

THE HEAVY ACCESSORY MINERALS OF THE VAL VERDE TONALITE

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Summary

The construction of the Metropolitan Water District Aqueduct for Los Angeles County, California has necessitated the drilling of long tunnels at various points en route from the Colorado River. One such tunnel situated near the town of Val Verde, California passes through some seven miles of tonalite. About a dozen samples of the tonalite were taken at approximately half-mile intervals in the Val Verde tunnel. These samples were studied to determine the accessory constituents present, and their variation in the section exposed in the tunnel.

The non-magnetic or weakly magnetic heavy accessory minerals consist of sphene, apatite, epidote-clinozoisite, zircon, zoisite, allanite?, pyrite, and calcite? in approximately decreasing order of abundance. From samples at one end of the tunnel tourmaline, monazite, abnormal blue anatase, and thulite? were recorded. Associated with the appearance of tourmaline and the other minerals just cited is an increase in zircon and decrease in apatite, suggesting a more acid phase in the tonalite at this point. An explanation may be furnished by the fact that the tonalite is here closer to overlying and intruded schists, and hence to the margin of the former.

The more magnetic minerals of the tonalite were biotite and hornblende (15%-30% of entire rock), and accessory magnetite.

Introduction

Study of the accessory minerals of igneous rocks by means of concentration is a fairly recent development in the field of petrology. While it appears that J.W. Evans early urged the study of the accessory minerals by crushing and concentration, it was not until 1917 that any real attempt was made to study the accessory minerals in detail. In this year, Rastall and Wilcockson published an account of, "The Accessory Minerals of the Granitic Rocks of the English Lake District." This work was soon followed (1923) by the classical researches of Brammal and Harwood on the Dartmoor granite. Their highly detailed work furnished the necessary impetus for much additional research by other investigators, and each year now finds an increase in the number of papers devoted to accessory mineral study. Originally, work of this type was intended as a means of demonstrating the parent rock from which heavy minerals of various sedimentary series had been derived. Once the study of accessory minerals was started, it was soon realized that many minerals of relatively rare occurrence could be missed in thin-section work, and that concentration methods served to increase detailed knowledge of the constituency of igneous rocks. Moreover, since the accessory minerals are among the first to crystallize from the

magma, their study indicates much as to the early sequence of events in the rock mass.

Investigation of accessory minerals in the directions given above has been of undoubted value. Somewhat more recently various workers have advocated the use of accessory minerals of igneous rocks as a means of correlation of igneous rock types. Correlation work is based on the theory that the accessory minerals generally crystallize from the magma at an early stage in cooling and thus, according to Groves,¹ "in their colour, inclusions, habits, and peculiarities, give valuable characteristics dependant

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Groves, A.W., Geol. Mag., p. 234, 1930.

on the original composition and early cooling history of the magma." In many cases their use has yielded results apparently of positive value. Thus for examples, Groves has demonstrated that the majority of the granites of northern Brittany, Jersey, and Normandy are to be considered as approximately of the same age, namely Permo-carboniferous. Stark and Barnes have found that successful correlation of granites may be anticipated if large series of samples are investigated. M.F. Boos was able to distinguish the older from the younger pre-Cambrian granitic rocks of the Front Range, Colorado. Extended study of the Wolf Mountain granite of Texas by McAdams has even suggested to that worker that the heavy minerals offer a means of determining the top and bottom of the Wolf Mountain mass, and indicate that the granite is probably a phacolith

rather than a batholith.

Nevertheless, data on the precision of this type of correlation is still being gathered, and studies concerned with the accessory minerals and their variation is of some importance at present. As is perhaps suggested above, the use of accessory minerals in the correlation of pre-Cambrian rocks is one phase of the work that will be of great value if the hopes of some investigators are realized. At the present time, the National Research Council, Committee on Accessory Minerals of Crystalline Rocks, is actively engaged in fostering and correlating research on accessory minerals.

The construction of the Metropolitan Water District Aqueduct for Los Angeles County, California has necessitated the drilling of long tunnels at various points en route from the Colorado River. One such tunnel situated approximately one mile south of Val Verde, California passes through some seven miles of tonalite. This locality offers a very favorable opportunity for the study of accessory minerals, and their variation through a continuously exposed section of igneous rock. The present paper embodies the results of a study of the accessories in the tonalite and their variation through about five miles of tunnel, which distance is the longest continuous exposure of the rock without faulting.

No account of the geology of the area has been published. Since the work carried on was not extensive enough to involve consideration of the history of emplace-

ment of the tonalite, discussion of the geology of the region has been omitted. E.F. Osborn of the California Institute of Technology is now engaged in a detailed petrographic study of the rocks of the Val Verde tunnel. He has kindly furnished the following description of the tonalite and its occurrence.

"The Val Verde Tonalite was so named because it outcrops in the vicinity of the town of Val Verde, and in particular it is essentially the only rock encountered in the seven-mile Val Verde tunnel of the Metropolitan Water District.

The tonalite outcrops over an area on the Perris Block of low relief at an elevation of about 1600 feet above sea level. From the vicinity of the tunnel, the land slopes gently toward the Santa Ana River, 15 miles to the north and northwest, and rises toward the more broken country surrounding Elsinore Lake, 15 miles to the south. There is also a general slope from the Val Verde District to the base of the San Jacinto Mts., 15 miles to the east.

Because of the low relief and consequent formation of a residual soil, the outcrops of the tonalite are scattered and are numerous only in the southern, higher part of the district. The outcrops are low, rounded knobs of partially disintegrated tonalite projecting above the soil.

A constant, conspicuous feature of the tonalite is the presence of abundant dark, fine-grained, round inclusions. These vary from a few inches to several feet in

diameter, but the average is about one foot across. In a few places the inclusions are practically absent and in others occur in swarms making fifty percent or more of the rock. In the latter instance they are more angular and more tabular in form and have a common orientation striking northwesterly and dipping steeply.

The tonalite is a coarse-grained rock, medium dark in color, and varying in composition only slightly throughout the district. The rock contains 50 to 60% andesine, 15 to 30% quartz, and 15 to 30% biotite and hornblende, the biotite commonly being more abundant than hornblende. Occasionally a very small percentage of orthoclase is present. Magnetite, sphene, apatite, and zircon are the common accessory minerals."

Sampling and Preparation of the Minerals for Study

Samples of the tonalite were taken at approximately half-mile intervals in the Val Verde tunnel. One of these samples (No. 11937) was studied in duplicate, one-half being panned to about one-third of its original weight, and the unpanned fraction compared with it. In addition, a sample of one of the numerous inclusions was also studied.

The specimen numbers actually represent hundreds of feet from an established bench mark. Hence, the distance between specimens can be readily determined. For example, the interval between Nos. 11730 and 11755 is 25x100 or 2500 feet.

The collected samples were crushed and sieved and 30 grams of material between 100 and 150 mesh grade size was taken for each determination. Each sample was then carefully panned to about one-half of its original weight. This operation served to eliminate much of the biotite along with the lighter minerals, and afforded a cleaner separation of "heavies" and "lights". Moreover, it effected a considerable saving of bromoform, and since rock flour was eliminated at the same time did not increase materially the amount of time consumed. After panning each sample was dried and the heavy minerals were separated out by means of bromoform (s.g. 2.86). After separation the sample was washed in acetone, dried, and the heavy fraction weighed.

The extremely large percent of biotite and hornblende so concealed any other minerals present in the heavy fraction that it was necessary to resort to an electro-magnetic separation of the heavy minerals into (1) extremely magnetic; (2) moderately magnetic; and (3) non-magnetic crops. The non-magnetic fraction was then separated again by bromoform, washed in acetone and dried. A second separation was necessary apparently because the large amount of flaky or platy minerals (biotite and hornblende) had dragged down a certain amount of "lights". A suitable fraction of the non-magnetic portion was mounted in A-chloro-naphthalene (R.I. 1.629) for study, and another fraction in canada balsam for a permanent record. Due to time limitations the strongly and moderately magnetic crops were

given only cursory examination.

Panning of specimens and examination of only the non-magnetic or weakly magnetic portions of the "heavy" crop may be legitimate objections to the method of attack. However, panning was resorted to only when it was found that very poor separations into heavy and light minerals were being made, and that bromoform was being consumed at a very rapid rate. As a matter of fact, the non-magnetic mineral yield was greater with panning than without it. The effect of panning on the mineral frequency will be discussed in a later section of this paper. Failure to study the magnetic portions is not as important a defect in method as it seems. The most important accessory minerals are zircon, apatite, and sphene, all non-magnetic. Mafic minerals are usually not considered in calculating frequencies because of their known variation within a rock type. Moreover, accessory minerals, as defined by the Committee on accessory minerals of crystalline rocks, National Research Council, comprise only those minerals which are more suitably studied by concentration than by other means. The mafic minerals of the Val Verde (biotite and hornblende) are present in such abundance as to render concentration unnecessary, and even to hinder the study of the other minerals. As far as could be determined the extremely magnetic crop consisted of magnetite, red iron oxide (magnetite? in part) derived from altered biotite grains, and fragments of metallic iron picked up during crushing in iron containers. The moderately magnetic portion consisted of

biotite and hornblende. No garnet was definitely observed, at least in the sample of this fraction examined.

Accessory Minerals of the Val Verde Tonalite

The following accessory minerals have been identified as occurring in the Val Verde tonalite: zircon, apatite, sphene, epidote, clinozoisite, zoisite, allanite?, tourmaline, monazite, anatase, calcite?, thulite?, and pyrite. In addition, several unidentified minerals were of sporadic occurrence. A complete list of "heavies" would also include hornblende, biotite, and magnetite.

In considering the non-magnetic or weakly magnetic accessory minerals of the Val Verde tonalite as a whole, the minerals which have been recorded fall into three categories.

(1) primary minerals, in sufficient quantity to have been recorded in all specimens examined and to be expected in any reasonable sample studied. An exception to this last statement perhaps should be made in the case of certain samples in which the percentage of zircon is low. However, zircon has been recorded in all cases even though computation of probable error in grain counting indicates its absence in some samples if the number of rock samples was increased. Minerals: zircon, apatite, and sphene.

(2) secondary minerals; usually present in sufficient quantity to be expected in a random count. Minerals: epidote group, composed of the following in varying proportions: epidote, clinozoisite, and zoisite (usually

rare).

(3) primary and secondary minerals sufficiently rare in all samples that their presence or absence in a particular sample can not be predicted. Minerals: tourmaline, monazite, anatase, calcite?, allanite?, thulite?, pyrite, and undetermined minerals. Monazite and more particularly tourmaline may have a range restricted to the higher-numbered samples but their rarity prevents a definite determination regarding their presence or absence.

Heavy Mineral Percentages: The percentage of heavy minerals obtained from the bromoform separation after preliminary panning of the specimens ranges from 5% to 11%. Sample No. 11937 was split and one fraction was separated into its "heavy" and "light" components without preliminary panning. The other fraction received standard treatment. Hence, comparison of the panned to the non-panned fractions of No. 11937 affords a means of estimating the actual heavy mineral content of the tonalite specimens. Such an estimate suggests that the actual heavy mineral proportion probably averages about 20% (between 10% and 25%).

Sphene apparently is the most abundant accessory mineral, although the effect of both panning and crushing may be to increase the number of grains of this mineral. Zircon is the least abundant mineral in group (1) except at the extreme western end of the tunnel where it increases rapidly in amount, apparently with concurrent decrease of

apatite. An average of panned samples gives zircon-17%; apatite-29%; and sphene-54%: or a ratio of Zi:Ap:Sp of about 2:3:5. A more normal ratio is probably 1:4:5.

Table 1 gives in tabulated form the results of a series of grain counts. Only the primary accessory minerals zircon, apatite, and sphene are recorded. The complete grain counts are presented in a later section of this paper.

TABLE 1
Table of Zircon-Apatite-Sphene Percentages

Number	Panned from- to- (gms.)	% Heavies >2.86 s.g.	Total Zi, Ap, Sp grains counted	Zircon		Apatite		Sphene		Crusher
				%	% \pm error	%	% \pm error	%	% \pm error	
11730*†(not panned)	---	5	265	12	11.2	54	3.8	34	5.7	mortar and Braun*
11755	30-12.1	7	621	5	12	41	3.5	54	2.5	mortar and Braun
11779	60-20	9	451	12	8.5	39	4	49	3.5	mortar and Braun
11804	30-16.2	10	333	4	16.5	21	7	75	2.5	mortar and C.I.T.†
11829	30-18	5	317	9	11	23	6.5	67	2.5	mortar and C.I.T.†
11866	30-12.8	6	619	15	6	35	4.5	50	3	C.I.T.
11895	30-10.8	7	523	13	7	46	3	41	4	mortar and Braun
11914	30-13.1	11	398	19	6.5	25	6	56	3	mortar and Braun
11937 †(not panned)	---	23	486	16	7.5	42	4	42	4	mortar
11937	49.9-17.2	9	390	23	6	31	5	46	3.5	mortar and C.I.T.
11962	30-14.2	5	299	29	6.5	16	9.5	55	3.5	mortar and Braun
11980	30-15.8	11	179	45	5.5	11	15	44	5.5	mortar and Braun
11742 (inclusion)	30-15.6	27	488	14	7.5	83	<1.5	3	>13.5	Braun

* % error calculated; others from probability curves

† sample washed before weighing

* Braun disc-crusher

† Calif. Inst. hand-crusher

Notes On Individual Minerals

1. Zircon

Zircon in the Val Verde tonalite is diagnosed by its positive, uniaxial character with very high relief and high birefringence. The mineral occurs as colorless, well-crystallized prismatic grains generally with acute terminations. A few crystals, mostly encountered in specimen No. 11937, exhibit faint zonal structure.

The average zircon is not noticeably elongate, but lengthened crystals occur throughout the series of specimens examined. A decided increase in average elongation of this mineral is to be observed in No. 11980. Some individuals in this sample perhaps deserve the term rod-like. There may be an increase in the ratio of length to breadth of zircon grains in samples of the 11900's as compared to lower-numbered specimens but this is not certain. Zircons from No. 11937 are no more elongated, on the average, than specimens of the mineral from other samples. Mackie² has indicated, for certain Scottish granites, a

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Mackie, W., Trans. Edinburgh Geol. Soc., 12, pp. 26-27, 1928.

relationship between acidity of magma and elongation of zircon crystals. Such a relationship would be difficult to establish in the present instance, but the decided elongation of zircons in No. 11980 may be indicative of a similar circumstance.

A number of the zircon grains, scattered throughout the series of specimens examined, show the effects of corrosion. Moreover, there appears to be a decided increase in corrosion in samples of the 11900's. Perhaps, corrosion in the present instance is also an index of the acidity or basicity of the magma, with the more acid rock types showing the most corrosion.

A number of the zircon crystals show markings on their crystal faces giving the grains a "blistered" appearance. This phenomenon is not necessarily linked with corrosion.

Most of the zircons possess a greater or lesser number of inclusions. The inclusions are usually too small to have their character determined. Perhaps, two types may be distinguished. The more common type is present as rather prismatic, sometimes acicular, colorless inclusions, with refractive index below that of zircon. This type may represent gas bubbles. A second form is indicated by brownish to opaque inclusions of less regular shape. There does not seem to be any directional variation in the relative abundance of inclusions.

2. Apatite

Apatite grains are distinguished by their optically negative, uniaxial character, together with moderately high index of refraction and low birefringence. The Val Verde specimens are colorless or perhaps at times slightly yellowish grains, generally prismatic with rounded terminations. In some cases the grains are terminated by crystal

faces, apparently either the pyramid or base, or a combination of the two. Many times the crystals possess only broken terminations. Rarely, the apatite consists of irregular fragments with all trace of crystal form absent.

Inclusions in the apatite are fairly common. The exact nature of these inclusions was not studied but in general they were of lower index than the surrounding mineral. In some cases the included material was zircon.

In several samples, notably in No. 11937, some of the grains were enclosed either partially or entirely by a shell of yellowish-red material, the nature of which was not determined.

Many of the apatite grains show an outline apparently indicating corrosion or resorption phenomena.

Apatite shows a marked decrease in relative abundance in the extreme high-numbered samples correlating with the increase of zircon at this point. This feature may point also to a gradation toward a more acid rock type. Other than relative abundance, no characters were noted in the apatite which exhibited any directional trends.

3. Sphene

Sphene is identified chiefly by its very high relief, very high birefringence, extreme dispersion, and positive, biaxial optical character. The Val Verde sphene is generally found as irregular fragments without crystal faces, although in some cases faces are present. A very few

grains are essentially euhedral. The usually transparent grains range in color from colorless through pale yellow-green to yellow or yellow-brown. Inclusions are encountered in some individuals, and others appear to be clouded by the presence of minute inclusions. Some of the colored types are pleochroic in brownish tints. Cleavage and fracture frequently combine to form a mosaic pattern.

In respect to color, the Val Verde sphene may be divided roughly into three groups: (a) colorless; (b) pale yellow-green (generally the most abundant type); and (c) yellow or brown, frequently clouded. An attempt was made to count these three groups separately but to place a number of the grains in either one or the other of the above categories is hardly justifiable, and probably all should be placed under one heading. However, the three divisions are given separate tabulation in the grain counts. Color variation is irregular and appears to bear no relation to the position of the sample. A considerable number of bright yellow-green, very clear grains characterized specimen No. 11866.

The percent of sphene in the Val Verde tonalite is relatively constant throughout the section examined. However, it was noted that the method of crushing of the rock sample has an influence on the number of grains of sphene appearing in the count. This will be discussed in another section dealing with probable causes of variation in abundance of the accessory minerals.

4. Monazite

Monazite is diagnosed chiefly through its yellow color, high relief and high birefringence, and positive, biaxial optical character. The mineral is quite rare in the Val Verde tonalite but has been recorded in No. 11937, and one doubtful grain was encountered in No. 11914. The typical monazite of No. 11937 is clove-brown or yellowish to reddish-brown. It appears usually as small but euhedral grains which are short, rather diamond-shaped prisms. There is no observable pleochroism. A few inclusions are sometimes present. The birefringence is high but notably less than in sphene. Grains are positive and supposedly biaxial although only "flash figures" could be obtained.

Monazite usually occurs in acid granite rocks. Its appearance in No. 11937 may furnish additional evidence in support of the view that the Val Verde tonalite is more acid at this point than in the 11700's and 11800's. However, Mackie has pointed out in connection with the Scottish granites that monazite disappears when sphene and hornblende make their appearance. Since hornblende and

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Mackie, W., op cit, p. 23, 1928.

sphene are important minerals everywhere in the Val Verde, this fact may cast some doubt on a determination of the present grains as monazite. Other grains which appear to be zircon and are partly colorless and partly yellow further suggest that the identification may be incorrect.

Several particles of somewhat lighter color also suggest colored zircon. However, certain crystals are so like monazite in characters that the identification is justified. One small irregular grain gave a biaxial figure with small optic angle. In this case the failure to extinguish, and the dispersion suggests sphene.

An alternative determination may be yellow zircon, but this variety of zircon is rare.

5. Tourmaline

Tourmaline is readily identified by means of its pleochroism with maximum absorption perpendicular to the direction of vibration of the polarizer, and by its parallel extinction.

The Val Verde tourmaline ordinarily exhibits pleochroism from strong dark blue or greenish-blue to very pale reddish-brown. One grain, found in No. 11980, exhibited dark brown pleochroism. In ordinary light the mineral is light brown, but darker than in position of minimum absorption in polarized light. The grains are generally prismatic without definite crystal form. A few of the grains are relatively pure but usually tourmaline is present as a replacement of feldspar. Tourmaline has been identified positively in only Nos. 11937 and 11980. One grain of doubtful identity was observed in No. 11914.

Unfortunately, tourmaline is too scarce in the samples in which it is found to assume that it is absent in the others. With the low percent present it could be scattered

throughout the rocks examined and not be present in a number of samples. However, since the percent of zircon increases at the point tourmaline makes its appearance, the tourmaline may be associated with increasing acidity of the rock, and may not be present in the lower-numbered samples.

No evidence points to the tourmaline as a post-consolidation phenomenon. However, it does not appear to be primary in a strict sense, and is apparently to be considered a secondary mineral formed as the result of pre-consolidation autopneumatolysis. Its presence is perhaps another reason for considering that the higher-numbered samples of the Val Verde tonalite represents a more acid phase of the rock as a whole.

6. Epidote-Clinzoisite-Zoisite

Epidote is characterized by its pistachio-green color, high, brilliantly-colored interference bands, high index of refraction, and biaxial negative optical character with large optic angle. Clinzoisite is colorless with lower interference colors than epidote, sometimes ultra-blue; possesses a high index of refraction, and is biaxial in character with large optic angle (sign positive, sometimes negative). Zoisite is colorless, and has a high index of refraction. The birefringence is low, usually ultra-blue. The mineral is biaxial positive with parallel extinction, and the optic angle varies considerably but may be very small.

It seems likely that epidote, clinozoisite, and zoisite are all present in the Val Verde. However, it is not possible always to distinguish between them, especially if the optic sign can not be determined. The Val Verde epidote may be colorless as well as pistachio-green, clinozoisite may be positive or negative, and the extinction in these two minerals is parallel or nearly so. The controlling cleavage usually results in grain orientations with low birefringence even in the case of epidote.

Epidote and clinozoisite are isomorphs of each other. Varying amounts of iron are responsible for the differences exhibited in the two minerals. In the grain counts, epidote and clinozoisite have been lumped together. In some of the counts made early in the study zoisite was not afforded separate recognition. At this stage zoisite was suspected but no optical signs of positive character had been obtained. The later division into epidote and zoisite is probably not altogether accurate but may approximate actual conditions. Generally, the colorless grains with ultra-blue interference colors, and with lower index of refraction and smaller optic angle than typical epidote were determined as zoisite.

Several examples of yellow or brown epidote were encountered.

Altered grains comprising a mixture of epidote and feldspar indicate the derivation of the epidote minerals from the calcic feldspars. These altered grains were especially numerous in samples in the higher 11900's.

Zoisite was found to be very common in specimen No. 11914. Epidote occurred frequently, sometimes in very pure grains, in Nos. 11730, 11755, 11914, and 11962. The position of the specimens in the tunnel apparently has little to do with the abundance of epidote. Noteworthy, perhaps, is the fact that the inclusion sample studied, No. 11742, was very low in both epidote and zoisite.

7. Abnormal Blue Anatase

Intense blue or bluish-black grains were encountered in several of the samples. The following characters were observed:

- (1) transparent to nearly opaque; grains colored a deep blue to bluish-black
- (2) slightly pleochroic; blue to lighter blue
- (3) refractive index greater than 1.7
- (4) birefringence fairly low
- (5) good extinction; probably parallel
- (6) cleavage well developed
- (7) biaxial?; positive?

These characters agree with those shown by blue anatase except for the low birefringence and the apparently biaxial positive optical character. Deep-colored varieties of anatase sometimes exhibit biaxial interference figures of small optic angle.

This mineral was found in Nos. 11866, 11895, 11937, 11980, and doubtfully in the case of a single grain in No. 11779.

Anatase is sometimes, but not invariably, a pneumatolytic mineral. Since its apparent distribution in the Val Verde tonalite is somewhat comparable to that of tourmaline its presence may be due to pneumatolysis.

8. Allanite?

A number of dark brown to yellow grains, scattered throughout the series of specimens examined, appear to represent the rare-earth epidote group mineral, allanite. This species, although probable present, is not an important member of the accessory mineral suite.

9. Thulite?

Specimen No. 11980 yielded one grain of a pleochroic mineral which may represent the manganese zoisite, thulite. The specimen presented the following characters:

- (1) transparent; practically colorless or slightly reddish
- (2) strongly pleochroic; strong red or reddish-brown to colorless
- (3) index of refraction high; about 1.7
- (4) birefringence very low
- (5) extinction parallel or nearly so
- (6) cleavage present

10. Pyrite

Several samples showed infrequent grains of an opaque (non-magnetic?) mineral apparently representing pyrite. These grains were yellowish in reflected light with metallic luster. Some of the grains were coated with a red

decomposition product (hematite).

11. Calcite?

Calcite or a related mineral was of sporadic and extremely rare occurrence in the Val Verde tonalite.

12. High index mica

A micaceous mineral with index of refraction about 1.7 has been recorded from the Val Verde tonalite. Relatively rare, it was probably of most frequent occurrence in No. 11742. This sample represents one of the numerous inclusions in the tonalite.

13. Undetermined minerals

Several undetermined minerals appear to be present in the samples. They are of too infrequent occurrence to be of much importance.

As mentioned previously, moderately magnetic hornblende and biotite form the vast bulk of the heavy minerals. The extremely magnetic crops of the Val Verde samples yielded magnetite, and a red iron oxide (magnetite? in part) apparently derived from altered biotite.

Sources of Variation of the Accessory Minerals

It will be noted from the percentages expressed in Table 1, and in the grain counts to be given later that

variation exists in the frequency of occurrence of the accessory minerals of the Val Verde tonalite. Since part of this variation is not due to changes in composition of the tonalite, it is necessary to consider the possible sources of variation as observed in the grain counts.

The first point to be considered is variation caused by lack of absolute control during preparation of samples for study. The bromoform method of separating "heavies" from "lights" does not afford a perfect separation, and a certain amount of fluctuation can not be avoided. The amount of variation from this cause is not readily determined.

A second factor of variation may be introduced by unavoidable variation in the effectiveness of the electromagnetic separation. Minerals which are only weakly magnetic may be separated out in the moderately magnetic crop in some instances, and in the non-magnetic crop in others. Since the more important accessories are non-magnetic this factor can not be of any great importance. However, in view of the fact that panning serves to increase the total non-magnetic crop, the separation of flaky or platy hornblende and biotite when these minerals are present in large quantities may carry the non-magnetic minerals with them. Preliminary use of the pan with consequent elimination of part of the biotite and hornblende would then reduce the loss in this fashion of non-magnetic minerals. Unfortunately, panning apparently eliminates apatite at a faster rate than either zircon or sphene so that the relative amount of

apatite is reduced by use of the pan. However, if we confine our attention to the panned samples although apatite may be reduced in an absolute sense, the variation of apatite from one panned sample to another will be a measure of actual conditions in the rock mass.

Sphene is generally present as irregular grains without much trace of original crystal form. Since in many cases the grains were traversed by a network of fracture and cleavage cracks it was suspected that during the course of crushing, a single grain of sphene might break into several. If attention is given to table 1 wherein are listed the percent of zircon, apatite, and sphene in regard to each other, it will be seen that the type of crusher used has affected the apparent abundance of sphene. Crushing by a Braun disc-crusher or the California Institute crusher resulted in the formation of a larger number of grains than in cases in which a relatively light mortar and pestle was used. For this reason, comparisons of the zircon-apatite-sphene ratios should be confined to panned samples which were crushed on either the Braun or California Institute crushers. The following table presents the zircon, apatite, and sphene percentages of table 1 in this revised form.

Table 2
Revised Zi, Ap, Sp Percentages

No.	Zircon	Apatite	Sphene
11755	5	41	54
11804	4	21	75
11829	9	23	67
11866	15	35	50
11914	19	25	56
11962	29	16	55
11980	45	11	44

Errors in identification is another source of variation in the grain counts. However, zircon, apatite, and sphene are by far the most important minerals present. These three are all readily recognizable and easily distinguished among themselves. Hence, errors arising through misidentification can have only a negligible effect on the results.

A very important source of variation is the strictly mathematical one of error introduced because only a limited number of grains can be counted on each slide. In general, the accuracy of the counts increases as the square-root of the total number of grains counted. For this reason, one soon reaches an accuracy beyond which it is not practical to go. Generally, about 300 grains are counted in each sample. In the present instance, the counts averaged between 300-400 grains of the primary accessories zircon,

apatite, and sphene. Table 1 gives the probable error, plus or minus, in each percentage for the Val Verde samples. Data for the probable error was taken from an article by A. Lincoln Dryden Jr. entitled, "Accuracy in Percentage Representation of Heavy Mineral Frequencies."⁴

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Dryden, A.L. Jr., Proc. Nat. Acad. Sci., Vol. 17, No. 5, 1931.

As may be seen from the table, this factor affects chiefly the minerals present in small amounts. For this reason, such species as tourmaline may not be recorded from samples in which it is actually present.

Lastly, variation in the frequency of mineral occurrence may be due to actual changes in the constitution of the rock mass. Considering the variations which are introduced by other means, it is difficult to reach an unequivocal determination of such variation. However, the Val Verde tonalite exhibits a directional variation which it seems reasonable to attribute to actual change in the rock. The next section is devoted to a statement of the mineralogical variations in the Val Verde.

Mineralogical Variations in the Val Verde Tonalite

In spite of a considerable amount of variation in the accessory minerals of the Val Verde tonalite, the composition is as homogeneous as one could reasonably expect in a rock mass as large as that surveyed. The

accessory mineral suite remains limited in number of species throughout the area examined, and is characterized by a large amount of sphene. Ratios of zircon to apatite are variable, but the variation is gradual and directional. Generally, apatite is much more abundant than zircon, and if variations due to panning and crushing are eliminated, apatite in most cases is quite comparable to sphene in abundance. The only other accessory minerals which are ever very common are the secondary minerals of the epidote group. Other minerals which may be occasionally present are always very minor in amount. Hence, the present study serves to bear out the belief of many investigators that in a homogeneous rock mass the accessory minerals remain fairly constant and distinctive.

The only variation in composition which appears to be important suggests the thesis that the rock is more acidic at one end of the Val Verde tunnel than at the other. Thus, in the higher-numbered samples there is an increase in zircon linked with a decrease in apatite. An increase in the amount of corrosion of zircon is also noted at this point. The average length of crystals of zircon may be somewhat greater. At the same time there is an introduction of tourmaline, monazite, and anatase. These minerals may also indicate a change in character of the Val Verde tonalite to a more acid phase. In this connection it should be stressed that the samples studied were typical examples of the Val Verde. In other words, these more acidic-appearing samples are not dike rocks or similar types.

An explanation of the more acid nature of the rock may be furnished by the fact that the tonalite is closer, at this point, to overlying and intruded schists, and hence to the margin of the tonalite.

Val Verde Inclusions

Inclusions are fairly numerous at certain points in the Val Verde tonalite. A description of their appearance has already been given.

A sample of one of these inclusions (No. 11742) was studied and proved to be quite distinctive when compared to normal specimens. The percent of heavy minerals was almost double that of the ordinary Val Verde specimens. Apatite was the chief accessory mineral present. On the other hand, sphene was extremely rare. The percent of zircon was similar to that of normal Val Verde specimens but the grains were considerably broken and fractured. Perfect euhedral crystals were not as abundant as in other samples, and many of the grains showed marked corrosion. Another point of interest was the extreme scarcity of epidote and zoisite in the sample. The inclusion occurred at a point in the tunnel in which epidote was very common.

A study of the accessory minerals of No. 11742 points to the intrusion of the tonalite into a rather basic type of rock, and the stoping or breaking off of fragments of the rock to furnish the material of the inclusions.

Grain Counts

After some consideration it was decided to restrict the calculation of percentages to the primary minerals zircon, apatite, and sphene. Neither the secondary minerals, epidote and zoisite, nor the primary minerals of rare occurrence are of much importance in a study of the constancy of accessory minerals in the Val Verde. In work of this type, attention is directed generally toward the relatively abundant primary accessories.

Representing mineral frequency of occurrence in percent has certain objections which have been pointed out by several workers. W.M. Cogen has reviewed recently the

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Cogen, W.M., Jour. Sed. Petrol., Vol. 5, No. 1, p. 5, 1935.

chief objections to percentage representation. By limiting the calculations in the present instance most of the objections are not serious. Since sphene remains fairly constant, the apparent increase of either apatite or zircon is essentially real. With the data as given in table 1, a general increase of all three minerals can not be detected. If the percent of these minerals to the total heavy fraction could be determined this would not be the case. However, no attempt was made to calculate the percentage of zircon, apatite, and sphene taken together for the following reasons:

(1) the abundance of the three important primary minerals was subject to much variation, ranging down to practically unweighable quantities.

(2) it was felt that much of the variation in (1) was not due to actual variation of the minerals, but to uncontrollable factors arising during preparation of the samples for study.

W.M. Cogen, in the just cited paper, suggested a method of representation which eliminates the objections raised to most modes. Essentially, the method is to determine the number of grains of each mineral per unit of sample, and compare with a standard control sample. In the present case this method could not be used successfully even if it were necessary to record frequency of all minerals present. Some of the non-magnetic samples were so small that the entire specimen was mounted for the count. Others possessed many times this amount, but the sample was always too small to make use of a miniature sample splitter or other device without serious danger of losing most of the crop. The larger samples were reduced by quartering, but this method is probably too inaccurate to apply the method suggested by Cogen. Aside from the above, all such attempts at more precise comparisons are based on a high absolute record of minerals which certainly was not obtained in the present instance.

The actual grain counts made during the course of the work are listed below.

No. 11730

Zircon--31
 Apatite--143
 Sphene
 (a)--8

(b)--83 (including Sp(c))
 Epidote--83 (including zoisite)
 Total: 348

No. 11742 (inclusion)

Zircon--68
 Apatite--404
 Sphene--16
 Pyrite--9
 Epidote--1
 Zoisite--1
 Calcite?--1
 Total: 500

No. 11755

Zircon--31
 Apatite--255
 Sphene
 (a)--116
 (b)--186
 (c)--33
 Epidote--208
 Zoisite--14
 Allanite?--2
 Calcite?--1
 Total: 846

No. 11779

Zircon--54
 Apatite--178
 Sphene
 (a)--3
 (b)--203
 (c)--13
 Epidote--55 (probably including zoisite, not more than
 four grains)
 Anatase?--1
 Total: 507

No. 11804

Zircon--14
 Apatite--69
 Sphene
 (a)--104
 (b)--126
 (c)--20
 Epidote--35
 Zoisite--4
 Total: 372

No. 11829

Zircon--30
 Apatite--74
 Sphene
 (a)--18
 (b)--162
 (c)--33
 Epidote--29
 Zoisite--11
 Total: 357

No. 11866

Zircon--91
 Apatite--217
 Sphene
 (a)--49
 (b)--177
 (c)--85
 Epidote--31
 Zoisite--5
 Allanite?--3
 Total: 658

No. 11895

Zircon--66
 Apatite--241
 Sphene
 (a)--16
 (b)--173
 (c)--27
 Epidote--43
 Zoisite--9
 Anatase--2
 Total: 577

No. 11914

Zircon--75
 Apatite--100
 Sphene
 (a)--66
 (b)--118
 (c)--39
 Epidote--125
 Zoisite--23
 Calcite?--1
 Total: 547

No. 11937 (not panned)

Zircon--79
 Apatite--204
 Sphene
 (a)--35
 (b)--159
 (c)--9
 Epidote--89 (including zoisite)
 Tourmaline--13
 Monazite--9
 Allanite?--2
 Total: 599

No. 11937 (panned)

Zircon--91
 Apatite--121
 Sphene
 (a)--9
 (b)--166
 (c)--3
 Tourmaline--10
 Monazite--7
 Anatase--3
 Epidote--58 (including zoisite)
 Total: 468

No. 11962

Zircon--86
 Apatite--48
 Sphene
 (a)--20
 (b)--98
 (c)--47
 Epidote--92
 Zoisite--15
 Allanite?--5
 Total: 411

No. 11980

Zircon--81
 Apatite--19
 Sphene
 (a)--4
 (b)--67
 (c)--8
 Tourmaline--3
 Anatase--2
 Epidote--49
 Zoisite--8
 Thulite?--1
 Total: 242

Conclusions

1. The Val Verde tonalite presents a relatively limited suite of minerals of fairly constant frequency.
2. High-numbered samples at the west end of the Val Verde tunnel point to a more acid phase than the tonalite as a whole.
3. The accessory minerals are sufficiently uniform and characteristic to suggest their use in correlation.

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