhere, which contain altered ilmenite and rutile in elevated beach sands.

Florida phosphate deposits contain titanium minerals, separable with difficulty because of fine grain size (Stow, 1968; Lamont and others, 1972).

Georgia.—Deposits of altered ilmenite in old beach sands of Georgia include those near Brunswick, on Cumberland Island, and in the Cabin Bluff-Woodbine area.

Silica sand operations near Junction City separate heavy minerals containing rutile and altered ilmenite (Force, 1981).

Hawaii.—The titanium-rich saprolites of Hawaii are believed not to be titanium resources as defined here. Titanium is present as titanomagnetite and titanomaghemite, which are too low in TiO_2, and as alteration products too fine to separate (Katsura and others, 1962; Patterson, 1971).

Idaho.—Residual clays on basalt of Latah County average 6.4 percent TiO_2 (Hosterman and others, 1960), about half as ilmenite.

The Idaho alluvial placer deposits are far too low in ilmenite con-

FIGURE 1.—Locations of titanium-mineral resources discussed in this paper. Numbers refer to those shown in table 1. Underlined numbers denote rutile resources. Where deposits are scattered within a geologic unit, the area of the unit is shaded; where data are inadequate, shading may stop at State borders.

tent to be listed as resources here. This status could change if monazite mining again becomes economic.

Maryland.—A chlorite rock in Harford County (Southwick, 1968) averages 1 percent rutile (Herz and Valentine, 1970). We have assumed that rutile extends to a depth of 50 m below the bed of Deer Creek.

Minnesota.—The Duluth Complex of mafic igneous rocks includes numerous bodies that together contain 220 million tons of material with 10 percent or more of TiO_2 (Minnesota Division of Minerals, 1977). About 50 percent of TiO_2 is separable as ilmenite (Grout, 1949-50) that contains as much as 48 percent TiO_2. If Duluth nickel-copper ores are mined, as much as 500,000 tons per year of ilmenite with about 50 percent TiO_2 could become available as a byproduct (Iwasaki and others, 1982).

Mississippi.—Ship Island, a modern barrier island, contains concentrations of low-TiO_2 ilmenite (Hahn, 1962).

New Jersey.—Our resource figure for the Lakehurst district is that of Markewicz (1969) adjusted for production. Miocene beach deposits (Carter, 1978) there contain altered ilmenite.

New Mexico.—Indurated Cretaceous shoreline sandstones have heavy concentrations containing ilmenite, some of which is altered (Houston and Murphy, 1962, 1970). Resources are from Chenowith (1957).

New York.—The Sanford Lake district contains ilmenite with 46-50 percent TiO_2 in anorthosite and gabbro (Gross, 1968).

In the Port Leyden area, ilmenite-bearing sands are found in Pleistocene glacial lake deltas (Force and others, 1976; Stone and Force, 1980). Ilmenite grade is only about 1.5 percent, as mixed grains with about 25 percent TiO_2. Resources listed are from Port Leyden Quadrangle only, as grades elsewhere are unknown.

North Carolina.—Yadkin Valley resources are from Broadhurst (1955), corrected for production. The deposit is of ilmenite in mafic schist.

Other North Carolina resources are given by American Paint and Coatings Journal (1977).

Oklahoma.—River deposits in the Wichita Mountains contain ilmenite with 45 percent TiO_2 (Hahn and Fine, 1960; Chase, 1952).

Oregon.—The Salem bauxite averages 6.5 percent TiO_2, 75 percent of which is recoverable as low-TiO_2 ilmenite (Corcoran and others, 1956; Peterson, 1966).

South Carolina.—Hilton Head Island contains altered ilmenite in old beach sands (Williams, 1967).

Force and others (1982) documented ilmenite resources in other old beach sands near Charleston. Resources listed include "anomaly K" of that report, a larger low-grade deposit.

TABLE 1.—*Identified U.S. resources of separable, altered ilmenite, ilmenite, and perovskite*

[These figures include reserves. Deposit numbers refer to locations shown on figure 1. Types are a, altered rocks; ah, altered rocks formed by hydorthermal alteration; aw, altered rocks formed by weathering; ia, igneous alkalic complexes; ig, igneous gabbro-anorthosite complexes; ma, metamorphic aluminosilicate bodies; p, placer deposits; pf, fluvial deposits; pg, glacial lake delta sands; and ps, shoreline sand bodies]

Deposit No.	State and district or description	Type	Thousand metric tons of contained TiO_2			
			Rutile + polymorphs	Altered ilmenite	Low-TiO_2 ilmenite	Perovskite
1.	Alabama; sand and gravel	p	—	100	—	—
2.	Arizona; porphyry copper ore	ah	4,000	—	—	—
3.	Arizona; Yuma County	ma	200	—	—	—
4.	Arkansas; Magnet Cove	ia	200	—	—	—
5.	California; San Gabriel Mountains	ig	—	—	4,800	—
6.	California; Ione placer	pf	—	600	—	—
7.	California; White Mountain	ma	300	—	—	—
8.	Colorado; Powderhorn	ia	—	—	—	20,000
9.	Colorado; Evergreen	ma	200	—	—	—
10.	Florida; old beach sand	ps	1,100	9,700	—	—
11.	Florida; phosphate	p	—	200	—	—
12.	Georgia; old beach sand	ps	500	2,400	—	—
13.	Georgia; silica sand	p	100	200	—	—
14.	Idaho; Latah County clay	aw	—	—	1,300	—
15.	Maryland; Harford County	a	700	—	—	—
16.	Minnesota; Duluth Complex	ig	—	—	10,000	—
17.	Mississippi; Ship Island	ps	—	—	100	—
18.	New Jersey; Lakehurst	ps	—	10,100	—	—
19.	New Mexico; Cretaceous sandstones	ps	—	—	700	—
20.	New York; Sanford Lake	ig	—	—	8,600	—
21.	New York; Port Leyden	pg	—	—	6,300	—
22.	North Carolina; Yadkin Valley	ig	—	—	200	—
23.	North Carolina; other	ps	—	400	—	—
24.	Oklahoma; Wichita Mountains	pf	—	—	3,900	—
25.	Oregon; Salem bauxite	aw	—	—	1,800	—
26.	South Carolina; Hilton Head	ps	100	300	—	—
27.	South Carolina; Charleston	ps	100	1,100	—	—
28.	Tennessee; Cretaceous sand	ps	1,300	8,400	—	—
29.	Utah; Bingham	ah	4,000	—	—	—
30.	Virginia; Roseland-Piney River	ig	1,000	—	5,500	—
31.	Virginia; Willis Mountains, kyanite	ma	300	—	—	—
32.	Washington; Spokane	aw	—	—	400	—
33.	Wyoming; Laramie Range	ig	—	—	2,700	—
34.	Wyoming; Cretaceous sandstones	ps	—	—	500	—
	Totals by deposit types	ig	1,000	—	31,800	—
		ia	200	—	—	20,000
		ma	1,000	—	—	—
		p	100	500	—	—
		ps	3,100	32,400	1,300	—
		pg	—	—	6,300	—
		pf	—	600	3,900	—
		a	700	—	—	—
		ah	8,000	—	—	—
		aw	—	—	3,500	—
	Totals by mineral		14,100	33,500	46,800	20,000
	Total, all minerals—114,400					

Numerous fluvial monazite placers are too small or too low in grade to list as titanium resources.

Tennessee.—Resources listed occur as Cretaceous shoreline sands (Wilcox, 1971) in several deposits.

Utah.—The Bingham porphyry copper deposit contains rutile of good purity as probably separable grains (Force, 1981; Czamanske and others, 1981).

Virginia.—Recent work by Force and Norman Herz is the basis for the resource figure used here; it includes all previous published work on rutile deposits at the contact of anorthosite and its country rocks, disseminated ilmenite near the bases of ferrodiorite sheets (now saprolitized), and minor nelsonite (see Force and Herz, 1982, for geology). Also included are estimates by the Bureau of Mines of ilmenite in hard impure nelsonite at Piney River.

The resource figure for Virginia kyanite deposits is based on rutile contents of identified kyanite resources (Force, 1981).

Washington.—Excelsior clay of the Spokane area contains an average of 7 percent TiO_2 (Thorsen, 1966; Hosterman and others, 1960), about half present as ilmenite.

Wyoming.—Laramie Range ilmenite-magnetite deposits in anorthosite (Hagner, 1968) contain about 30 million tons of material averaging 20 percent TiO_2 (Pinnell and Marsh, 1954). Most ilmenite is not separable from magnetite, but their intergrowths can be upgraded to form a concentrate suitable for smelting (Back and others, 1952). Lower grade deposits are not included in resources as defined for this report.

Cretaceous shoreline sands contain concentrations of ilmenite, some of which is altered (Houston and Murphy, 1962, 1970). Resources listed are half those shown by Dow and Batty (1961), as much of the TiO_2 is present as magnetite.

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