Titanium mineral resources of the Western U.S.—an update

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with a section on

Ione Basin, California

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Contents

Abstract

Thirteen deposits or districts in the western U.S. have been examined in which titanium-mineral resources have been reported or implied. These deposits are of the following general types (in probable order of importance): 1) Cretaceous shoreline placer deposits, 2) silica-sand deposits of California, 3) fluvial monazite placers of Idaho, 4) anorthosite-related deposits, and 5) clay and bauxite deposits of the northwestern U.S.

Relative to previous reports, this one shows some greater and some lesser resources (table 1). In any case, titanium-mineral resources of the western U.S. (west of 103^{o} longitude) remain modest at world scale except as unconventional (especially perovskite) and by-product (especially porphyry) resources. Some deposits, however, have enhanced value to the titanium explorationist for the geologic relations they illustrate. Among the new conclusions are:

a) Loci of Cretaceous shoreline placers form linear patterns, nested as a function of age, that can be traced for thousands of kilometers, permitting focused exploration in whole new mountain ranges.

b) Medial hematite-ilmenite solid-solution, which is highly magnetic, is a major carrier of TiO_2 values in the Cretaceous deposits of Wyoming. This phase was previously thought to be relatively rare.

c) Regressive shoreline placer deposits in indurated Cretaceous sequences expose intricate facies relations, such as the construction of shoreface sequences by long-shore drift over tidal-channel fill, without much loss of paleogeographic information.

d) Due to deep weathering, virtually every Eocene sediment that accumulated in the Ione basin at the foot of the Sierra Nevada has economic value, permitting recovery of altered ilmenite and zircon along with silica, clay, coal, and gold. Ilmenite is most abundant in newly recognized shoreline sands.

e) Upper Tertiary fluvial placers of Idaho formed in and filled fault-bounded basins and thus are far more voluminous than deposits in the modern valley system. Previously reported resources are thus far too low.

f) Mafic igneous rocks of Proterozoic age near Bagdad, Arizona are of ophiolitic affinity, but contain nelsonitic ilmenite enrichments associated with anorthositic layers.

Introduction

The most recent tabulations of titanium-mineral resources of the U.S. were published by Force and Lynd (1984) and Force (1991a, table 5). Resources in the western U.S. (here taken to be west of longitude 103^{o}) were reported to be modest (table 1), and descriptions of deposits there were cursory, except for California's San Gabriel Mountains, unconventional resources such as Colorado's Powderhorn district, and by-product resources such as porphyry copper deposits (see also Czamanske and others, 1981).

The author's re-assignment to the western U.S. made possible visits to a number of other districts where titanium-mineral deposits or their host rocks have been reported. New evaluations have produced new estimates of resources (table 1), some higher and some lower than previous estimates. Not all reported titanium deposits could be checked, however, and much remains to be done. Substantial field investigations for this report are limited to those in the Ione (CA) district (See Force and Creely, herein). Mineralogic investigations are concentrated on the Cretaceous shoreline deposits. Information in this report was presented in a short course organized by the Center for Mineral Resources in January 1999.

The definition of a titanium-mineral resource for this report remains basically as outlined by Force and Lynd (1984), i.e. 1 or more percent ilmenite at recoverable grain size in unconsolidated deposits, or equivalent grades of rutile polymorphs and/or in hard rock in terms of price/mining cost ratio. Titanium oxides containing as little as 25% TiO_2 are included if they can be turned to high TiO_2 slag. A further requirement of importance for this report is the listing of the same titanium minerals at lower grades (but at the same grain sizes) if another product is being produced from the same ore.

Cretaceous shoreline deposits

The western shores of the Cretaceous interior seaway are marked by enrichments of titanium- and other minerals from New Mexico to Montana (Houston and Murphy, 1977). They occur in swash-zone deposits in regressive sequences of upper Cretaceous age. More than a hundred individual high-grade enrichments have been located. However, all the deposits described in the literature contain modest volumes (Dow and Batty, 1961). My investigation was directed in part toward the possibility of less-conspicuous large low-grade deposits. The districts visited (fig. 1) are described below from south to north.

Sanostee Mesa (San Juan basin), New Mexico.-- From an economic perspective, much literature on deposits of the San Juan basin focuses on the Sanostee deposit (fig. 1, #1), on the Navajo reservation southwest of Shiprock (Chenowith, 1957; Dow and Batty, 1961; Bingler, 1963). The deposit forms a belt of enrichments trending N. 30^{o} W. in horizontal Gallup Sandstone (upper Turonian), about 7300 feet long, 500 feet wide, and locally more than 4 m thick. Bingler describes the enrichments as six discrete lenses, but Dow and Batty and Houston and Murphy (1977) treat the enrichments as continuous, with the above dimensions. My own observations indicate that two intermittently-exposed, imbricate east-facing enrichments (Force, 1991a, back cover), each locally about 2 m thick, extend most of the length of the deposit and represent the majority of the resource.

Heavy mineral contents per se are not reported. Average analyses reported by Dow and Batty (1961) are 15.6% TiO_2 and 2.6% ZrO_2. According to Bingler (1963), the heavy mineral fraction consists largely of ilmenite and its alteration products, zircon, and a little tourmaline and rutile. Modal grain size of the heavy minerals ranges from about 0.06 to 0.10 mm, whereas the mode for light minerals is about 0.12 to 0.15 mm (see also

Table 1. Revised titanium-mineral resource figures for the western U.S. (in thousand tonnes of contained TiO_2, reserves included, rounded to 10^5 tonnes). Resource figures in parentheses unchanged.

[Mineralogic symbols: 1 rutile and its polymorphs, 2 altered ilmenite, 3 low-TiO_2 ilmenite, 4 perovskite, 5 medial ilmenite-hematite, locally altered, with anatase cement. Combinations show relative abundance.]

STATE	DISTRICT OR DESCRIPTION AND MINERALOGY	RESOURCE FROM THIS REPORT	RESOURCE FROM FORCE (1991a)
Arizona	porphyry copper ore; 1	(4000)	4000
Arizona	Bagdad; 3	100	-----
California	San Gabriel Mountains; 3	(4800)	4800
California	Eastern Transverse Ranges	0	-----
California	Ione; 2	4000	600
California	White Mountain; 1	(300)	300
Colorado	Powderhorn; 4	(20,000)	20,000
Colorado	Evergreen; 1	(200)	200
Idaho	Latah Cty. Clay; 3	0	1300
Idaho	monazite placer	see text	-----
New Mexico	Sanostee; 3>5	(700)	700
N.M.-Colo.	NW San Jan basin	0	-----
Oregon	Salem bauxite; 3	0	1800
Utah	Bingham; 1	(4000)	4000
Utah	Escalante; 3>5	200	-----
Washington	Spokane clays; 3	0	500
Wyoming	Grass Valley; 5>3	700	}500
Wyoming	Rock Springs; 5=3	300	

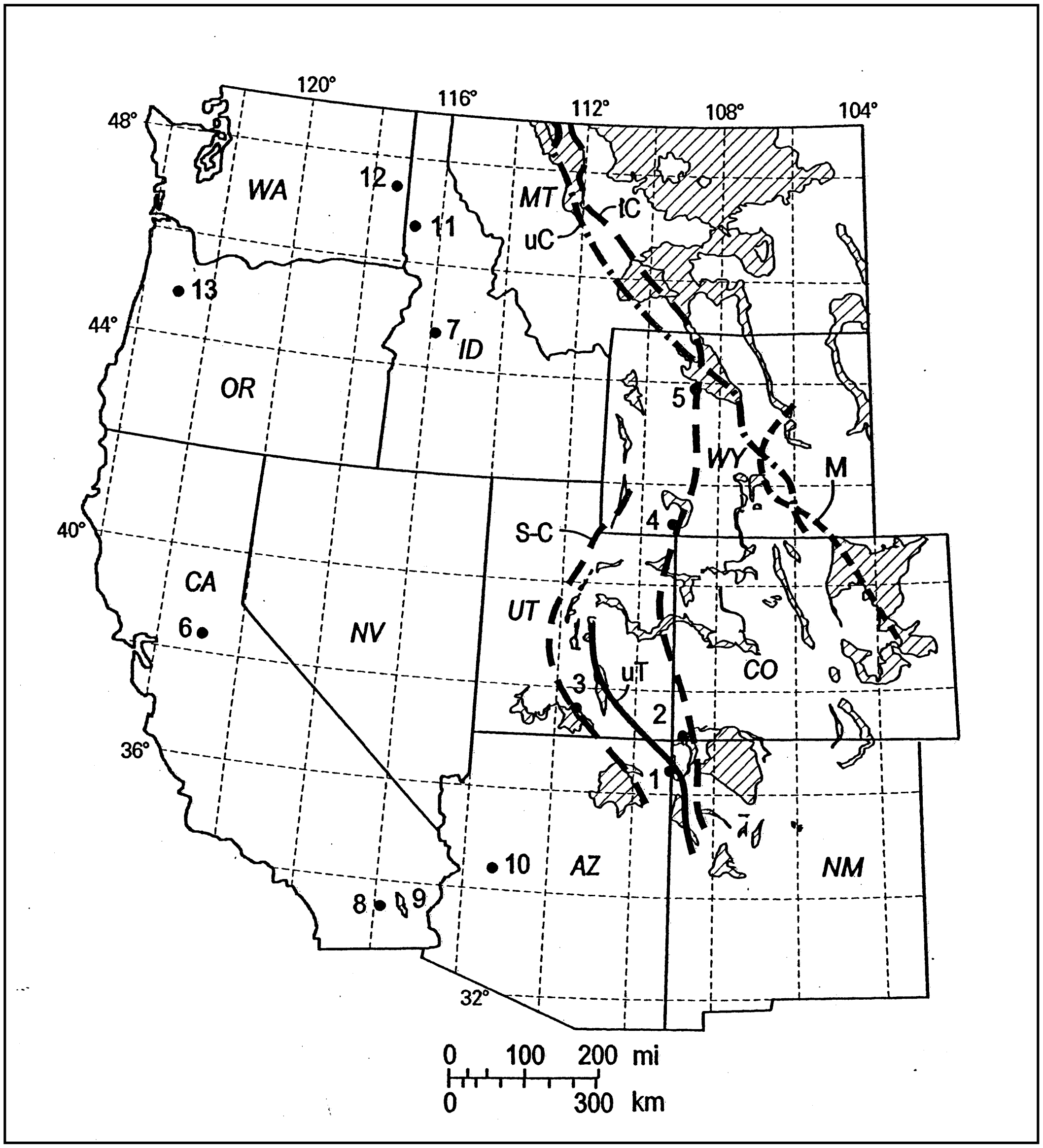

Figure 1. Location map for titanium-mineral deposits in the western U.S., including paleogeographic map of Late Cretaceous shoreline trends. Numbered deposits and districts: 1) Sanostee, NM; 2) other deposits of NW San Juan Basin, NM and CO; 3) Escalante and other Kaiparowits Plateau deposits, UT; 4) Rock Springs uplift, WY; 5) Grass Creek, WY; 6) silica deposits of the Ione area, CA; 7) fluvial monazite deposits of the Cascade, ID area; 8) Orocopia Mountains, CA; 9) jotunitic rocks elsewhere in the Eastern Transverse Ranges, CA; 10) Bagdad area, AZ.; 11) clay deposits of Latah County, ID; 12) clay deposits of Spokane County, WA; 13) bauxite deposits of the Salem area, OR. The shoreline trends shown are for uT, upper Turonian; S-C, Santonian-Coniacian; lC, lower Campanian; uC, upper Campanian; M, Maastrictian stages of the Late Cretaceous, listed from oldest to youngest.

Houston and Murphy, 1962, plate 3).

Bingler (1963) showed the ilmenite fraction to be homogeneous or with etched-out (presumably hematite) lamellae parallel to (0001). Houston in Chenowith (1957) noted a lack of magnetite intergrowths and the presence of rutile polymorphs in alteration products. Houston and Murphy (1962) found the ilmenite fraction to contain 46% to more than 50% TiO_2, and that an altered ilmenite fraction contains 59% TiO_2.

Stratigraphically, the enrichments form a resistant ledge at the top of the lower part of the Gallup Sandstone, above marine lower Mancos Shale and below non-marine parts of the Gallup (Bingler, 1963). All authors seem agreed that the enrichments represent regressive shoreline environments.

My field work (with John Smart of Wimmera Industrial Minerals) included some new geologic mapping (fig. 2) of subunits in the Gallup Sandstone. The greatest enrichments in the lower member occur in a flat-laminated upper facies, overlying a cross-bedded facies, both Ophiomorpha-bearing. Two enrichments are separated by a lower-grade sand, locally cross-bedded, and form imbricate lenses dipping and thinning eastward (fig. 2). Parts of the mesa expose the overlying middle member of the formation, consisting of gritty sands and carbonaceous shale, resting on a ferruginous surface. This surface was probably protected from Cenozoic oxidation by carbonaceous shale, so probably represents weathering prior to middle-member deposition. The upper member (fig. 2) consists of pebbly sand containing Ophiomorpha again, locally with sharks teeth. It may be a ravinement unit.

My specimens show that enriched intervals consist of interlaminated lower- and higher-grade sands, with heavy mineral content varying from about 25% to almost 100%. Of the heavy fraction, about 70% is opaque, about 20% is zircon, and perhaps 1% is rutile. Opaque grains are mostly well-defined and crystalline, consisting of homogeneous ilmenite-hematite with little or no magnetite. The proportion of "leucoxene" rims on opaque grains varies from 10 to 100% (complete replacement). Cement is of carbonate, clay, and hematite.

Low-grade margins of high-grade enrichments seem to be minor in both volume and grade. Stratigraphic separation from enrichment of only a meter commonly produces heavy mineral grades that are ambient for the area, about 1%. Down-dip, the enriched layers thin to 0.2 m within about 150 m and contain 4 to 10% heavy minerals. The low-grade margins contain significant proportions of the less-dense minerals garnet, aluminosilicates, and tourmaline. Both stratigraphic and lateral facies margins tend to have more-altered opaque minerals.

Resources in high-grade enrichments as given by Chenowith (1957) are consistent with my view of the continuity of two imbricate lenses, because Chenowith (and Houston and Murphy, 1977) did not use a 6-separate-lense geometry of enrichment as proposed by Bingler (1963). Resources are probably about 700,000 tonnes of contained TiO_2.

Other San Juan basin enrichments (New Mexico and Colorado).-- A swarm of heavy-mineral enrichments in flat-lying Point Lookout Sandstone (lower Campanian) span the boundary of western Colorado and New Mexico, west of Mesa Verde (fig. 1, #2). All but a few are in the Ute Mountain Ute and Navajo Indian reservations (Dow and Batty, 1961).

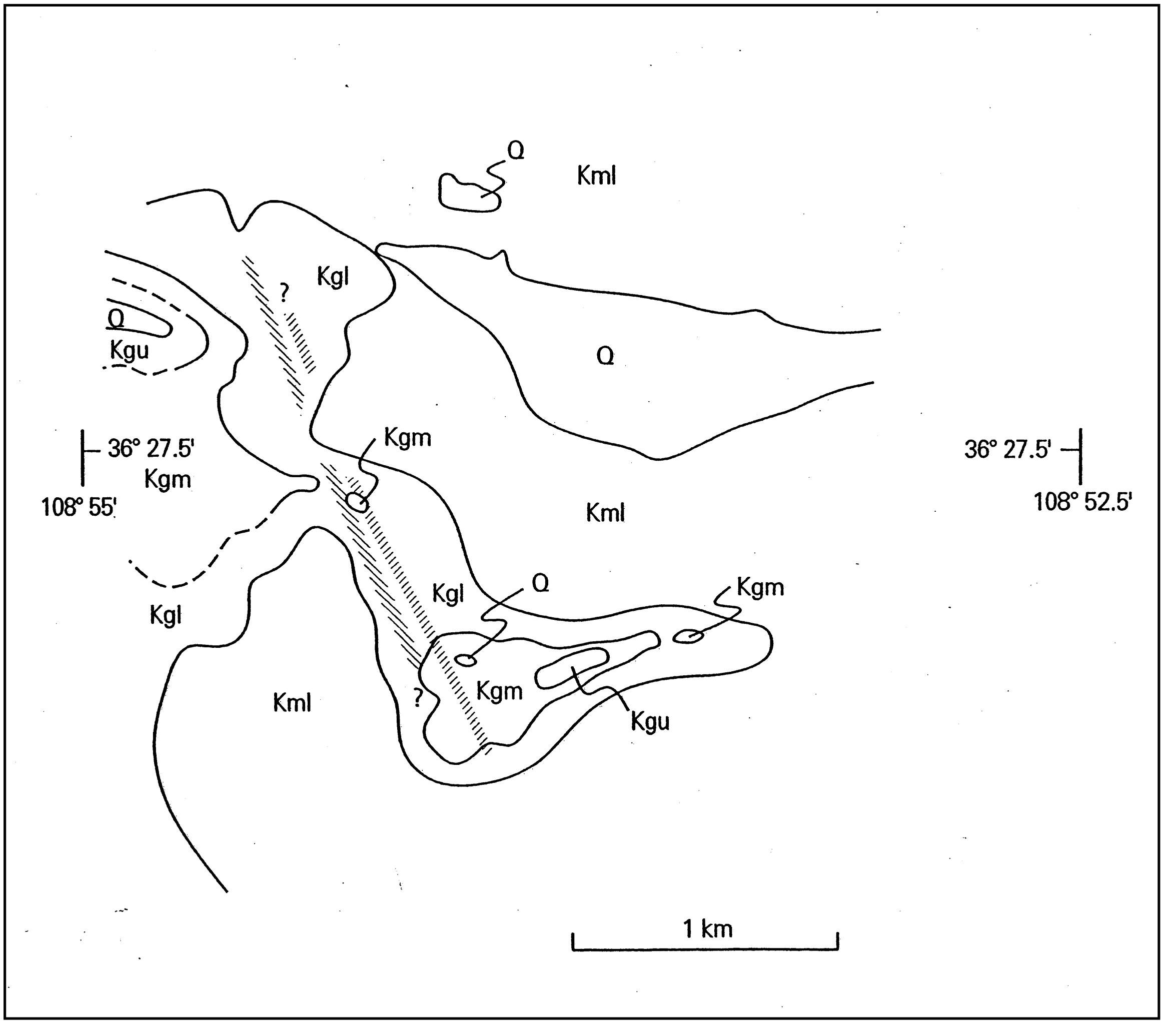

Figure 2. Geologic map of Sanostee mesa, New Mexico, incorporating some information from Beaumont (1954) and Dow and Batty (1959), plotted on Sanostee West 1:24K topographic base. Cretaceous units after Bingler (1963) from the base are Kml, lower Mancos Shale and Kgl, Kgm, and Kgu--lower, middle, and upper Gallup Sandstone, respectively. Much of surficial unit Q is basalt. Patterned units are the two E-facing enrichments, shown where probable in subsurface.

Zech and others (1994) describe the 29 heavy-mineral enrichments in the Ute Mountain Ute Indian Reservation. Their approach was largely chemical, geophysical, and sedimentologic (but without much grain-size information). Enrichments are in the upper shoreface-facies part of the Point Lookout Sandstone, which overlies marine Mancos Shale and underlies fluvial sandstones of the Menefee Formation that are coarser, poorer sorted, and locally carbonaceous. Enrichments are along imbricate NE-facing regressive shorelines oriented N. 55^{o} W. to N. 60^{o} W. Thicknesses of enrichments up to 2.3 m are reported, in individual deposits a few tens of meters wide, locally amalgamated. Strike lengths are less than a kilometer, though the authors hypothesize that some buried extensions would produce strike lengths of more than a kilometer. Some rows of deposits are as much as 2.3 km long. The larger individual deposits might contain 2 x 10^5 m^3 of rock.

Heavy-mineral contents are not listed by Zech and others (1994), though the heavy-mineral assemblage is described as ilmenite-hematite, magnetite, zircon, and monazite. Chemically, enriched samples average 7.9% TiO_2 and 1.45% Zr, with high values of Cr and rare-earth elements. Thorium averages 280 ppm, with Th/U about 5. Houston and Murphy (1962, plate 9) show garnet in these deposits, and heavy mineral contents locally over 50% (their plate 3).

Other deposits in the swarm are described only by Dow and Batty (1961), who also give total resources for the entire swarm (their "Shiprock deposits"). Their total is 693,000 tons of sandstone averaging 2.78% TiO_2 and 0.42% ZrO_2. This miniscule figure is derived in part from their chemical analyses of chip samples, 26 (out of 36) of which showed less than 1.0% TiO_2 and 0.1% ZrO_2. Eighteen of Dow and Batty's low-TiO_2, low-ZrO_2 deposits are represented among the 44 specimens analyzed by Zech and others (1994); all but one of the Zech analyses of these 18 show TiO_2 contents of 4.5% or more. One deposit (#10 in both studies) for which Dow and Batty show 0.5% TiO_2, is represented by 13 Zech analyses, ranging 0.4 to 13.2% TiO_2, averaging 5.0% TiO_2. Total resources of the swarm using the Zech approach could be on the order of 10^6 tonnes of TiO_2 contained in 15 x 10^6 tonnes of rock. This is a serious discrepancy.

My approach is petrographic, because TiO_2 values, though useful in resolving the dispute, may nevertheless give a misleading impression of economic potential. I sampled eight enrichments. Polished sections of most of these specimens show no preserved opaque minerals. The positions of former opaque grains are taken by red hematite and leucoxene in a network of more reflective hematite. Minor magnetite, now altered and marked by trellis leucoxene lamellae, was among the precursor minerals. In samples where ilmenite is preserved, it is as spongy relics. Grades above 10% of discrete and recognizable heavy minerals were not encountered.

My specimens are feldspathic sandstones, locally with appreciable lithic fragments. Heavy minerals are 0.125-0.15 mm average diameter, whereas quartz and K-spar are about 0.2 mm. Enriched horizons are visibly finer grained than surrounding barren horizons. Most but not all enrichments are indurated by iron oxide cement, but such cementation is extremely variable and apparently replaces carbonate. Lower-grade enrichments contain tourmaline, andalusite, and staurolite as well as garnet.

Enrichments typically display Ophiomorpha. The sands immediately underlying enrichments are typically cross-bedded in a way that suggests tidal-channel rather than shoreface deposition. That is, cross-beds are at fairly high angles, in large sets, showing transport to the SE and NW parallel to deposit length due to channel migration, and NE and SW due to tidal action.

I am not disputing the existence of high-grade enrichments with well-preserved heavy minerals in this area, but I do suggest that these form the exception among enrichments mapped by Zech and others (1994). Dow and Batty (1961) may have been optimistic with their resource estimates.

Escalante area, Utah.-- Dow and Batty (1961) described five deposit groups between Escalante and Lake Powell in the Kaiparowits Plateau-Straight Cliffs area (fig. 1, #3). The deposits were not well described until recently (Gloyn and others, 1997). All the deposits are in the John Henry Member of the Straight Cliffs Formation (Peterson, 1969), of Santonian age (Houston and Murphy, 1977), which toward the northern end of the plateau contains several stacked shoreline sand bodies. Heavy-mineral enrichments occur at the tops of shoreline sequences that overlie marine units and are immediately overlain by non-marine units, commonly containing coal beds.

Heavy mineral grades are locally very high; values exceeding 60% are reported by Gloyn and others (1997). Individual enrichments are commonly several meters thick, and typically consist of an upper indurated zone and a lower semi-indurated zone that in several sections is richer in zircon.

Ilmenite, zircon, garnet, staurolite, and minor allanite, monazite, tourmaline, aluminosilicates, rutile, sphene, apatite, chromite, and gahnite are reported by Gloyn and others (1997) from the high-grade concentrations Dow and Batty (1961) report magnetite but Gloyn and others show none. Secondary titania, mostly anatase and brookite, is common in some samples. Total titanium oxide minerals average about 50% and zircon about 25% by weight of the heavy mineral assemblage in high-grade samples. Grain sizes are shown by Houston and Murphy (1962, plate 3) for one "Escalante" sample; the mode for heavy minerals is about 0.1 mm. Dow and Batty give TiO_2 values of 13 to 24% and ZrO_2 values of 7 to 18% of such samples.

I visited the Calf Canyon-Dave Canyon and Mann(-Longshot)-U429 deposits, but have little new to add on the latter (southern) group. Subsequent comments concern only the northern deposit, where Gloyn and others (1997) quote average grades of 21% TiO_2 and 16% ZrO_2, and about 52% of the ilmenite altered to >57% TiO_2 without much secondary anatase-brookite.

The described enrichments form a single body trending N25-30W, extending about 1500 m from Calf to Dave Canyon across a gentle divide (fig. 3). It is at the top of the "G" sandstone of Gloyn and others (1997). Zeller (1973) shows the areal and stratigraphic context.

The enrichment is just east of a monocline-like kink along the eastern limb of the Alvey syncline, separating rocks to the east, dipping 15-20^{o} west, from those to the west

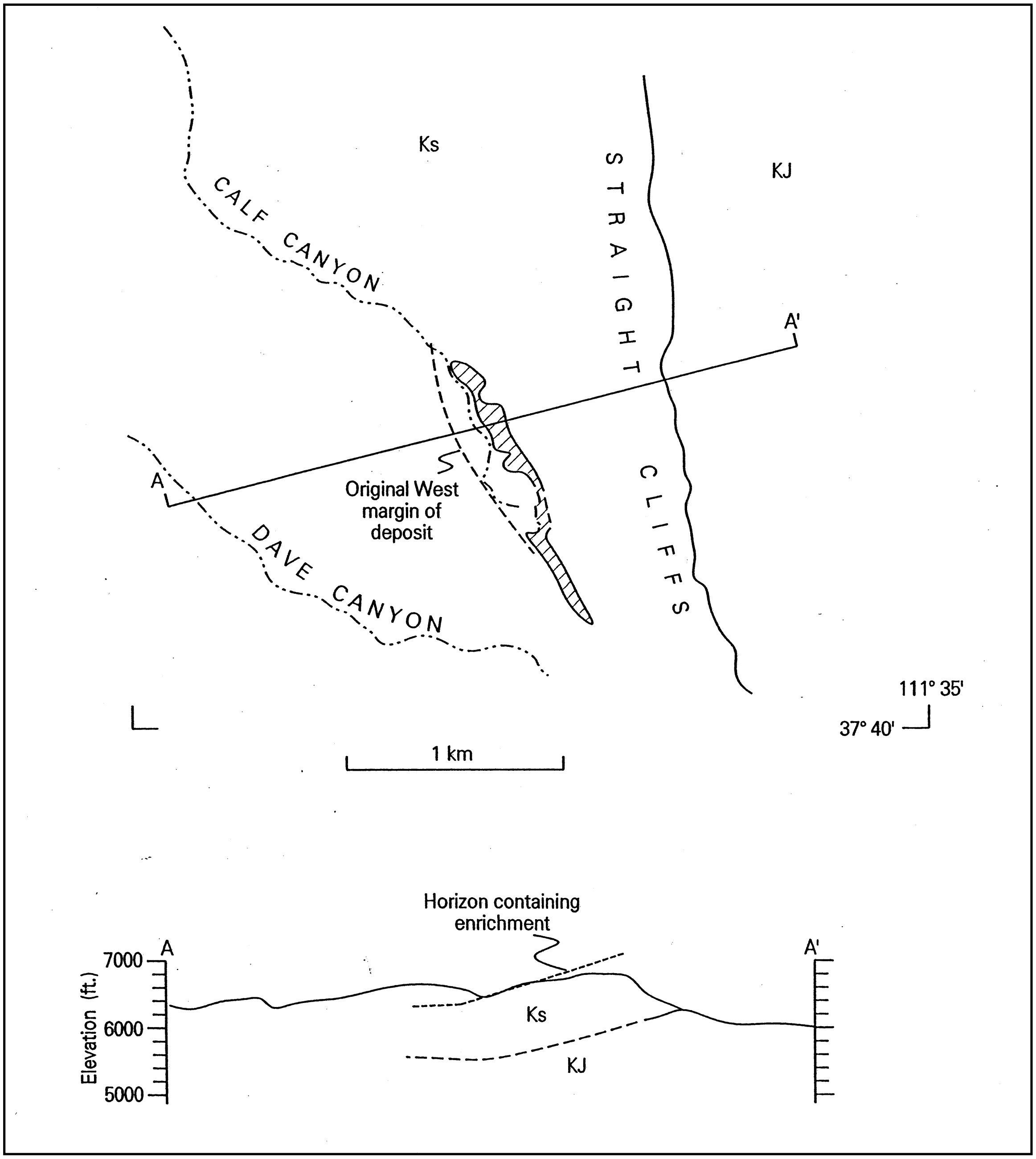

Figure 3. Geologic map and cross-section of the Calf Canyon-Dave Canyon deposit, Utah, plotted on Dave Canyon 1:24K topo base. Enrichment zone shaded; units Ks, Straight Cliffs Formation (and remnants of overlying Wahweap); KJ, underlying Mesozoic rocks, from Zeller, 1973.

dipping about 3^{o} west (Zeller, 1973). Thus the horizon in which enrichment occurs is above the land surface except for a few pinnacle-like outliers to the east, and passes westward into the subsurface (fig. 3), rapidly in the center of the deposit but over a greater distance in Calf and Dave canyons. The enriched zone itself, however, pinches out on its western margin before the horizon becomes concealed (fig. 3).

The steep relief of the canyons has locally given rise to slumping, so that care is required in measuring thicknesses of enriched zones. The thickest enrichment I saw is about 3.5 m, and includes the upper and middle zones of Gloyn and others (1997). Thicknesses decrease both along and across strike, so that an average thickness of high-grade material might be 1.6 m. An average width of enrichment between the erosional east edge and the pinchout along the west edge (fig. 3) is about 100 m. The southern end of the deposit is eroded off. The northern end, however, apparently plunges into the subsurface so the total length is unconstrained.

The stratigraphic context of the deposit is especially informative. Underlying the enriched interval is ostreid-bearing sandstone at least 5 m thick with ripples accentuated by linear calcareous nodules trending S25E. Interbedded thin shaly layers decrease upward and outline 0.2-1.1 m gently dipping cross-sets show transport toward N60E. <u>Ophiomorpha</u> are sparse but increase upward. This unit contains few heavy minerals, but at the top are thin tongues of enriched sand, also dipping N60E. Thus the underlying unit clearly records a shoreface oriented about N30W facing a seaway to the northeast.

Nominally overlying the enriched interval is a thick non-marine section including the Alvey coal zone. Fluvial granular coarse feldspathic sandstone is predominant, but eolian sandstone with high-angle cross-bedding is common. Coal beds were noted only west of the trend of heavy-mineral enrichment, but immediately overlie the western flank of the enriched zone. The coals and their underclays are pyritiferous, so could be lagoonal. Their depositional sites were apparently bounded by enrichments that represent beach deposits, so enrichment probably occurred in a barrier-island environment with coeval or slightly younger lagoon deposits accumulating to the west. The overall regressive sequence shows that non-marine units eventually buried the barrier island and prograded seaward.

The enriched zone itself is everywhere laminated, though an oxidation-induration overprint makes this less obvious in the upper part. Lower-grade interbeds are present in all sections. <u>Ophiomorpha</u> are common. The less-indurated lower enriched zone includes tidal-channel deposits. Imbricated stratigraphically higher enrichments to the east are mentioned by Gloyn and others (1997). I saw none; their occurrence is plausible if the erosional surface passes slowly enough downsection to the east. However, care is required in mapping enriched zones; some overlying zones reported by others proved to be due to iron cementation only.

The Calf Canyon-Dave Canyon deposit is unusual in that its ilmenite is altered without the formation of much anatase-brookite cement (Gloyn and others, 1997) and in that some high-grade enrichments are little-indurated. Probably these two features are related, because in these deposits elsewhere, cements of hematite and/or anatase are commonly derived from ilmenite alteration. The different character of these deposits may be related to anoxic diagenesis, due to the presence of organic matter and pyrite in the immediate environment. Supporting this supposition are pyrite pseudomorphs in the enrichments themselves.

Cretaceous deposits larger than that of Calf Canyon-Dave Canyon are known (table 1). The economic promise of this deposit is likely to lie in its unusual diagenesis (permitting easier cleaner separation of a high-TiO_2 product) and its high zircon content.

Rock Springs uplift, Wyoming.-- A chain of deposits trend N. 30^o E. across the southeastern flank of Rock Springs uplift and the margins of Clay basin to the south, in Sweetwater County, southwestern Wyoming (fig. 1, #4). Dow and Batty (1961) describe 7 individual deposits, Houston and Murphy (1962) describe 3, and Roehler (1989) describes 6, all by different names. I have cracked the code, and find the synonymy as follows (from the south): Red Creek=Richards Gap, Murphy #1=Titworth Gap=Salt Wells Creek, Murphy #2=Camel Rock, Union Pacific (#2)=Brady Road, Zalenka=Black Butte.

In the most recent terminology, that of Roehler (1989), the deposits occur toward the top of the McCourt Sandstone Tongue of the Rock Springs Formation (upper Campanian), over marine shales and under fluvial sandstones, carbonaceous shales, and coal. Enrichments, in *Ophiomorpha*-bearing swash-zone sands, locally underlie eolian or lagoonal deposits, or a weathering surface. Imbrication of enriched zones is not reported, but Roehler noted that the deposits dip eastward more steeply than the foreshore facies that contain them.

Roehler (1989, figs. 7, 22) concluded from deposit distribution and facies assemblages that the chain of deposits represents alternation of barriers and tidal inlets along a single shoreline. Noting that primary dips in sands immediately underlying enrichments are dominantly to the southwest, he suggested that the dips resulted from accumulation in tidal channels from longshore currents toward the southwest.

Thickness of enriched zones is as great as 2 to 3 m; width is as great as 60 m (Dow and Batty, 1961; Houston and Murphy, 1962; Roehler, 1989). Length where measureable is as great as 800 m, but elongation is locally downdip, so that length can not be observed.

The sands are feldspathic and locally contain volcanic-lithic grains. Enriched sandstones have median grain sizes of about 0.10 to 0.17 mm, whereas barren hosts are about 0.15 to 0.20 mm (Houston and Murphy, 1962, figs. 4, 6, pl. 3). The coarsest deposits are those at the NE end of the chain of deposits.

Average heavy-mineral contents of enrichments range from 24 to 55 % (Houston and Murphy, 1962). Heavy minerals include their "ferrian ilmenite" (with 15-46 % TiO_2), zircon, garnet, tourmaline, rutile, monazite, and a few others, but not magnetite (see their fig. 11). The average TiO_2 contents of enrichments vary from 14 to 27 % (Dow and Batty, 1961; Houston and Murphy, 1962). Dow and Batty list average ZrO_2 contents of 1.4 to 3.4%.

My observations indicate that the less-dense minerals staurolite, tourmaline, epidote, and garnet, though minor constituents in the richest concentrations as previous authors show, become significant constituents of low-grade concentrations (as noted locally by Houston and Murphy, 1962). This factor limits the potential of larger, lower-grade deposits.

The original opaque mineral assemblage apparently included both ilmenite-hematite and lesser magnetite. The magnetite now consists of translucent red hematite with ilmenite trellis lamellae. Much of the ilmenite-hematite has been pitted and rimmed by anatase leucoxene. Such leucoxene comprises some entire grains and is present in the matrix also.

The distribution of deposits lends itself to analysis of original continuity. The deposits to the NE crop out along a topographic escarpment nearly parallel to the chain of deposits, with re-entrants at valleys. Roehler (1989) along with "GQ" maps cited therein can be used to surmise that deposits are missing at Titworth Gap itself, north of the Camel Rock deposit, south of the Cooper Ridge deposit, and both north and south of the Black Butte deposit, but probably none missing at Brady Road, i.e. five deposits and five gaps between them over 39 km. In the absence of drilling evidence, we can probably assume a continuation of this spacing and subequal proportion for the 25 km concealed by the Red Creek syncline.

Resources per deposit seem to be on the order of 4 x 10^4 tonnes of contained TiO_2 in 2 x 10^5 tonnes of deposits. Resources for 64 km of the chain could total 3.6 x 10^5 tonnes of TiO_2.

Grass Creek anticline (Big Horn basin), Wyoming.-- These deposits, in Hot Springs County in the northern part of Wyoming (fig. 1, #5), are thought to be among the largest in the state (Houston and Murphy, 1962). The northern deposit is well exposed in sandstones toward the base of the Mesaverde Formation (upper Campanian), between Cody Shale below and non-marine parts of the Mesaverde above. Houston and Murphy described enrichments as much as 4.9 m thick, over an area as much as 200 x 1700 m. They found that heavy mineral content averages 30% and average TiO_2 content is 16%. Average figures given by Dow and Batty (1961) are 2.4 m thickness over 90 x 1130 m, and 21.5 % TiO_2.

Houston and Murphy (1962) conducted some detailed mineralogic work on this deposit via x-ray diffraction, polished sections, and titanium content as a function of magnetic susceptibility. They found that heavy fractions average 78% opaque minerals, consisting mostly of "ferrian ilmenite", containing 24 to 36% TiO_2, variably altered to rims of anatase, rutile, hematite, and goethite. Other detrital minerals include zircon (18%), garnet, tourmaline, rutile (1%), and monazite. The modal grain size of high-grade enrichments is about 0.10 mm, i.e. very fine sand, whereas for barren samples the mode is about 0.15 mm.

The north and south deposit define a trend of the former shoreline of about N. 15^{o} W. across the anticline, the intermediate part having been eroded. This trend is the same as that of enrichments within the north deposit. The cliff exposures, however, trend about

N. 30^o W., and thus are an oblique cross-section of the deposit. Heavy-mineral-enriched rocks actually form imbricated lenses averaging about 2 m thick, facing southeast, that dip to the east an average of 4.8^o steeper than underlying shore-face deposits (total n=15). This suggests regression or progradation of the shore toward the seaway to the east.

Enrichments are found at the top of massive feldspathic sandstone about 25 m thick, above flaggy sandstone with shale partings about 15 m thick, showing ripples trending N. 8$\pm$5^o E. The ripple trend probably is normal to incoming storm waves from the east, which thus suggests a northward longshore current along the NNW-oriented coast. These rocks are poor in heavy minerals, but contain minor glauconite.

At the north end of the north deposit, heavy-mineral enrichments rest on sands with high-angle cross-sets indicating transport toward N. 60^o E. and due south. These are probably tidal-inlet fills.

Immediately overlying the enrichments are carbonaceous shales and calcareous fine sandstone with linguloid ripples. About 10 m higher are lignites, underclays, and sandstones with wispy clay lenses and plant impressions.

Imbricate enrichments are separated by low-grade septa that in one case is coarser-grained sand 0.6 m thick. The septum is gradational into the lower enrichment but channelled by the upper enrichment, i.e. it formed by progradation as storm activity waned but was eroded in the next storm. Locally, septa-like sands are the uppermost part of the sequence and thicken eastward. Both enrichments and septa display the trace fossil Ophiomorpha . Some branched forms parallel to bedding may be Thallassinoides.

An unpublished plate in the USGS titanium files, apparently prepared for the Houston and Murphy (1962) report, shows TiO_2 contents of six "barren" as well as enriched sands. These sands, two overlying the heavy-mineral enrichments, two septa, and two underlying sands (0.6 and 0.9 m below enrichments), all contain 2 to 9% TiO_2, averaging 5.6%.

High grade enrichments are magnetic in their central portions, and contain zircon and rutile. Margins and pinchouts of such enrichments are weakly magnetic due to greater alteration to hematite and anatase. All the enrichments are cemented by iron and titanium oxides; anatase cement is locally quite coarse.

Petrographic descriptions of opaques by Houston and Murphy (1962) emphasize variations in alteration with magnetic susceptibility, but perhaps do not sufficiently evoke the extreme variability within single specimens. Opaque minerals in single polished thin sections vary from completely altered red translucent oxides, through fresh "ferrian ilmenite" cores rimmed by translucent mixtures of red oxides and porcellaneous white oxides, to fresh "ferrian" ilmenite grains. All of these are commonly well rounded. Original sub-planar intergrowths in the ilmenite have mostly been etched out or altered, so that homogeneous ilmenite remains. No suggestion of trellis-type magnetite-ilmenite intergrowths is present, nor are fresh magnetites apparent. However, probably martitic hematite is common. About half of the opaque-mineral population consists of grains with little coherence.

The granular variability is probably the result of two factors. First, the detrital mineral assemblage was apparently disparate, including homogeneous "ferrian ilmenite",

ilmenite-hematite exsolution intergrowths, and magnetite$\pm$martite. Secondly, the weathering history of opaque grains already differed at the time of deposition, such that already-altered grains could become well-rounded. For example, some of the hematite is apparently pre-depositional, as shown by smooth rounded grain surfaces.

Total resources of the Grass Creek area are not published, but average dimensions and grades listed above by Dow and Batty (1961) and Houston and Murphy (1962) imply 1.6×10^5 and 7.9×10^5 tonnes of contained TiO_2, respectively. William H. B. Graves (written commun., 1991) lists reserves more consistent with the latter figure. For this deposit as with all the Cretaceous deposits, the recoverability of the ilmenite is a potential problem due to the induration of high-grade horizons and the local lack of grain cohesion.

Depositional summary.-- The Cretaceous deposits show us a few details of the stratigraphic development of shoreline heavy-mineral enrichments that can not be studied in modern deposits. All the deposits formed along regressing shorelines; they overlie fine-grained marine units and underlie non-marine units. In greater detail, the deposits form the upper parts of sand units that progress upward from lower to upper shoreface environments. All these facies are commonly well exposed.

Individual components of the depositional environment can be related to paleogeography of these deposits, and their orientations and evolution established. For example, in the Calf Canyon-Dave Canyon deposit of Utah, facies can be related to each other either in a progradational stratigraphic sense or in a time-slice sense revealing a lagoon, a barrier island, and a shoreface. My observations suggest that tidal-inlet deposits actually form a greater proportion of sands under the heavy mineral deposits than is suggested by their descriptions in the literature (with the partial exception of Roehler, 1989). However, this relation is well described in modern shoreline deposits (cf. Hoyt and Henry, 1967)

Some regional paleogeographic information can be gleaned from the deposits also, as first noted by Houston and Murphy (1977). For example, the coeval Grass Creek and Rock Springs districts were apparently both deposited under the influence of waves from the east, but because the shorelines in the two districts were oriented differently, opposite longshore current directions prevailed. A late Campanian headland is required between them, consistent with grain-size trends within the Rock Springs district (and Gill and Cobban, 1973, fig. 14).

At an even larger scale, individual shoreline trends characteristic of different stages of the Upper Cretaceous can be traced virtually from Canada to Mexico. On figure 1, the deposits described above, and many other shoreline deposits noted by Houston and Murphy (1977), are plotted as a function of age (from their table 1). Coeval deposits form discrete shoreline trends. Shoreline maps of Gill and Cobban (1973) using even more finely subdivided ammonoid ages show that trends on figure 1 are probably slightly diachronous. If so I have mapped moving loci of heavy mineral concentration within individual transgressive-regressive wedges. Either way, such maps are potential exploration tools—intersections of heavy mineral concentration loci with appropriate geologic map units can be examined in currently unexplored mountain ranges.

Mineralogic summary.-- Magnetite has not been encountered in many of these deposits, yet the freshest high-grade enrichments are highly magnetic. In Wyoming, Houston and Murphy (1962) showed that the dominant opaque mineral in the Cretaceous sands is a homogeneous "ferrian ilmenite". Their data and that listed above shows that the same mineral is characteristic of the Cretaceous shoreline sands from northern New Mexico to southern Montana, and from the upper Turonian to the lower Maastrichtian, i.e. most of Late Cretaceous time, but varies in proportion to other opaque oxides (table 2).

The magnetism described by Houston and Murphy (1962) is too great for ordinary ilmenite, and the Fe_2O_3 content they determined (at Grass Creek only) is too high. Figure 4 shows that the composition corresponds to hematite and ilmenite in solid solution in the approximate ratio hem45ilm55. Such medial hematite-ilmenite is quite magnetic at room temperature (Akimoto, 1957; Nagata, 1961), and the variation in magnetic susceptibility as a function of composition in the Cretaceous sands (from data in Houston and Murphy, 1962, table 5) matches their curves closely. Thus the opaque minerals of the enriched Cretaceous sands include a phase thought to be unusual and with anomalous magnetic properties.

Opaque minerals with these properties have been noted in other Upper Cretaceous sands of the region, however. In a paleomagnetic study, Butler and Lindsay (1985) showed in the San Juan basin that similar medial hematite-ilmenite solid solution is the dominant producer of magnetism in sandstones spanning the Cretaceous-Tertiary boundary. Zech and others (1994) reported magnetic hematite-ilmenite in the Upper Cretaceous of the San Juan basin also. Reynolds (1977) described detrital magnetic hematite-ilmenite from Jurassic rocks of the San Juan basin and Cretaceous rocks of southern Wyoming. Butler in Force and others (in press) found this mineral in Cretaceous-Tertiary boundary sections of Wyoming and Montana. It seems possible, therefore, that medial hematite-ilmenite in solid solution is very common in the region and has been misidentified as magnetite.

The new identification of this opaque mineral has implications for source rocks. Hypersolvus intermediate hematite-ilmenite implies temperatures of over 670^{o} C. (Ghiorso and Sack, 1991) and occurs in volcanic rocks, mostly of intermediate composition (Frost and Lindsley, 1991). The presence of a population of detrital Late Cretaceous zircons in the same enriched sandstones in Wyoming (Houston and Murphy, 1962) shows that contemporaneous igneous activity was one component of mineral supply. More information on the distribution of the hematite-ilmenite grains in space and time is needed to specify sources, but their diagenetic stability relative to magnetite suggests that they can be recycled.

The opaque mineralogy also has implications for separation and recovery method. This titanium-bearing phase is the most magnetic in the rock, and can be separated with low-intensity magnets, rather than those used for normal ilmenite. It is sufficiently low in TiO_2 that a smelting, rather than a chlorination, recovery method is indicated. Indeed, the smelting method was originally developed for hematite-ilmenite grains of a similar bulk composition (from Quebec).

The proportion of medial hematite-ilmenite decreases relative to more stoichiometric ilmenite from north to south (table 2). In addition, the degree of TiO_2

Table 2. Relative proportions (in wt %) of opaque oxide minerals in some Cretaceous shoreline placer deposits, estimated from data in Houston and Murphy (1962, fig. 9, table 5, and plate 3), Gloyn and others (1997, table 2), and my own polished-section observations.

	Medial hematite-ilmenite ss.	Ilmenite (45-57% TiO_2)	Altered ilmenite (>57% TiO_2)	Other
Sanostee (NM)	5	35	40	20
Escalante (UT)	10	38	52	--
Rock Springs (WY)	35	49	--	16
Grass Creek (WY)	77	15	8	--

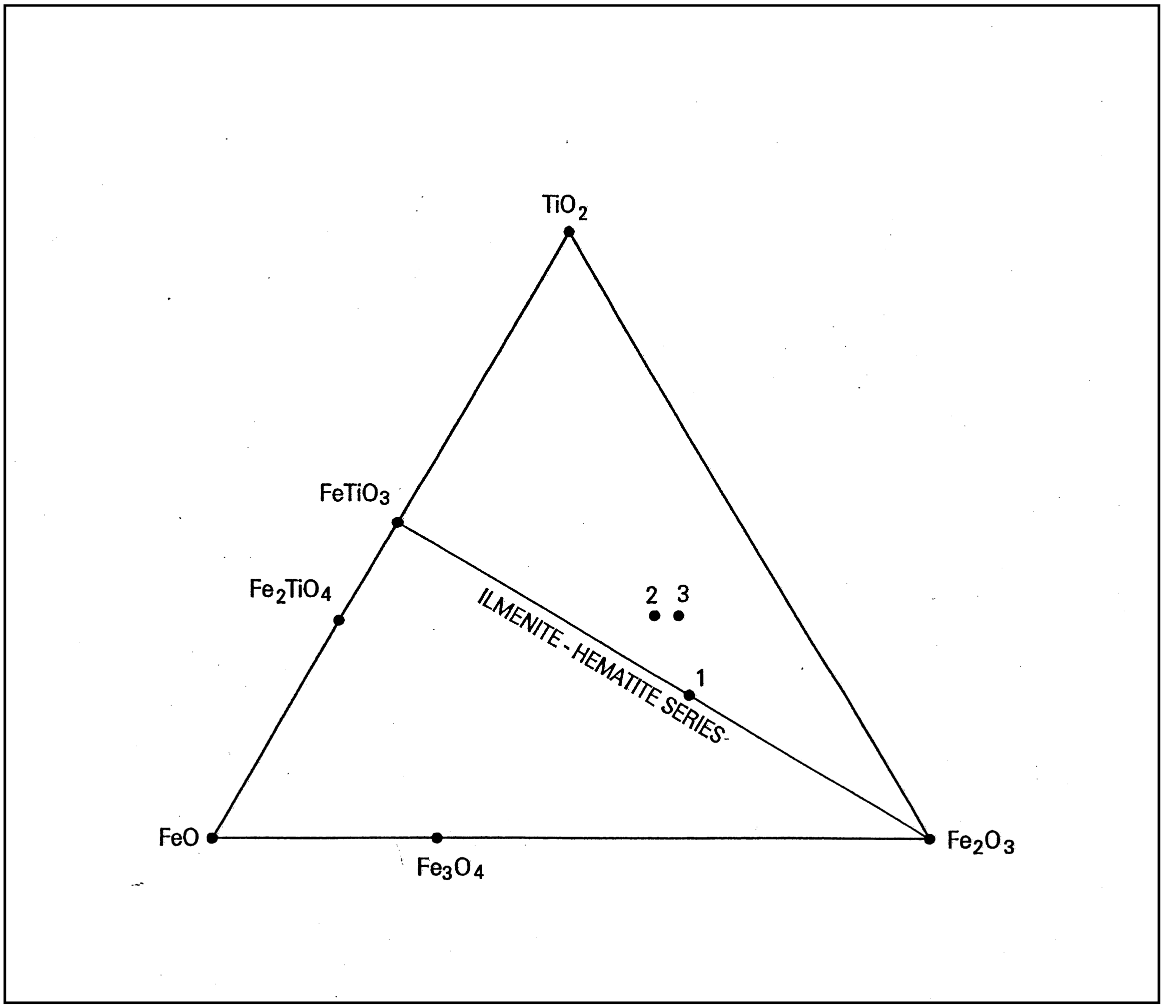

Figure 4. Compositional diagram for opaque minerals in the Grass Valley placer, from data in Houston and Murphy (1962), plotted in weight percent. The numbered fractions are 1) ferromagnetic, 2) separated at 0.05 amp, and 3) 0.1 amp. See also Force and others (in press) fig. 5.

enrichment due to weathering of ilmenite seems also to increase to the south, a phenomenon observed in younger shoreline deposits also (reviewed in Force, 1991a, see fig. 53).

Zircon contents generally increase southward in the Cretaceous deposits, but reach their highest observed values in the Escalante deposit (Houston and Murphy, 1962, plate 9). Garnet is higher toward the south also, especially at Sanostee. Otherwise the suite of transparent heavy minerals is similar in all the deposits, and vary together in relative abundance, inverse to total heavy-mineral percentage. Few of these minerals are labile, yet all the enrichments occur in feldspathic sands, locally with cherty and/or volcanic grains.

Thus the sands on the western shore of the Cretaceous interior seaway are not quite as mineralogically mature as most titanium-mineral placer sands, including those on the eastern shore of the same seaway (cf. Wilcox, 1971). Nor did source areas supply as valuable a mineral suite as in many other provinces (reviewed by Force, 1991a). The western sands acquired a suitably restricted mineral suite only where hydraulic concentration weeded out less-dense minerals. Low-grade margins of deposits have less attractive assemblages.

Diagenesis of primary mineral assemblages is extensive in most deposits, and preferentially attacks the marginal low-grade material. This diagenesis produces weaker grains but stronger cements, compromising grain recoverability. Locally, reducing diagenesis may better preserve primary assemblages and grain morphology.

Resource summary.-- Generally speaking, the Cretaceous shoreline placers constitute small, high-grade deposits enveloped in nearly-barren deposits with less-favorable mineral assemblages. The sizes of individual deposits are such that though some may prove valuable, this deposit type will probably not become significant among world titanium-mineral resources.

The combination of variable amounts of an unusual opaque oxide phase and variable diagenesis and cementation makes the resource potential of individual deposits as much a matter of recovery technology as of geology, and quite different from each other. Our end members are 1) the Sanostee deposit with mostly-normal ilmenite in discrete grains that could survive a well-designed separation procedure, 2) The Grass Creek deposit with primary medial hematite-ilmenite variably altered to high-TiO_2 products including coarse anatase cement, suggesting one smelter product and one valuable "leucoxene" product if separable, and 3) the Escalante deposit, unindurated parts of which can be separated in the conventional manner.

Ione basin, California

By Eric R. Force and Scott Creely

The Ione Formation (lower to middle Eocene) near Ione, California (fig. 1, #6) is a major source of silica sand, refractory clay, specialized lignites, and other materials for

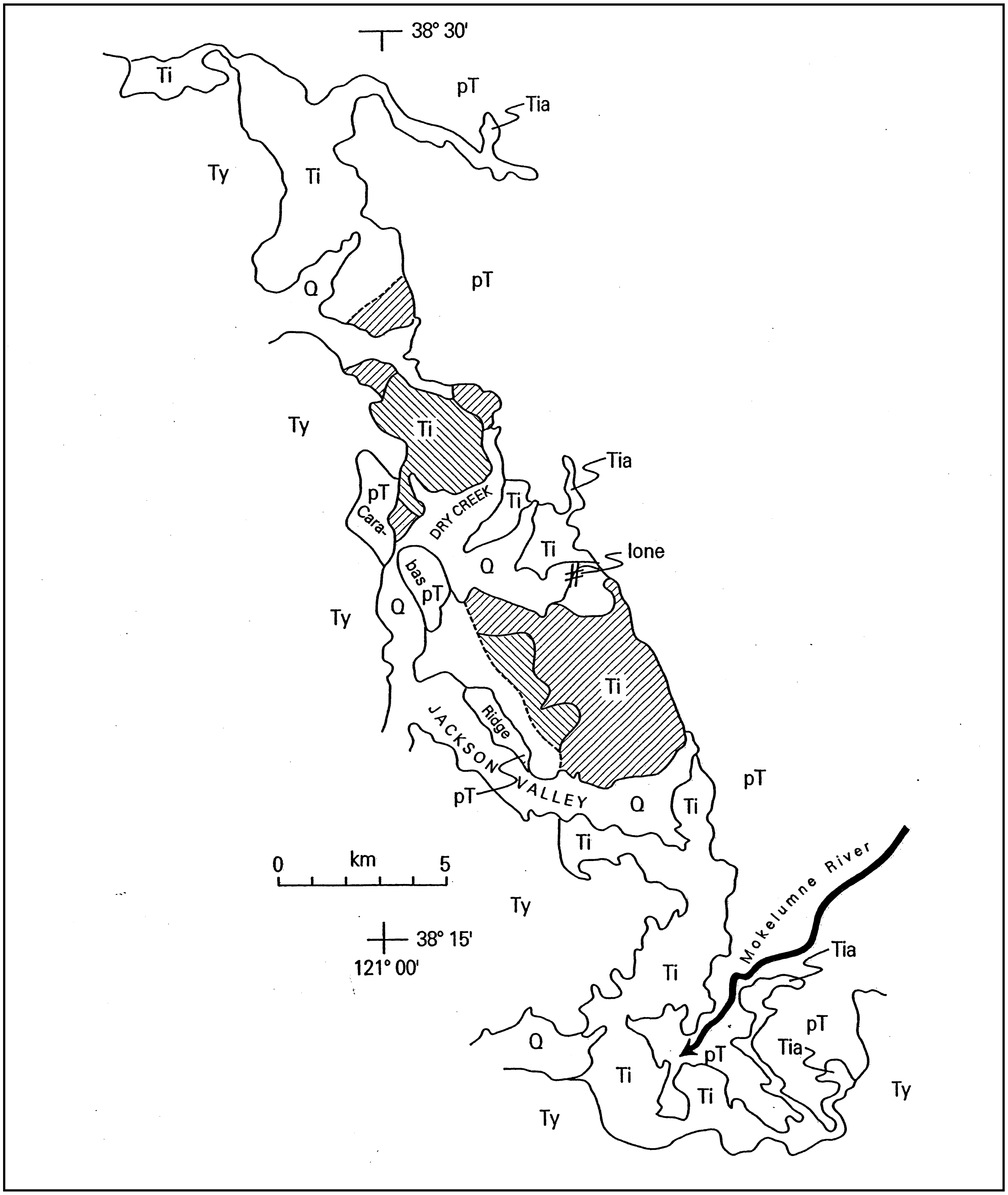

Figure 5. Geologic map of the Ione area, California, generalized but unmodified from Bartow and Marchand (1979) and adjacent Valley Springs and Clay quadrangles. Shaded area is approximate outcrop area of Ione sand; in patterned area it is present in subsurface. Units (from oldest to youngest) are: pT, pre-Tertiary bedrock; Ti, Ione Formation including Tia, "auriferous gravel" facies; Ty, younger Tertiary units; Q, Quaternary.

the western U.S (California Division of Mines, 1956). Its outcrop belt defines the margin between the Great Valley and the Sierra Nevada foothills for 300 km, as the west-dipping unit commonly is the basal sedimentary unit resting on Sierran bedrock. In the Ione area, the formation is the main fill of a discrete basin between Sierran bedrock and the mostly-buried Carabas paleo-ridge (fig. 5) and is the subject of a comprehensive separate study by the authors.

Previous descriptions of the Ione Formation include Allen (1929), Bates (1945), Pask and Turner (1952), Chapman and Bishop (1975), and Wood and others (1995). Recent geologic maps of the basin are by Bartow and Marchand (e.g., 1979). The formation rests on lateritic bedrock and local fill of older Eocene channels and is overlain by the volcaniclastic Valley Springs Formation (upper Oligocene and lower Miocene). The Ione is up to 200 m thick, and consists mostly of kaolinitic clay, clayey sand (notably including crystalline kaolinite grains locally called anauxite), sand and sandstone, locally feldspathic, and lesser conglomerate and lignite. Most of the rocks of the Ione Formation are bleached (though locally iron-stained), and all reflect intense weathering at the source and/or during deposition.

Basinal Ione Formation sediments and underlying channel fills together correlate broadly with and grade into the Eocene auriferous gravels (fig. 5) of the Sierra foothills, formerly the main source of placer gold (Lindgren, 1911). Indeed, our study was spurred partly by a desire to link deposition of gold and other heavy mineral resources, and tie them to concepts of basin-margin rotation (Force, 1991b)

Heavy-mineral content of Ione Formation sand ranges in our measurements from less than 0.1% to more than 4%, varying with grain size of the sand, stratigraphic position, location in the basin, etc. Host sands are micaceous, variably feldspathic, and locally rich in clay chips (Pask and Turner, 1952; Wood, 1995). Quartz grains are remarkably angular. Heavy mineral assemblages are mature and homogeneous. Generally the order of abundance everywhere is ilmenite >zircon> tourmaline = andalusite > rutile (cf. Allen, 1929; Morris, 1962). Minor allanite and/or staurolite is common in our specimens; Morris reports a little corundum, garnet, and chromite. Allen records sillimanite. The presence of trace amounts of monazite is suggested by chemical analyses of Wollenberg and Dodge (1973). Labile heavy minerals such as epidote and magnetite are absent in our specimens except toward the base of the section at the extremities of the study area.

Morris (1962) found opaque minerals (+leucoxene) to constitute 65-75% of the heavy mineral assemblage (by number in sized fractions). Our polished sections show that ilmenite is the predominant opaque mineral, commonly as pitted grains suggesting precursor intergrowths with hematite. Skeletal ilmenite suggestive of precursor magnetite-ilmenite trellis textures is less common. Secondary hematite-TiO_2 alteration is strong in some specimens.

Titanium-mineral resources of the formation occur as potential by-products of silica sand mining (Gomes and others, 1979). These silica sand operations are in a fine-grained sand unit (locally a little feldspathic) of the northern part of the basin, which has been referred to as the Ione sand. We find this unit to be marginal marine (Creely and Force, 1999).

Figure 5 shows the generalized distribution of Ione sand in the broad sense) in outcrop and subsurface, an area of about 50 km^2. To the west (downdip) it pinches out against the Carabas paleo-ridge. To the east it commonly laps against the bedrock contact, i.e. the unit originally extended eastward. Correlation of the unit south of Jackson Valley and north of Dry Creek is unclear, but similar marginal marine sands are present north of Dry Creek. Thickness of the unit is as much as 30 m in the areas of current silica mining (Gillam, 1974), but average thickness is probably about 10 m, taking into account its partial erosion where it is exposed (fig. 5). Thus the total volume of Ione sand is probably on the order of 5×10^8 m^3, including areas where it has been mined.

Heavy mineral content varies as much in Ione sand as elsewhere in the basin, locally reaching 4.3%, but seems to average about 1% in our samples. The heavy mineral assemblage is the same as elsewhere in the formation. Gomes and others (1979) showed that ilmenite in the Ione Formation is altered partly to pseudorutile and typically contains 63.5% TiO_2. Their figures imply that such ilmenite constitutes 78% of the heavy mineral fraction, the remainder being mostly zircon.

Ione sand could thus contain approximately 7×10^6 tonnes of altered ilmenite, some of it already in heavy-tailings piles. The viability of this resource is highly contingent on the extent of sand mining and efficient heavy-mineral separation. Zircon, aluminosilicates, and possibly gold are prominent co-product possibilities.

Idaho fluvial placers

Deposits of ilmenite, magnetite, garnet, sphene, monazite, columbite, and euxenite in fluvial deposits derived from the Idaho batholith are well documented. Storch and Holt (1963) review titanium-mineral aspects of these deposits, originally described on a stream-by-stream basis, mostly as monazite deposits in Atomic Energy Commission reports from the 1950's.

The deposits are widespread through the area of granitoid rocks of the Cretaceous batholith. Schmidt (1964) showed that the distribution of monazite and of ilmenite in source rocks is not the same. Monazite is enriched along the west side of the batholith whereas ilmenite is more common to the east. However, the deposits with greatest volume and average heavy mineral content are along the western margin of the batholith, in western Valley County, in tributaries of the north fork of the Payette River, near Cascade and the Long Valley (Storch and Holt, 1963). I therefore selected this area for further work (fig. 1, #7).

Ilmenite commonly contains 45-47% TiO_2 in this area. Fe_2O_3 is commonly 10-13% (Storch and Holt, 1963), suggesting hematite intergrowths. The ilmenite fraction also contains niobium. The range in average ilmenite grade, listed as pounds/$yard^3$, converts to approximately 0.1 to 0.35 %. Thus these are resources only on the basis of possible by-product recovery. Monazite was mined in the area from 1950 to 1955, but demand for monazite is currently very low. Zircon recovery has apparently not been considered, and in my opinion its concentrations have been underestimated.

Sampling reported by Storch and Holt (1963) was conducted largely by churn drilling in valley sediments consisting of clay, feldspathic micaceous sand, and gravel. I find that granular coarse to medium sand, locally pebbly, is the most important host of medium- to fine-sand-sized heavy minerals.

Deposit volumes per se are not reported, but the description as valley-bottom fill in bedrock drainages implies little volume. However, based on subsequent mapping and my own work, this is emphatically not the case. Instead, the hosts of heavy mineral deposits include the tilted fills of fault-bounded older basins (cf. Schmidt and Mackin, 1970). Basin geometry is thus the primary control on deposit volume, and deposit volume is currently unconstrained.

Figure 6 relates geology to areas explored for monazite in this area. Faults separating basin fill from granitoid rocks and their regoliths strike north to N. 30^{o} E. and are steep. They can form either eastern or western margins of basins. Basin fill adjacent to the faults is more immature and locally derived than toward basin interiors. Basins are elongate parallel to the bounding faults, and two main basins are present, a Long Valley basin and a Horsethief-Scott basin. Both faults and unconformities locally form basin margins. Dips of basin fill are 10 to 20^{o} to either the SE or NW from Corral to Pearsol creeks, and are recorded by clay layers. The basin fill, shown as "QTd" of early Pleistocene or Pliocene age by Schmidt and Mackin (1970), is preglacial, and thought by them to be similar to deposits underlying Columbia River Basalt. It may correlate with the Payette Formation (middle and upper Miocene) found in a similar mini-basin about 30 km to the south (Fisher and others, 1992). Thus in figure 6 I show them as Tertiary.

Churn drillholes reported by Storch and Holt (1963) vary in significance (fig. 6). In some valleys (Beaver, Pearsol, Corral), most of the holes were drilled in basin fill. However, in other valleys (Big, Scott, Horsethief, Gold) the reported resource consists mostly of valley fill. Many holes collared in valley fill probably include older basin fill or regolith at depth.

Thus an important question concerns possible systematic differences in mineral grades and assemblages between basin and valley fill. The basin fill is pre-glacial and thus contains a more mature heavy-mineral suite with higher grades, as noted by Schmidt and Mackin (1970). My calculations based on partitioning the drillholes reported in Storch and Holt (1963) between "QTd" and younger units on the map of Schmidt and Mackin gives an average total heavy mineral grade for 111 holes in basin fill of about 0.25% (13.9 lb/yd^{3}), ilmenite constituting about 0.2% (11.8 lb/yd^{3}). These values vary by factors of about two in different parts of the Long Valley basin. Valley fill varies about as much but in different ways; the average of total heavy minerals is considerably less than that of basin fill in the Beaver and Pearsol Creek areas but slightly greater in Corral Creek. Ilmenite as a percentage of heavy minerals is everywhere greater in basin fill, in part due to lesser magnetite and garnet. The TiO_2 contents of ilmenite concentrates reported by Storch and Holt from areas dominated by basin fill are 46-47%, a little higher than the values for valley fill (45-46%).

Staatz and others (1980) calculated monazite resources from churn drillhole and other data, but used conservative assumptions on deposit volume assuming they were

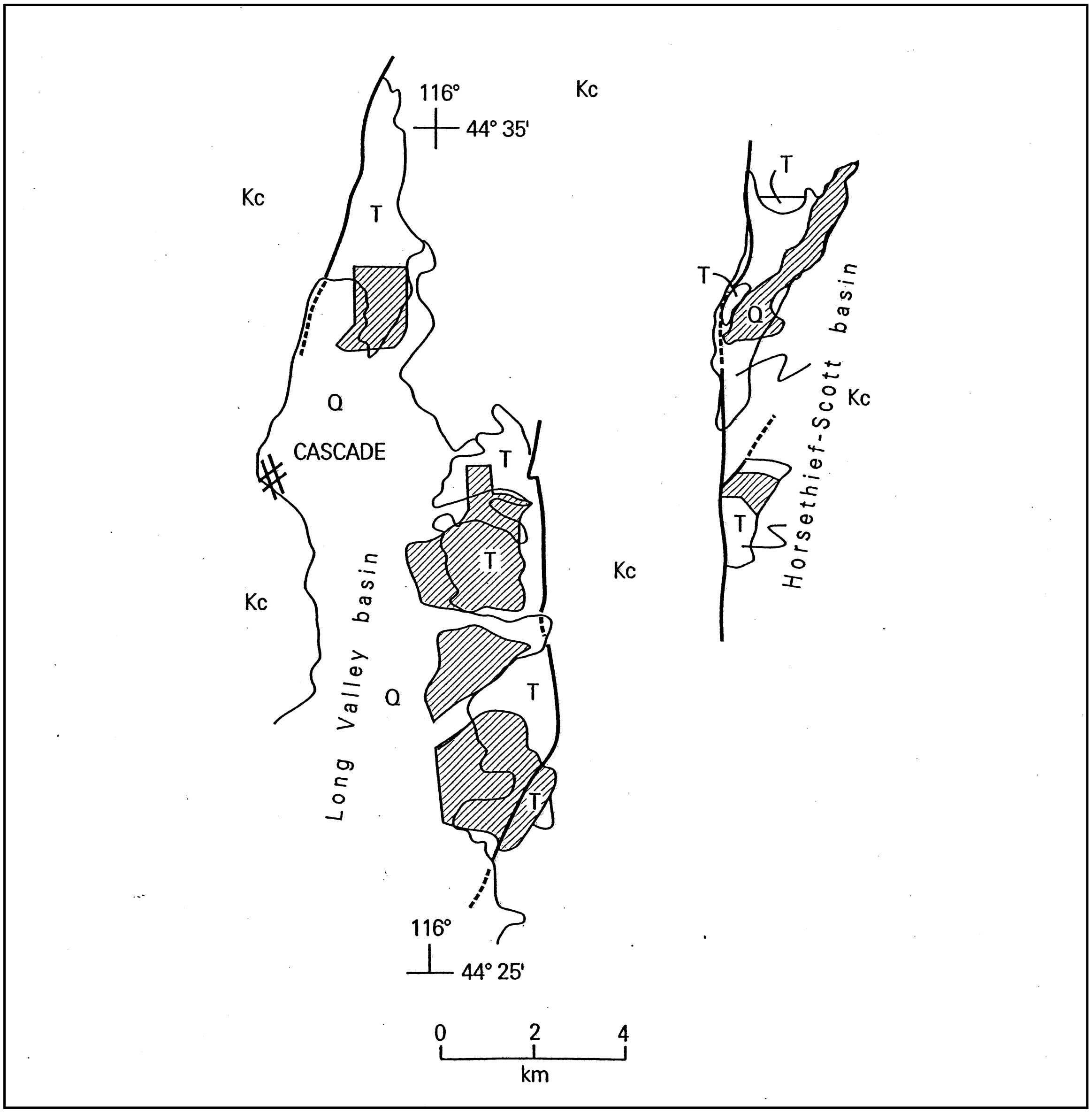

Figure 6. Geologic map of the Long Valley area, Idaho, simplified and very slightly modified from Schmidt and Mackin (1971), showing areas (shaded) drilled for monazite (reviewed by Storch and Holt, 1963). Units are Kc, crystalline rocks; T, pre-glacial basin fill as described in text; Q, Quaternary valley fill. Heavy lines are faults that bound T unit.

valley fill. Heavy mineral resources in basin fill can not be specified, because only two drillholes (of 204, as deep as 43 m) hit bedrock. Obviously, fault-bounded basins may contain large volumes of deformed fill. The gravity survey of Kinoshita (1962) suggests that basin fill is a minimum of 600 m thick in the part of the Long Valley described here.

Anorthosite-related deposits

Deposits of this type, responsible for a considerable share of world and U.S. titanium-mineral resources, are uncommon in the western U.S. Accordingly I adopted an adventurous approach in investigating two possibilities of this type.

Eastern Transverse Ranges, California.-- Magmatic ilmenite resources in the western San Gabriel Mountains of southern California are well documented (Carter, 1982a; Force, 1991a). Anorthosite and related rocks that host these deposits (Crowell and Walker, 1962; Carter, 1982b) extend eastward but are cut by the San Andreas fault. The same rock suite was recognized by Crowell and Walker in the Orocopia Mountains of the Eastern Transverse Ranges (ETR), where they describe some ilmenite-rich mafic rocks. Elsewhere in the ETR similar rock suites were mapped by Powell (1981, 1982, 1993). However, the titanium-mineral potential of these rocks east of the San Andreas fault seems not to have been addressed directly.

Massive anorthosite has been found only in the Orocopia Mountains, about 15 km from the San Andreas (fig. 1, #8). However, rocks described as mangerite-jotunite, syenite, and granulite by Powell (1981, 1982, 1993) elsewhere in the ETR are associated with Orocopia anorthosite, and correspond to host rocks of ilmenite deposits in the San Gabriel Mountains (Carter, 1982b). Thus these rocks should have some titanium-mineral resource potential. I inspected the jotunite-mangerite units where Powell mapped them in the Eagle, Chuckwalla, and Little Chuckwalla Mountains (fig. 1, #9), and anorthosite, diorite, gabbro, and syenite where Crowell and Walker (1962) mapped them in the Orocopia Mountains.

The Orocopia Mountains contain the most complete lithologic assemblage, so will be described first. Pre-anorthosite gneissic leucogabbro-mangerite and syenite are megacrystic, containing plagioclase or mesoperthite. The original mafic mineral assemblage has been retrograded to epidote-clinozoisite, chlorite, and actinolite. Opaque minerals are rimmed or replaced by biotite and sphene. Anorthosite is virtually monomineralogic plagioclase without intergrowths, locally altered to epidote, and contains minor sphene. Post-anorthosite ferrodiorite is massive and equigranular. Primary minerals include mesoperthite, myrmekite, apatite, and mafic minerals now extensively uralitized Cross-cutting relations are common and are described at numbered localities of figure 7.

The anorthosite forms the core of an elongate dome, and adjacent rocks apparently form a synform west of it (fig. 7). A few grains of rutile are present along the contact of anorthosite with gneissic leucogabbro-mangerite. The axis of the syncline, in megacrystic leucogabbro-mangerite gneiss, was closely examined because nelsonitic rocks commonly form in such synclines (Roseland, VA; Cheney Pond, NY; reviewed in Force, 1991a). A

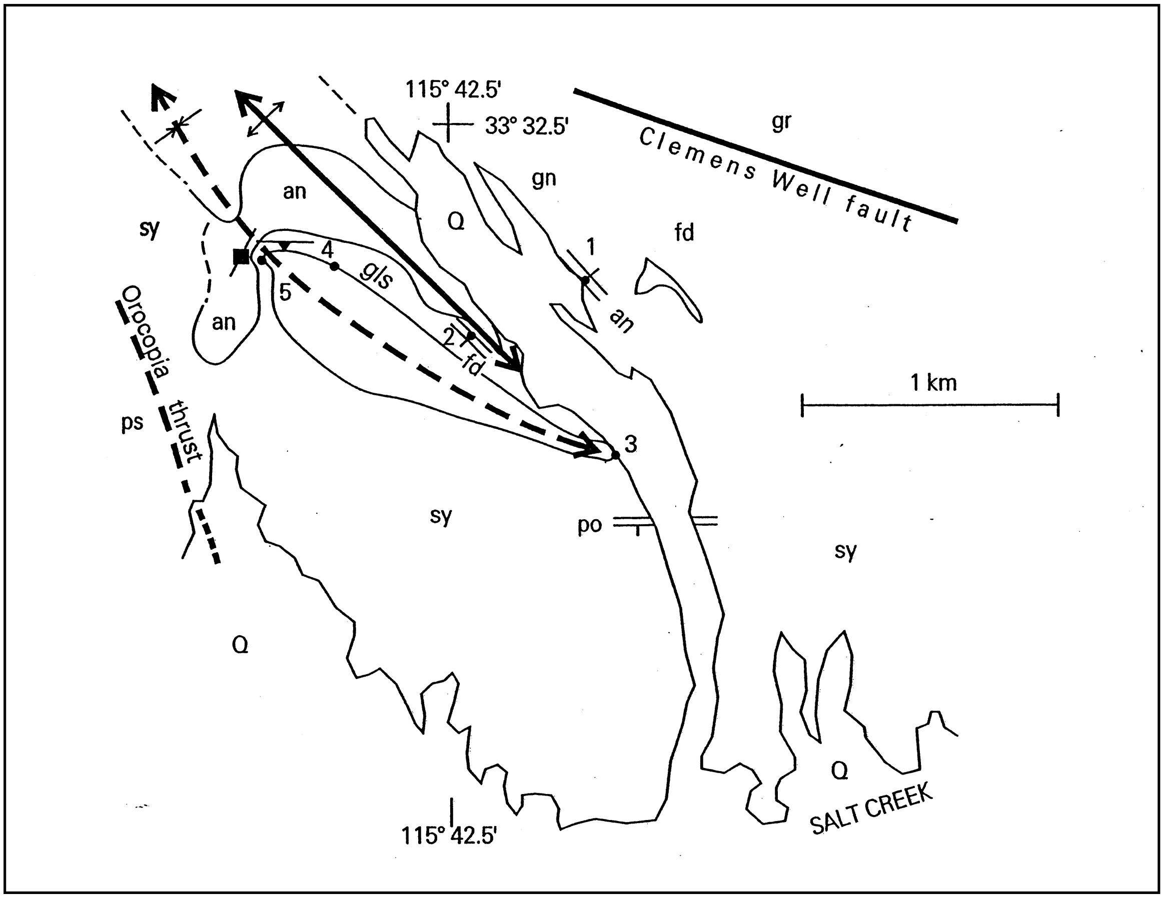

Figure 7. Geologic map of anorthosite and related rocks, southern Orocopia Mountains, California, plotted on Red Canyon 1:24K topo base Precambrian units from the oldest: sy (syenite), gn (gneiss), and gls (gneissic leucogabbro-mangerite and syenite) are related units differing in deformation and composition; an, anorthosite; fd, ferrodiorite. Phanerozoic units: ps, Pelona Schist; po, porphyry; Q, Quaternary. Note that I show the Orocopia thrust differently than Crowell and Walker (1962). Numbered localities: 1, anorthosite cuts gneissic leucogabbro-mangerite; 2, anorthosite metasomatically alters gneissic leucogabbro-mangerite, both cut by ferrodiorite; 3, ferrodiorite cuts syenite; 4, ferrodiorite cuts foliation in gneissic leucogabbro-mangerite; 5, base of massive ferrodiorite and foliation in gneissic leucogabbro-mangerite both synformal, with ilmenite-apatite enrichment in ferrodiorite.
Double-line structural symbols are dikes.

few dikes enriched in ilmenite and apatite were found there, but ilmenite contents are only about 10%. Crowell and Walker (1962) imply the existence of such bodies that consist mostly of opaque minerals, but I saw none.

The mangerite-jotunite unit of Powell (1981, 1982, 1993) in the remainder of the ETR seems aptly named in that it contains massive ferrodioritic rocks, correlating with post-anorthositic rocks of the Orocopia Mountains and similar to jotunites as described elsewhere, and gneissic leucogabbro-mangerites, correlating with pre-anorthositic rocks of the Orocopia Mountains and similar to mangerites as described elsewhere (cf. Herz and Force, 1987).

The ferrodioritic component of this unit, found in the Eagle, Chuckwalla, and Little Chuckwalla Mountains, consists of massive pyribole-feldspar rock, generally altered to actinolite, biotite, sphene, epidote, and local magnetite. Ilmenite, apatite, and minor zircon are relict primary minerals, but ilmenite content is only 1-3%. A modal analysis of such a rock from the Chuckwalla Mountains by Powell (1981, table 3-IV) shows "opaques" 2.0%, apatite 1.6%, and zircon 0.3% in a rock dominated by plagioclase and uralite after pyroxene(?) with 13% biotite and 6% quartz.

The gneissic leucogabbro-mangerite component, found in the Eagle and northern Chuckwalla Mountains, contains perthite, plagioclase, and uralitic mafic minerals, and locally contains anorthositic dikes. Quartz where present is blue. The average of four modal analyses of such rocks by Powell (1981) shows "opaques" 0.6%, uralite with relict clinopyroxene 14%, mesoperthitic feldspar 79%, biotite 2%, and quartz 4%.

Titanium-mineral potential of this terrane appears minor; the rock suite is promising but the ferrodioritic rocks apparently contain little TiO_2, perhaps too little to permit much immiscibility of nelsonitic liquids. Similarly, anorthosite-margin rutile is present but exceedingly minor. Titanium-mineral potential seems to be greater in the Orocopia Mountains than elsewhere in the Eastern Transverse Ranges.

Bagdad, Arizona.-- Proterozoic host rocks of the Laramide porphyry copper system at Bagdad, Arizona (fig. 1, #10) include an unusual assemblage of mafic rocks, mapped and described by Anderson and others (1955) and Bryant and others (1992) The assemblage on the south and west margins of the Laramide porphyry intrusive consists largely of Bridle Formation, defined by marine pillow lavas and related rocks, but here in my experience including sheeted diabase dikes and sills and gabbro, i.e. an ophiolite-like sequence. However, farther west is a stratiform suite of gabbros and anorthosites that is the subject of my discussion here. The relation of the stratiform and ophiolitic suites of Precambrian mafic rocks has not been described.

The terrane containing gabbros and anorthosites extends about 8 km NE-SW, and is as much as 1.5 km wide. As many as seven sheets of anorthosite are shown by Anderson and others (1955), locally coalescing, some as thick as 100 m. Dip of the sheets is shown as steep to the northwest, parallel to foliation. The sheets were thought by Anderson and others to be dikes.

In detail, Bryant and others (1992) and I find that intervals that are properly called anorthosite are only 8 m or less thick, grading via concordantly banded leucogabbros into gabbro. Thus the sequence probably represents a modally layered mafic intrusion and is partly cumulate.

Anderson and others (1955) report these gabbros to consist of primary augite and labradorite, generally replaced by hornblende and more sodic plagioclase, and further recrystallized to greenschist assemblages in deformed zones. Accessory ilmenite, magnetite, and apatite are characteristic. Anorthosite according to Anderson and others now consists of hornblende and calcic andesine, possibly secondary based on the presence of epidote.

Associated with this rock suite are nelsonite dikes. Anderson and others (1955) reported these as magnetite-ilmenite dikes locally up to 6 m wide in gabbro, but did not map them. They report equigranular magnetite>ilmenite with a little secondary specularite, and whole-rock Ti contents up to 10%.

The bodies I saw were massive and discordant with sharp contacts against leucogabbro. They contain about 5-15% equant apatite (by volume) of about 0.5-1 mm grain size and thus are nelsonitic. The opaque minerals are as described by Anderson and others (1955) and are typically 1-2 mm. No primary accessory minerals were found.

Anderson and others (1955) did not differentiate between gabbros associated with the Bridle Formation and those associated with anorthosite, and note that all of them seem to be characterized by high magnetite, ilmenite, and apatite contents. I agree with their assessment, implying in turn that the stratiform mafic rocks may themselves be ophiolitic. Anorthosites are not common in such sequences but Ashwal (1993) reports seven occurrences that include some classic ophiolite localities. Anorthosite thicknesses he shows for this association are only up to 20 cm (see his fig. 5.4) and An contents are higher than those of Bagdad, but intergrading modal layering and feldspar alteration, respectively, at Bagdad strengthen the similarity.

This would apparently be the first report of nelsonitic rocks in ophiolitic assemblages. Discordant magnetite-dominant nelsonitic rocks are locally associated with layered mafic complexes (reviewed by Force, 1991a), and I would suggest these as the closest relatives of the Bagdad nelsonites.

The titanium-mineral potential of the nelsonitic rocks near Bagdad is unclear, but probably not great due to the dominance of magnetite. Because these occurrences are apparently of a slightly different, undescribed type, they should be examined for other commodities such as platinum and vanadium.

An intriguing side issue comes up at Bagdad. Anderson and others (1955) were the first to suggest the possible importance of rutile as a by-product of porphyry copper deposits, based on the occurrence of rutile in their biotite-albite-orthoclase alteration zone. Perhaps somewhere in the subsurface, nelsonitic rocks intersect this zone, and contain their 10% Ti as 16% rutile.

Resource figures for ilmenite in the nelsonites are uncertain because extent and number of dikes are unknown. If several dikes a few meters thick extend 100 m or more, as seems likely, resources would be on the order of 100,000 tonnes of TiO_2.

Bauxite and clay deposits

Some older reports have suggested that ilmenite in clay and bauxite deposits of the northwestern U.S. is a resource. I have checked these occurrences from the point of view of the titanium-mineral industry.

Latah County, Idaho.-- The Latah formation (mid to upper Miocene) consists of fluvial and lacustrine deposits that interfinger with (and in part are dammed by) Columbia River basalt at the margin of the volcanics in eastern Idaho (fig. 1, #11). Clays, mostly kaolinite and halloysite, are mined from this formation and are described by Hosterman and others (1960). Among the clay types is residual clay on basalt, which in this area contains as much as 5.6% TiO_2, averaging 3.6% in the Olson deposit. Hosterman and others report unaltered ilmenite in this residual clay.

Residual clay derived from basalt averages about 3m thick, and averages 1.64 in specific gravity (Hosterman and others, 1960). Alumina averages about 30% and iron oxides about 9%, both values greater than those for other clay types of the area. Vesicles and other structures in the basalt are commonly preserved. This type of residual clay commonly overlies fresher basalt and underlies other clay types.

In order to evaluate the possibility of by-product ilmenite, I visited two of the seven deposits in Latah County, the Olsen and Bovill deposits, which contain residual clays derived from basalt (17 and 11 % respectively of these deposits according to Hosterman and others, 1960). In the Olson deposit, this clay is reported to average 25 m thick. The residual clays generally preserve scoriaceous basalt textures and remain somewhat indurated. Ilmenite constitutes about 5% of the rock, suggesting that more than half of the TiO_2 is in ilmenite.

Ilmenite forms shreddy plates typically 0.5 mm across but only about 0.02 to 0.05 mm thick. Clay has commonly nucleated around ilmenite, making separation difficult. Resource evaluation of these deposits is postponed to the section on the similar deposits of the Spokane area.

Spokane County, Washington.-- The geology of the "Excelsior" clay deposits in the Spokane area (fig. 1, #12) is the same as that in Latah County, Idaho, across the state line. They are described by Hosterman and others (1960) and Hosterman (1969).

As in Idaho, unweathered ilmenite is reported in residual clay derived from basalt. In the Excelsior deposits such clay constitutes almost all of the resource. A few features noted by Hosterman may be unique to the Spokane area; these include TiO_2 values in residual clay up to 9.1% and zonation of TiO_2 in paleosol profiles such that TiO_2 maxima occur in mid-profile, coinciding with Al_2O_3 maxima but above Fe maxima. My observation of weathering here is that Fe-silicate minerals and groundmass are altered lower in the profile than plagioclase feldspar; thus at the lower horizons Fe has been depleted but Al_2O_3 and TiO_2 not yet much enriched.

As Hosterman (1969) noted, residual clay derived from basalt is not preferred material for refractory clay, in part because of the presence of nontronite, and in part because of ilmenite impurities that must be washed free. Indeed, the active clay operation near Mica carefully avoids clay derived from basalt. Thus ilmenite must be treated as a co-product in this deposit type even where the relative value of ilmenite is minor.

Another problem, not addressed by Hosterman, is variation in the crystallinity and grain size of basalt. Some of the basalt in the Spokane area is or was glassy, with few phenocrysts not including ilmenite. In some other basalts, ilmenite was phyric but exceedingly fine. Most commonly ilmenite forms plates 0.05 mm thick, which thus are fragile. The proportion of basalt that contains recoverable ilmenite has not been established.

Ilmenite recovery from residual clays of Washington and Idaho seems contingent on too many factors to regard them as a titanium-mineral resource. First, residential land use has already neutralized much of the clay resource. Second, residual clay on basalt is the least valuable of the clay resources. And third, ilmenite is not recoverable from much of the clay due to grain-size variations in parent basalt.

Salem area, Oregon.-- Weathering of basalts correlative with Columbia River basalts in the Salem Hills of the Willamette valley of Oregon (fig. 1, #13) has produced thick laterites, and locally ferruginous bauxite draped over interfluves (Corcoran and Libbey, 1956). Such bauxite averages 4.4 m in thickness, but is as thick as 10 m. Gibbsite is present as pseudomorphs of plagioclase laths and as nodules and massive replacements. Ferruginous bauxite contains an average of 6.5% TiO_2, and as much as 10.2% TiO_2. Reported ilmenite contents range from 2 to 17%, depending in part on the amount of magnetite. Ilmenite contents of about 10% with a little "leucoxene" are most common. Edwin Roedder (in Corcoran and Libbey) found that ilmenite grain size is mostly 0.05-0.085 mm, and that separates contain 40 to 49% TiO_2 except where contamination is suspected. His calculations suggest that about 75% of the TiO_2 in the rock is generally present as ilmenite.

Had these bauxite deposits been mined, the contained ilmenite would have become a resource. Residential land use has now made mining unlikely, and I recommend omission of these deposits from U.S. resources.

Resource evaluation

Compared to listings in Force (1991a), table 1 shows both greater and lesser titanium-mineral resource figures following this reevaluation. Gains occur largely as potential by-products, however. Overall the western U.S. seems likely to remain a minor factor in the country's titanium-mineral exploitation, unless porphyry-type deposits begin to yield a rutile by-product or perovskite becomes an economic mineral. Components of these conclusions are: 1) the Cretaceous shoreline placers are restricted to small, high-grade deposits, because diagenesis has destroyed more voluminous low-grade envelopes, and the economic mineralogy of low-grade deposits is diluted by the denser silicates. 2) Anorthosite-related deposits of the Eastern Transverse Ranges seem to have formed in a low- TiO_2 environment. 3) Residual enrichments in paleosols of the northwestern U.S. contain inseparable ilmenite and/or have been negated by residential development. 4) Deposits and districts studied herein that have appreciable titanium-mineral resources are so low in grade that they would become producers only on a by-product basis.

Other implications

This report, concerned as it is with resource magnitudes, nevertheless reaches some conclusions of more general interest. Those that seem most important to me are:

a) Subdivision of the Cretaceous deposits into finely divided age cohorts, and placing them in the array of known shoreline trends as a function of age, allows exploration for more deposits on a paleogeographic basis.
b) Much of the titanium in oxides of Cretaceous deposits over thousands of kilometers is in a phase previously thought to be unusual, a medial hematite-ilmenite solid solution that is highly magnetic. This mineral gives the deposits their magnetic character, as magnetite is generally not present.
c) The Cretaceous shoreline placer deposits make a wonderful natural laboratory for the study of three-dimentional geometry, facies relations, and sedimentology of coastal heavy mineral enrichment.
d) The Ione Formation of California (Eocene) is an economic geologist's dream—virtually every rock type has value. Altered ilmenite and zircon are concentrated in a newly recognized shoreline environment, which may extend beyond the type area we studied.
e) The volumes of monazite-bearing sands of Idaho are far greater than the AEC-USBM literature implies—they fill entire Upper Tertiary basins. If these sands are ever mined again, the contained ilmenite resource is correspondingly increased.
f) Nelsonitic rocks of Proterozoic age near Bagdad, Arizona are apparently the first reported in association with ophiolitic rocks.

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