MAGNETITE FROM INTRUSIVES AND ASSOCIATED CONTACT DEPOSITS
LINCOLN COUNTY NEW MEXICO

by

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Submitted in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE IN GEOLOGY

NEW MEXICO INSTITUTE OF MINING AND TECHNOLOGY

JUNE 1964

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ACKNOWLEDGMENT

The writer wishes to express his gratitude for the help given him by many on the staff of New Mexico Institute of Mining and Technology. Equipment and facilities were generously made available by Dr. Roshan B. Bhappu, Professor Morris F. Stubbs, and Dr. Frederick J. Kuellmer. Dr. Kuellmer, Dr. Clay T. Smith, Dr. Antonius J. Budding and Dr. Robert H. Weber read this paper and made suggestions for its improvement. Dr. Kuellmer served as advisor for this study and is deserving of special thanks for his guidance and encouragement.

ABSTRACT

Magnetites from four Lincoln County plutons (laccoliths?) and associated contact deposits were studied petrographically, spectrochemically, and by means of x-ray diffraction. The plutons are porphyritic and are chiefly of kalialaskitic, kaligranitic, and syenitic compositions.

Many of the accessory magnetites of the intrusives form intimate intergrowths with hornblende, biotite, sphene, and apatite. The textures indicate that some magnetite has formed at the expense of hornblende, biotite, and sphene. Magnetite grains are also disseminated among and apparently contemporaneous with feldspar groundmass grains.

Quantitative spectrochemical analyses of the magnetites were made for aluminum, calcium, magnesium, and titanium. The magnesium contents of the limestone replacement magnetites are greater than those of accessory magnetites and of magnetites from veins and pods in igneous rock. Most of the magnesium concentrations of the limestone replacement magnetites lie within the range 1 to 2% Mg. The magnetites from the Carrizo pluton all have about 2.5% Ti, and most magnetites from the other plutons have less than 1% Ti. The greater titanium content of the Carrizo magnetites does not appear to have been due to greater titanium concentration in the Carrizo magma. Instead, greater titanium content probably resulted from crystallization of the Carrizo magnetites at a lower partial pressure of oxygen than that at which the magnetites of the other intrusives crystallized. No consistent relationship was established between modes of occurrence and the relatively high aluminum and calcium contents of several magnetites.

The unit cell size of the magnetites studied has not been appreciably affected by the substitution of aluminum, magnesium, and titanium for iron, but the magnetite unit cell size does appear to increase with an increasing proportion of hematite accompanying the magnetite. A slight expansion of the magnetite unit cell prior to conversion to hematite is indicated. Two accessory magnetite samples have contracted unit cells which may be due to the oxidation of much of the magnetite to maghemite.

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INTRODUCTION

This study of magnetite was undertaken to determine the interrelationships among magnetite occurrence, composition, and unit cell size.

Specimens were collected from four intrusive bodies and associated contact metasomatic deposits in west-central Lincoln County, New Mexico (see figure 1). Additional geologic details and further references on Lincoln County may be found in Griswold (1959).

Spectrochemical analyses and x-ray diffraction measurements were made on magnetite separated from 27 intrusive rock specimens and from 19 specimens of iron vein and pod deposits. The textural relations and paragenesis of the magnetites were studied by means of 25 thin sections.

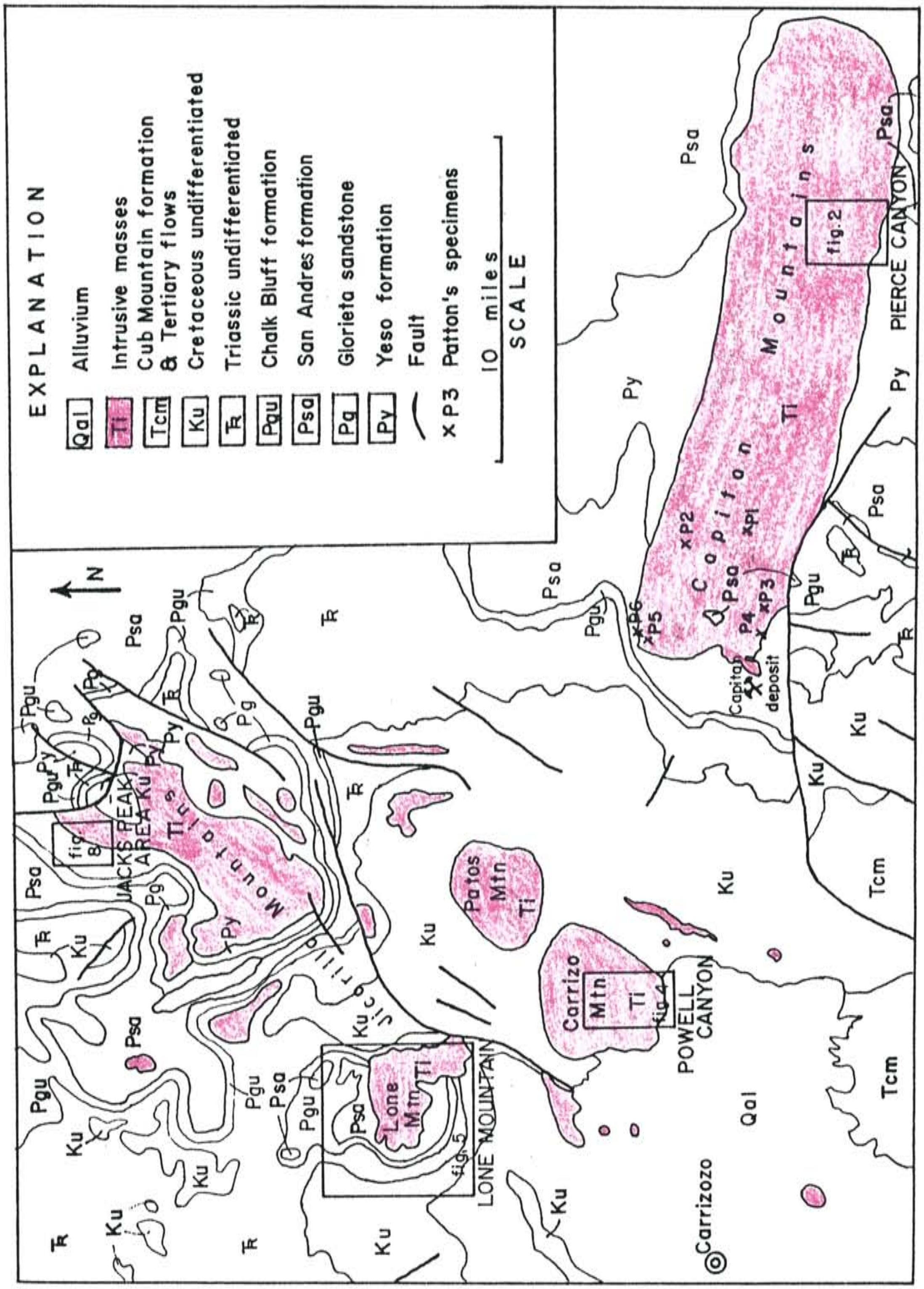

Figure 1. Geologic map of west-central Lincoln County, New Mexico. The areas covered by larger scale maps are outlined. This map is modified from Griswold's (1959) Plate 2.

SPECIMEN LOCATIONS AND MEGASCOPIC FEATURES

Introduction In this and following sections, data on intrusive rock specimens, and on magnetite obtained from them, are grouped by the intrusives from which the specimens were collected. Data on magnetite ore specimens are grouped under the name of the ore deposit. For purposes of comparison and discussion, however, additional groupings or classifications have been established.

Igneous rock specimens have been classified either as near-contact or as interior specimens. Most near-contact specimens were collected near outcrops of sedimentary rock. The strict criterion for inclusion of a specimen in the near-contact category, however, is that the groundmass grain size (determined in thin section) be markedly smaller than that of most specimens collected at least a few hundred feet from any sedimentary rock outcrop.

The magnetite of this study is classified as accessory, in igneous, or in sedimentary according to the rock in which the magnetite occurs. Accessory magnetite is that which occurs as disseminated grains or small aggregates in intrusive rock specimens. In igneous magnetite comes from iron oxide veins, veinlets, or pods in intrusive rock. In sedimentary magnetite comes from small to large massive iron oxide bodies which are enclosed by sedimentary rock or by green silicate material presumably derived from sedimentary rock.

Capitan Mountains The Capitan Mountains are an east-west trending series of peaks connected by an almost continuous high ridge about twenty miles long. The igneous rock forming the mountains is likely a single intrusive to judge from the uniform appearance of the rocks. The common kalialaskitic composition of the rocks both at the west end of the mountains and in Pierce Canyon supports this hypothesis. The texture of the rock varies from porphyritic to aplitic. The surrounding sedimentary rocks are the Permian Yeso and San Andres formations which dip away from the intrusive contact. The occurrence on the west end of the mountains of a cap of sedimentary rock similar to the sedimentary rock at the conformable west intrusive contact is offered by Kelley (1949, pp 144, 149) as evidence for a laccolithic shape for the intrusive. Patton (1951) made petrographic modal analyses of Capitan intrusive specimens from the western third of the Capitan Mountains. The locations of his specimens are shown in Figure 1, and his analyses are reproduced in Table I.

The largest known iron deposit in Lincoln County is the Capitan deposit which has an estimated ore reserve of one million tons (Kelley, 1949). This deposit, which is not included in this study, is located in limestone about 1/2 mile west of the intrusive contact (see fig. 1). Several small deposits near the intrusive contacts are described by Kelley (1949) and by Griswold (1959). These small deposits are limestone replacements and also iron bodies within the intrusive mass near the sedimentary contact. Griswold (1959) mentions the Tide iron deposit from which specimens were taken for this study.

Five intrusive rock specimens for this study were collected along a traverse up Pierce Canyon (fig. 2) and from the Tide iron deposits which are located at the mouth of Pierce Canyon (fig. 3). Megascopically, all the specimens from Pierce Canyon are very similar in texture. In all of them, feldspar phenocrysts compose about one quarter of the rock, are subhedral columnar and lathlike, and range in length from 1.5 cm down to groundmass size. The groundmass is predominantly aphanitic, although some minute grains can be distinguished by means of cleavage reflections. The dark mineral content is small in all of the rocks, and varies from about 5% in A33 down to about 1% in A30 and A26. The dark minerals recognized are hornblende, biotite, and magnetite. Euhedral sphene grains, which attain lengths greater than 1 mm, are quite noticeable in A26 (the only Pierce Canyon igneous rock specimen not studied in thin section).

The two igneous rock specimens from the iron deposits, A26 and A30, lack visible quartz and are more pink than the intrusive rocks collected farther up Pierce Canyon. In contrast to the definite pink of these rocks, the color of A36 and A37 is only faintly pink, and the color of A33 is light gray. Some quartz is recognizable in the latter three rocks. With the exception of A26, which is a dull pinkish gray-white, the intrusive rock specimens are fairly fresh-appearing and the feldspars therein are

TABLE I INTRUSIVE ROCK MODAL ANALYSES

Compositional figures are volume percent

	Specimen	Johannsen number	Classification	K-feldspar	Plagioclase	Quartz	Pyroxene	Hornblende	Biotite	Magnetite +hematite	Sphene	Apatite
Capitan	A30	119	n-c	97.4	x	1.6	-	xx	-	.6	xx	-
	A37	115	int	80.0	11.5	16.0	-	-	xx	.4	xx	x
	A36	"	"	81.3	2.1	13.7	-	-	xx	.4	xx	xx
	A33	215	"	80.0	2.5	11.5	-	1.0	3.0	.6	xx	xx
	P1	115	?	71.5	-	27.2	-	-	-	1.0	-	-
	P2	215	?	71.8	-	22.1	dark minerals = 6.0				-	-
	P3	115	?	75.2	-	24.2	-	-	-	.5	-	-
	P4	"	?	83.0	-	16.5	dark minerals = .2				-	-
	P5	"	?	72.6	-	26.7	-	-	-	.6	-	-
	P6	"	?	71.5	-	27.2	-	-	-	1.6	-	-
Carrizo	A69	115	n-c	91.5	-	6.5	x	-	-	1.0	1.0	x
	A68	215	"	84.5	xx	6.5	-	4.0	3.0	.9	-	xx
	A67	215	int	86.5	xx	7.5	-	3.5	xx	1.0	-	xx
	P7	119	?	91.2	xx	3.8	[illegible]	1.9	1.3	1.3	-	.3
	A65	215	int	86.4	1.0	5.7	xx	3.6	xx	2.0	-	xx
	A64	"	"	87.2	1.7	5.9	-	3.3	xx	2.7	x	xx
	P8	119	?	91.7	xx	3.7	-	2.5	1.2	.1	-	.1
	A62	115	n-c	83.5	xx	13.8	-	-	x	2.4	xx	-
Lone Mountain	A11	119	n-c	97.5	xx	2.0	-	-	-	x	x	-
	A41	115	int	87.5	1.0	8.0	3.5	x	-	.02	xx	-
	A12	"	"	88.0	1.0	9.5	1.5	x	x	?	xx	-
	A14	"	"	89.0	2.5	8.5	xx	x	-	?	xx	x
	A42	219	"	87.5	2.5	4.5	3.5	xx	-	.15	1.5	xx
	A44	115	"	87.0	2.5	8.0	4.0	-	-	.04	xx	-
	A45	215	"	89.0	xx	6.0	3.5	xx	-	.005	1.0	x
	A47	2210	"	71.5	13.5	4.5	1.0	2.5	xx	4.5	2.5	xx
	A49	115	"	83.0	xx	16.0	-	x	-	.15	x	x
	A5	"	"	90.5	1.5	6.0	-	xx	-	xx	1.5	xx
	A4	"	"	84.0	2.5	8.5	xx	1.5	xx	1.5	1.5	xx
	A3	"	"	85.5	4.0	5.5	-	2.5	-	1.0	1.0	xx
	A2	"	"	82.0	4.0	9.5	xx	3.0	xx	xx	xx	xx
Jacks Pk.	A60	2210	n-c	53.0	17.5	xx	1.5	14.0	-	13.0	-	1.0
	A61	"	int	39.5	31.0	1.5	3.0	14.0	2.0	9.0	xx	xx

Explanation

n-c	near-contact
int	interior
xx	.2% to 1.0%
x	<.2%
-	not observed in thin section, or not reported by Patton.

Johannsen numbers:

115	kalialaskite - leucocratic rock composed of quartz and alkali feldspa
119	orthosite - rock composed entirely of orthoclase
215	kaligranite - normal granite except that plagioclase is<5% of feldspa
219	kalisyenite - " syenite " " " "<" " "
2210	syenite

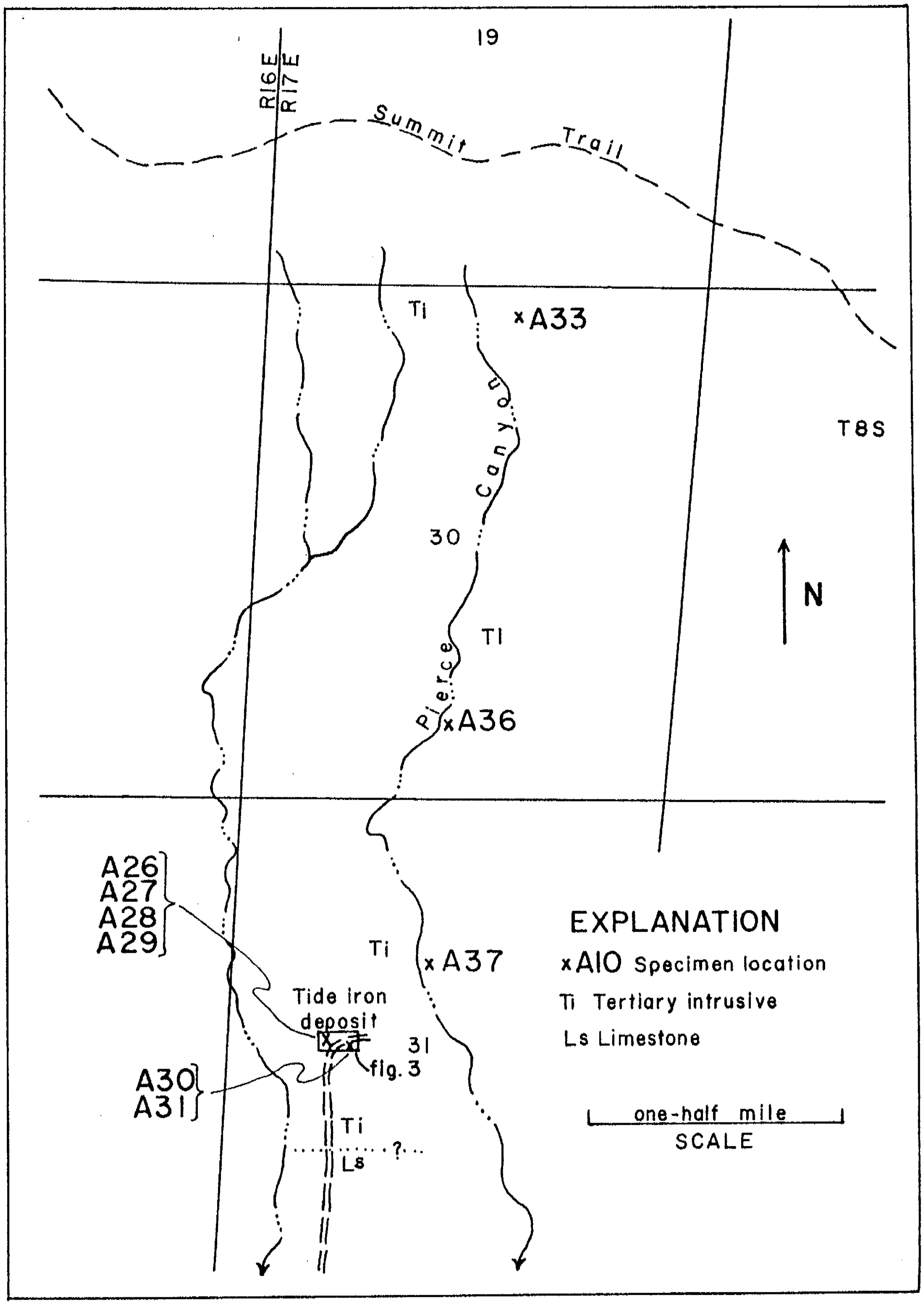

Figure 2. Map of Pierce Canyon area, Capitan Mountains, showing specimen locations.

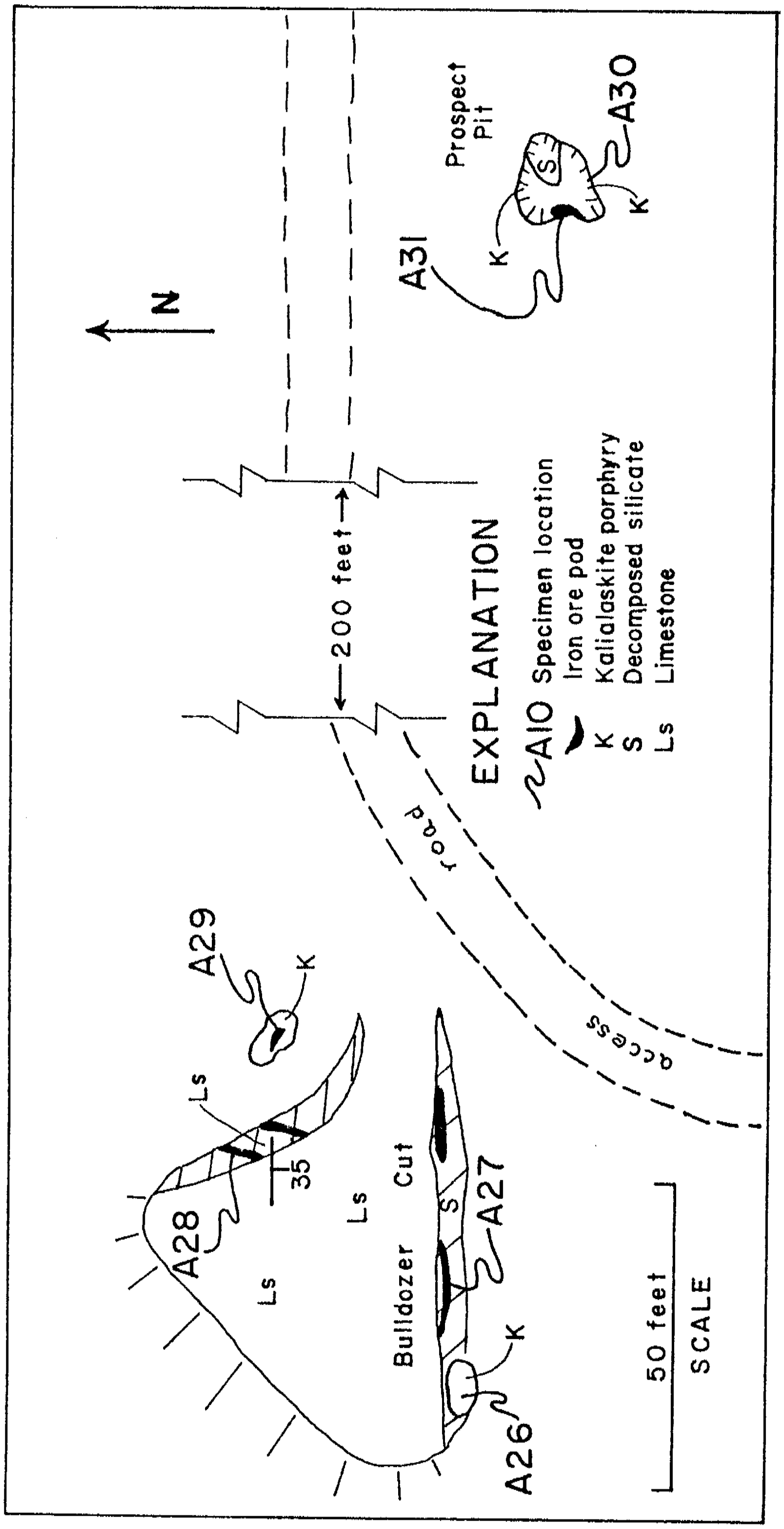

Figure 3. Sketch map of the Tide iron deposit, sec. 31, T. 8S., R. 17E.

only slightly altered. The biotite grains appear unaltered, but some of the hornblende grains have limonitic cores.

Specimen A30 is classified as near-contact because it has a smaller groundmass grain size (verified in thin section) than interior specimens A33, A36, and A37.

At the Tide deposit outcrops, the iron appears to have replaced selectively certain beds in limestone xenoliths. Iron lenses, composed of magnetite and hematite, are as much as one foot in thickness and have strike lengths of less than ten feet. Some of the limestone adjacent to the iron bodies has been silicated. Hornblende, muscovite, and quartz are recognizable, but most of the silicate is soft, decomposed, greenish material that was not identified.

Figure 3 shows the two Tide prospects that were examined and the location of the specimens taken therefrom. The ore specimens were collected from the most magnetic parts of the iron lenses. A27 and A28 are in sedimentary ore specimens, and A29 and A31 are in igneous specimens. A26 and A30 are intrusive rock specimens.

Carrizo Mountain The rock which forms Carrizo Mountain is predominantly kaligranite porphyry. No detailed geologic study of the mountain and its relationship to the surrounding sedimentary rocks has been made, but, on the basis of reconnaissance work, Allen and Jones (1951) say: "Mesaverde apparently dips under Patos and Carrizo Mountains, which are thus extrusive plug domes rather than laccoliths." Aside from the development of trachytic textures, however, the Carrizo Mountain rocks do not differ greatly in appearance from the hypabyssal rocks which form Lone Mountain and the Capitan Mountains. No iron deposits have been reported in the vicinity of Carrizo Mountain.

Specimens of the Carrizo Mountain intrusive were collected in Powell Canyon. In addition to specimens collected for this study and designated by the prefix A, the Powell Canyon map (fig. 4) shows the approximate location of Patton's (1951) specimens which are indicated by the prefix P.

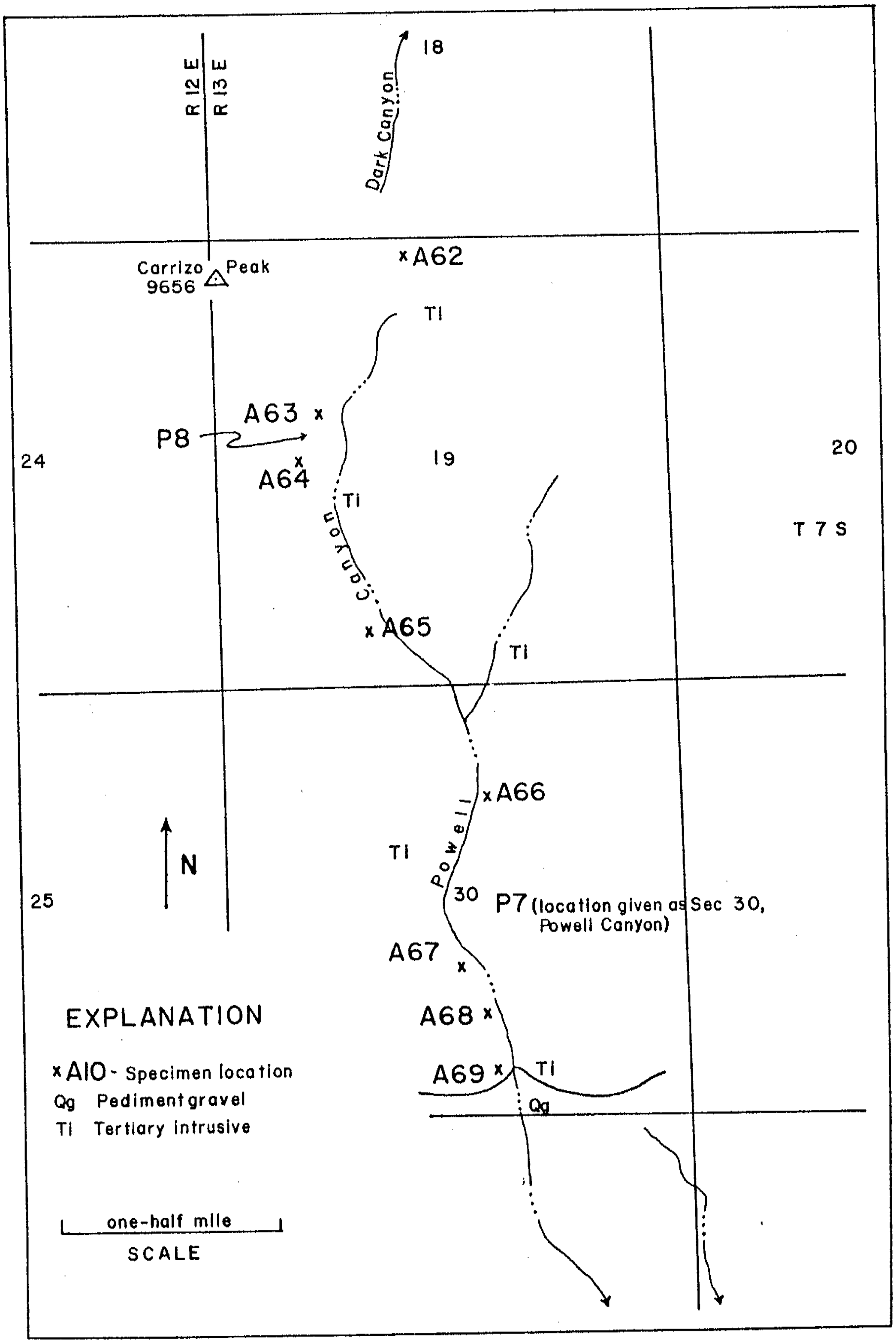

Figure 4. Map of the Powell Canyon area, Carrizo Mountain, showing specimen locations.

The rocks in Powell Canyon are fairly uniform in appearance and are light gray and porphyritic. The feldspar phenocrysts reach 5 mm in length and the groundmass is fine-grained to aphanitic. A few elongate and lath-like biotite and hornblende grains are of phenocryst size, but most of the biotite and hornblende, as well as the magnetite, is fine-grained and uniformly distributed throughout the groundmass. Only a few quartz grains are megascopically visible in these rocks.

In A68, alignment of biotite laths draws attention to the fact that the elongate feldspar phenocrysts show the same lineation. The feldspar phenocrysts in A66 also have a strong lineation, but none of the other specimens has a lineation which is megascopically evident.

Specimens A69 and A62 have a different appearance from the other specimens because they contain few phenocrysts and seem to have few dark minerals. By means of a hand lens, however, one can discern tiny black specks which are uniformly distributed throughout these two specimens. Both A69 and A62, as well as A68, are classified as *near-contact* intrusive rock specimens because their groundmass grain size (as observed in thin section) is smaller than that of the other *(interior)* Carrizo Mountain specimens. None of these specimens, however, was collected near a sedimentary rock outcrop. A62 was collected near the mountain top and may have been near the upper contact of the intrusive. A69 is from the southernmost exposure of intrusive rock, and A68 was collected about 600 feet to the north.

Lone Mountain Lone Mountain is formed of kalialaskite porphyry. The Permian and Mesozoic sedimentary rocks are domed up by this intrusive and have a semicircular outcrop pattern as shown in the Lone Mountain geologic map, Figure 5.

A number of small iron deposits have formed as replacement of limestone at the outer intrusive contacts and, more commonly, as replacements of limestone xenoliths within the intrusive. Kelley (1949) and Griswold (1959) describe the larger deposits. Among these is the Yellow Jacket mine, whose production record of 20,000 tons of ore makes it the largest producer

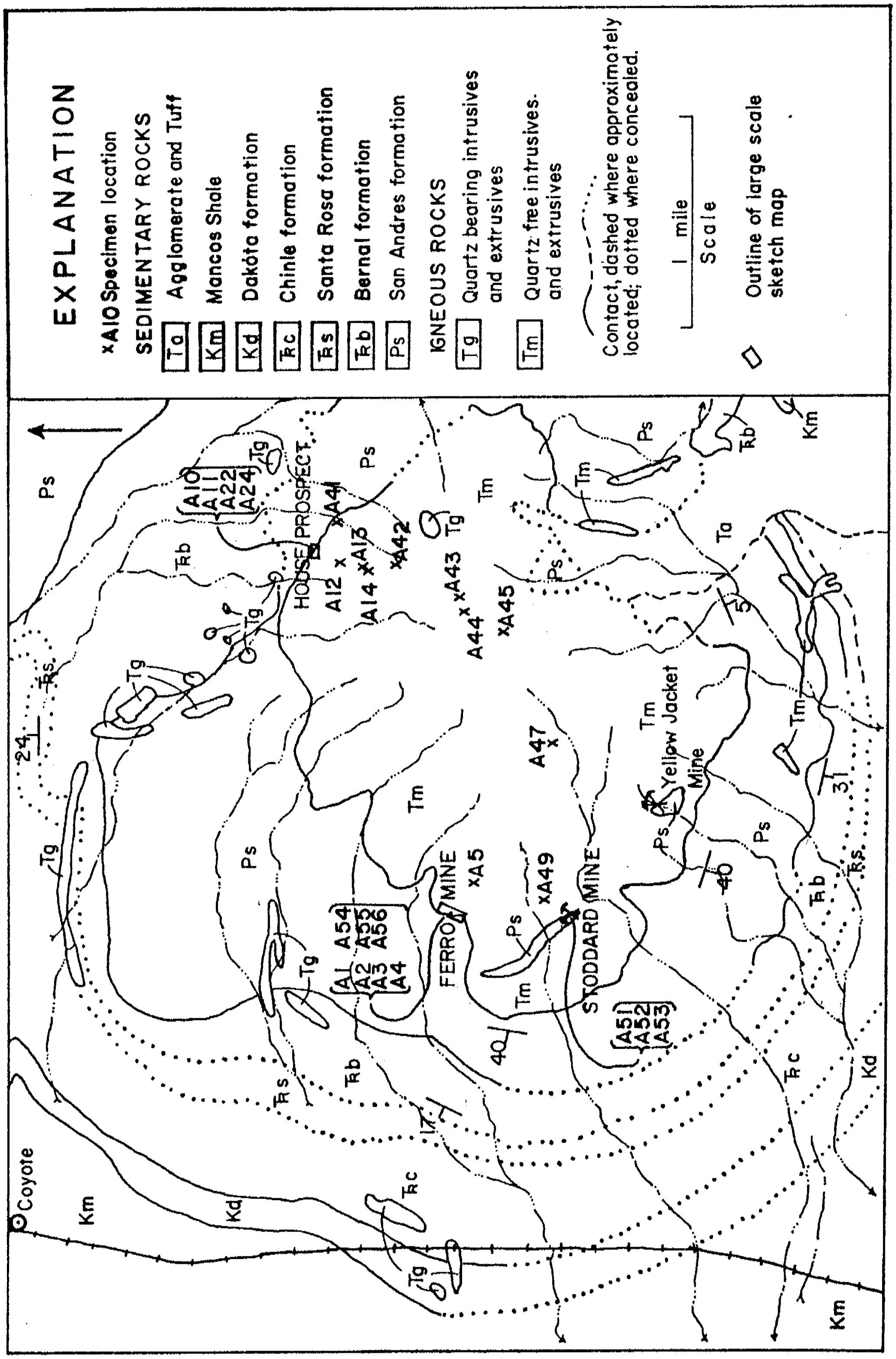

Figure 5. Geologic map of Lone Mountain showing specimen locations. Geology by Smith and Budding (1959).

of iron ore in Lincoln County. For this study, magnetite specimens were obtained from the House prospect, the Stoddard mine, and the Ferro mine on Lone Mountain. Fifteen specimens of the intrusive were collected near the ore deposits and along a traverse across the center of the mountain (fig. 5).

From one side of Lone Mountain to the other, the intrusive rock is remarkably uniform in appearance. The color of a fresh rock surface is a distinctive brownish-gray. Feldspar phenocrysts compose about one-third of the rock and reach 5 mm in size. Little quartz is visible in the rock.

The dark mineral content of most Lone Mountain specimens is about 5%, but the mineralogy of these dark minerals varies. In specimens obtained near the Ferro Mine and in specimen A47, the dark minerals are hornblende, biotite, and magnetite. In the northeast half of the mountain, however, bright green pyroxene is the dominant dark mineral, and it is accompanied by some hornblende. No magnetite or biotite is visible in specimens from this side of the mountain.

Lone Mountain intrusive rocks weather to a dull reddish-brown. Because hornblende decomposes readily, some hornblende grains are partially altered to limonite. This alteration can even be observed on otherwise fresh rock surfaces.

Specimen A47 differs from the rest of the Lone Mountain specimens in its comparative abundance of dark minerals (about 10%) and also in its higher than average plagioclase content (about 14%), as determined in thin section (table I). The color of this rock does not differ greatly from that of the other rocks, although it is discernibly less brown and more gray. In texture, it resembles the other specimens.

The smaller phenocrysts of specimen A49 differentiate it from A47 and the intrusive rock specimens collected near the Ferro mine. The dark mineral content of this rock is relatively low and it appears to contain more quartz than any of the other Lone Mountain specimens.

Specimen A11 has the same color as the rest of the Lone Mountain intrusive rock, but its entirely aphanitic groundmass causes it to appear denser than the other intrusive rock specimens, whose groundmass is both aphanitic and fine-grained. Because of its finer grained groundmass, A11 is the only Lone Mountain intrusive rock specimen that is classified as near-contact. A11 contains few dark minerals and did not furnish enough magnetite for analyses (< 25 mg of magnetite from 2 kg of rock).

The House prospect (fig. 6) is a small iron deposit from which there has been no production. It is located on the northeast side of Lone Mountain. Some of the iron ore is reported to be uraniferous (Walker and Osterwald, 1956), but uranium was not detected spectrographically in any of the magnetite specimens and none of these specimens is radioactive. The iron ore is predominantly magnetite and occurs in irregularly shaped bodies surrounded by decomposed green silicate minerals. Small pods and veinlets of magnetite are also found in kalialaskite porphyry within a selvage of epidote and actinolite. Although limestone crops out near the deposit, no limestone was observed in contact with iron ore. Ore specimens A10 and A22 are classified as in sedimentary, and ore specimen A24 is classified as in igneous.

Notable are the veinlets and fracture fillings of green silicate in the intrusive rock. A thin section of specimen A11 includes a veinlet, and the green silicate is pyroxene (pale green, slightly pleochroic, C∧Z = 66° - aegerine-augite?). In the longer adit (fig. 6) and in the pit and trench, the veinlets are closely spaced from several inches to one foot apart. In the pit, a breccia of unaltered gray limestone and kalialaskite fragments is contained in a soft, greenish-black matrix. It is thus evident that fracturing and veining occurred after crystallization of at least the outer margin of the intrusive.

Intrusive rock specimens A14 and A13 were collected from the high point of a ridge south of the House prospect. The magnetite obtained from A14 was in thin (one to several millimeters thick) fractures and veinlets. Specimen A13 is a piece of float which has the appearance of a conglomerate because rounded bits of porphyry of all sizes are contained

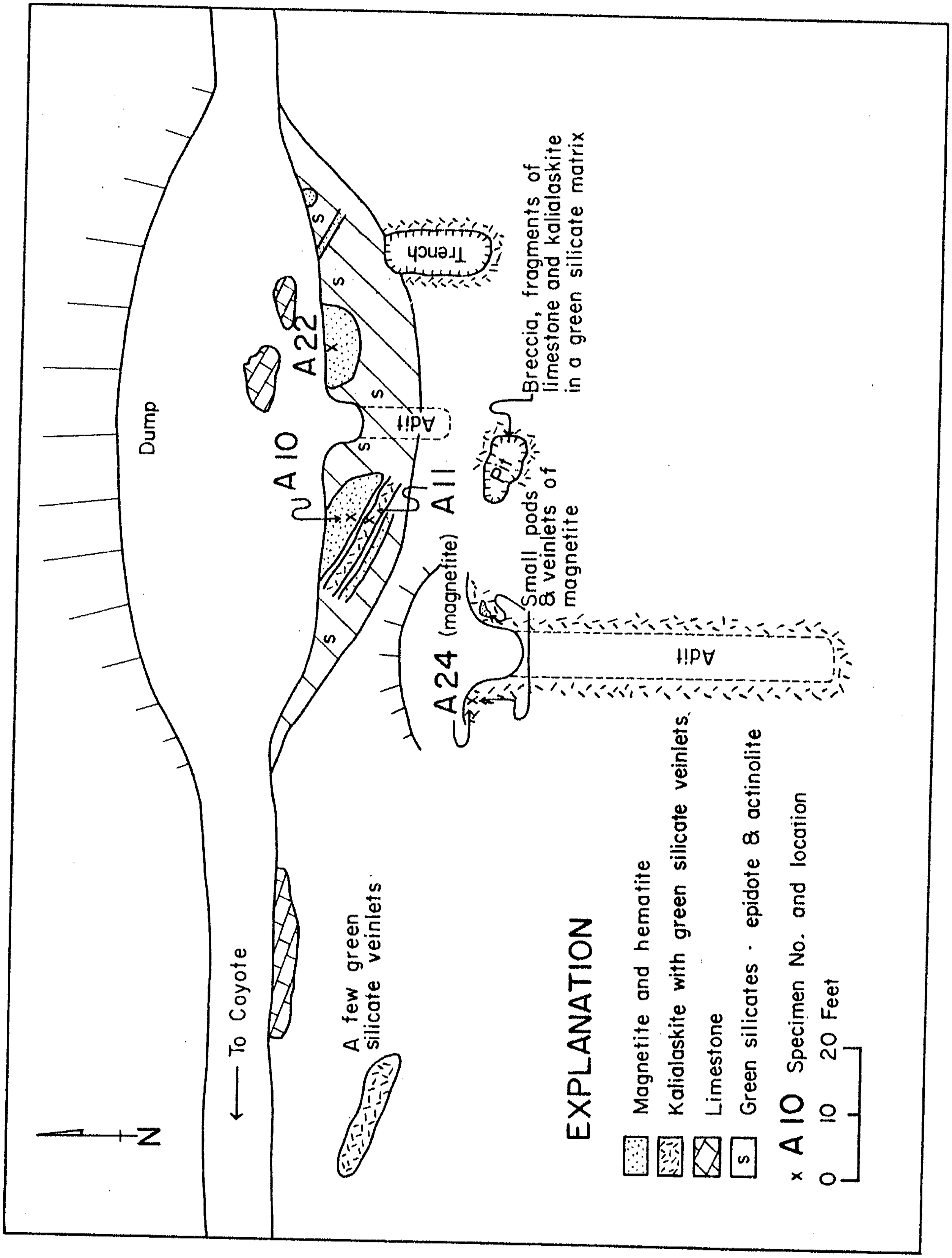

Figure 6. Sketch map of the House prospect, sec. 14, T.6S., R.11E.

in a magnetite matrix. No silicates appear to be accompanying the magnetite in either specimen. The magnetite from both A14 and A13 is classified as in igneous.

The Stoddard mine (fig. 5) began operation in 1962 and is located on the west side of Lone Mountain. Magnetite, accompanied by a little hematite and pyrite, has selectively replaced nearly flat-lying limestone beds in a large limestone xenolith. Only a little silication occurs with the iron mineralization.

Bleached porphyry, which contains no magnetite, is exposed in the north end of the quarry pit. Magnetite specimen A51 was obtained from a pod of ore in the narrow marble band next to the intrusive rock exposure. Magnetite specimens A52 and A53 were collected 100 feet and 200 feet respectively south of the intrusive contact. All three ore specimens are classified as in sedimentary.

The Ferro mine (fig. 7) is located on the northwest side of Lone Mountain. Griswold (1959) states that the tonnage of iron ore shipped from this mine may have been as high as 8,000 tons. The iron vein, which is conformable to the enclosing sedimentary rocks, strikes northeast and dips southeast toward the intrusive. Mine workings expose the vein for 500 feet. The vein reaches 6 feet in thickness in the central portions, but it becomes discontinuous at both ends and fingers out among altered sedimentary rocks. Where the vein is fairly well defined, the hanging wall is composed of gray limestone and the footwall of limey quartzite. The quartzite of the footwall contains pods and stringers of decomposed green silicates.

The ore is predominantly dense magnetite with some hematite and a few small pods of pyrite. The locations of four magnetite ore specimens and of three intrusive rock specimens obtained from this area are shown in Figure 7. All the ore specimens are classified as in sedimentary.

Jacks Peak Area Jacks Peak is a north-south trending ridge at the northern end of the group of peaks and ridges that comprise the

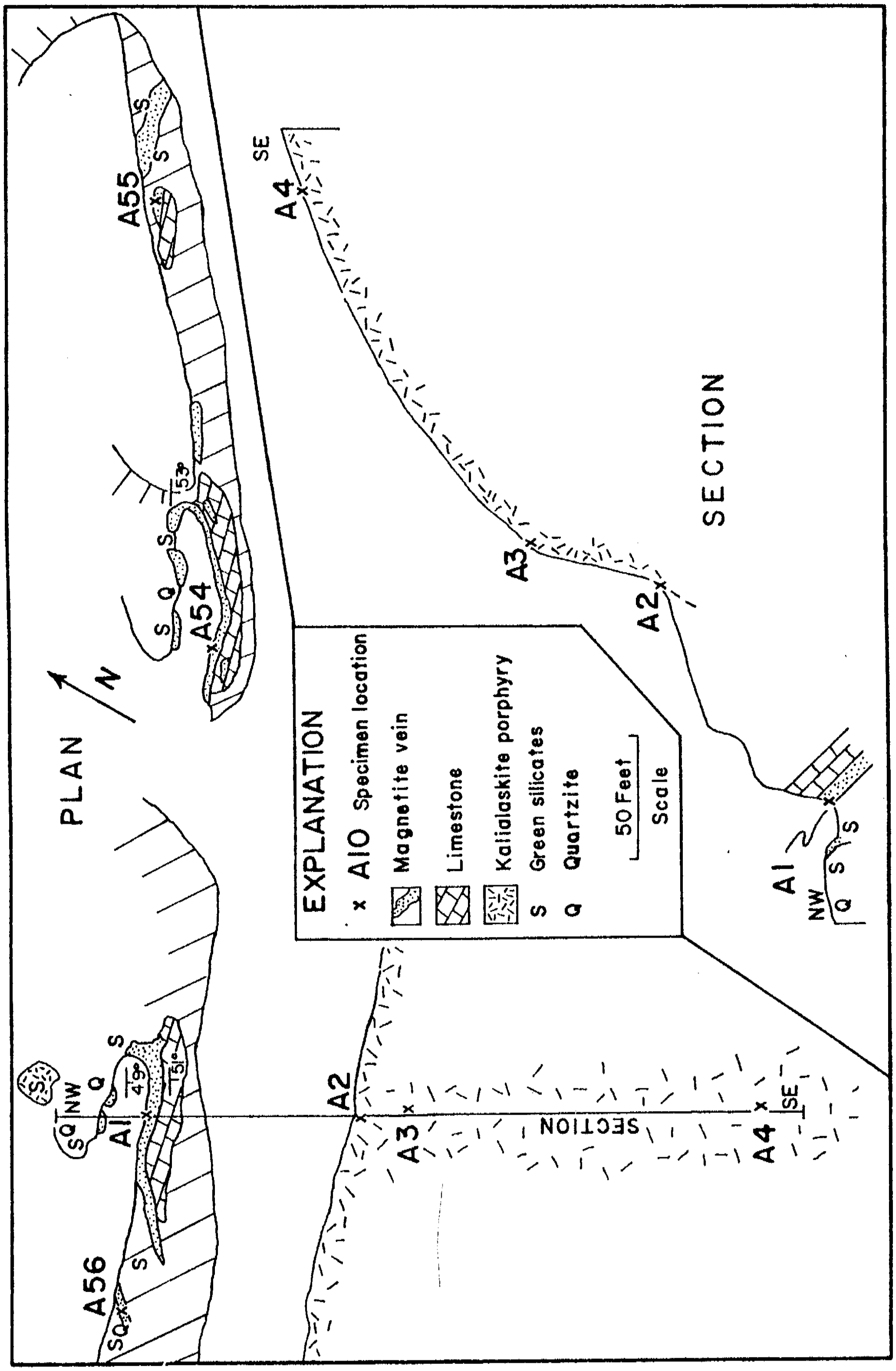

Figure 7. Sketch map of the Ferro mine sec. s 15 and 16, T.6S., R.11E.

Jicarilla Mountains. The irregular outcrop pattern of intrusive and sedimentary rocks in the Jacks Peak area (fig. 8), and in the Jicarilla Mountains in general, probably results from the partial unroofing of a large intrusive body rather than from the exposure of a number of smaller intrusives. Similarity of composition among the intrusive rocks throughout the Jicarilla Mountains and structural evidence (Budding, 1961, oral communication) support the hypothesis of a single large intrusive.

A60 and A61, the two intrusive rock specimens collected for this study from the Jacks Peak area (fig. 8), are both hornblende syenite, (or monzonite because plagioclase is nearly as abundant as orthoclase) but they differ markedly from one another in texture. A 60 is porphyritic with an aphanitic groundmass and A61 is granular with a somewhat seriate, medium grain size. The hornblende phenocrysts of A60 are dark green and euhedral and average several millimeters in length, although a few are 1 to 2 cm long. The hornblende grains in A61 are lighter green than those in A60. They are also anhedral and most are of medium grain size.

Specimen A60 is gray and contains only a few feldspar phenocrysts in addition to the hornblende phenocrysts which compose about one-quarter of the rock. The hornblende phenocrysts exhibit a crude lineation. Because of its fine-grained groundmass and proximity to outcrops of sedimentary rocks, A60 is classified as a near-contact intrusive rock specimen.

A61 is a light pinkish gray and is about three-fourths medium-grained feldspar. Hornblende forms about one quarter of the rock. A small part of the rock is formed by euhedral biotite grains which reach several millimeters in diameter.

Kelley (1949) and Griswold (1959) give brief descriptions of various small iron deposits in the Jicarilla Mountains. The deposits are magnetite and hematite replacements of limestone beds at or near intrusive contacts. Little silication accompanied the iron emplacement.

The Jack No. 1 and Jack No. 3 mines (fig. 8) together have produced 3,736 tons of iron ore, about one-half the total production of the Jicarilla district. Kelley (1949) has published a geologic map and section for each

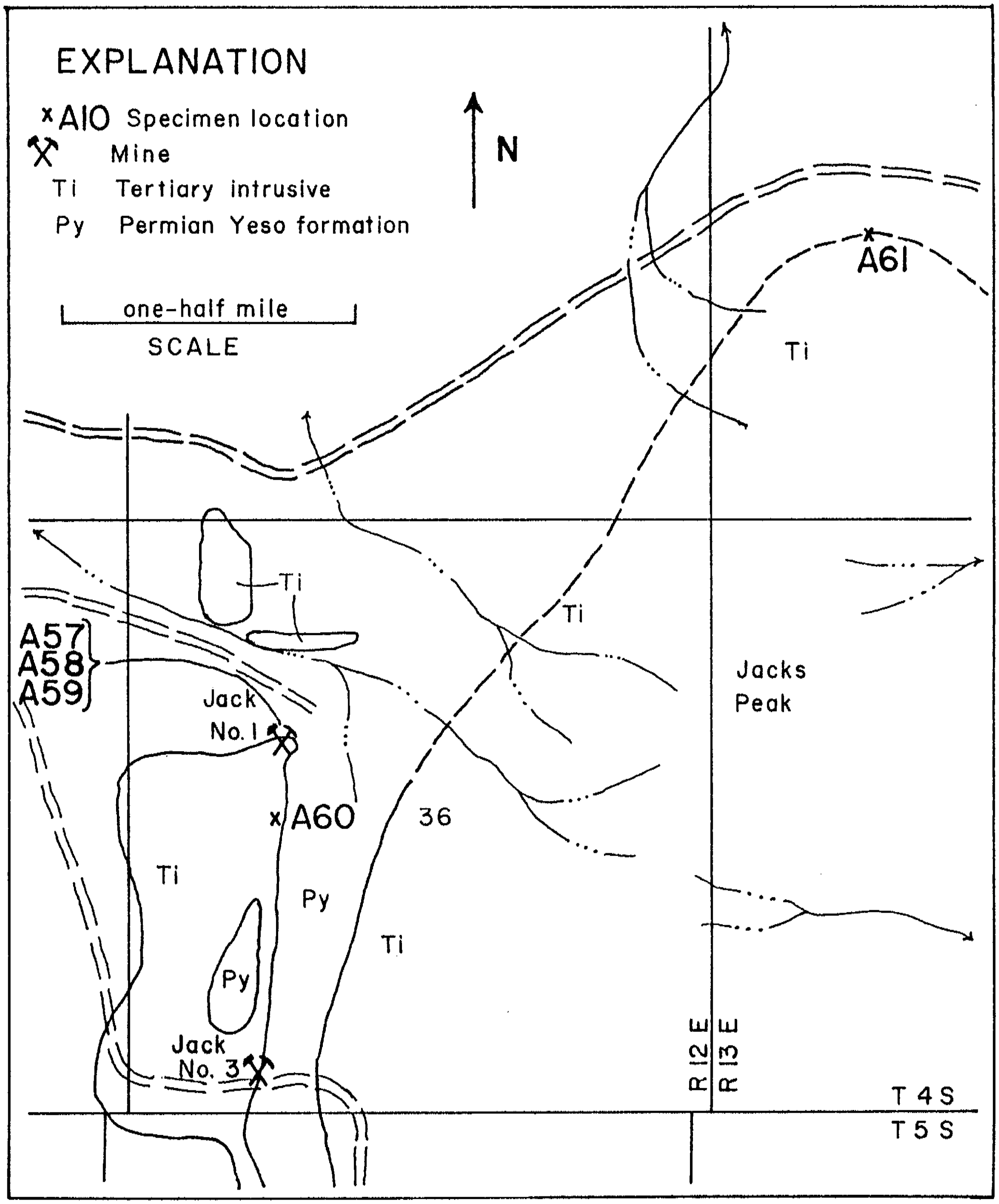

Figure 8. Map of Jacks Peak area, Jicarilla Mountains, showing specimen locations. Geology from Hibert (1960).

of the two mines. Magnetite and hematite ore have replaced limestone beds which are arched up against the syenite intrusive on the west. The two deposits lie along the same contact and are at the north and south ends of a low ridge formed by the intrusive rock. At the Jack No. 1 mine on the north end, the iron ore outcrops continuously for 250 to 300 feet, and discontinuously for an additional 700 feet southward. The outcrop width ranges up to 10 feet. At the Jack No. 3 mine, the ore deposit is smaller and, by trenching and mining, it has been exposed parallel to the intrusive contact for about 150 feet.

Ore specimens A57, A58, and A59 were collected from the iron ore outcrop 20 feet, 140 feet, and 400 feet south, respectively, of the northernmost exposure of the ore at the Jack No. 1 mine. All three of these specimens are classified as <u>in sedimentary.</u>

MICROSCOPIC FEATURES

Modal Analyses Table I contains the modal analyses which were made for this study. Patton's (1951) analyses are included and his specimen numbers are identified by the prefix P. Of twenty seven intrusive rock specimens collected, four were not studied in thin section. They are Capitan A26, Carrizo A63 and A66, and Lone Mountain A43.

The Johannsen classification for igneous rocks is used in this study and was also used by Patton. In Table I, the Johannsen numbers are used in lieu of rock names, but at the bottom of Table I, the rock names corresponding to the numbers are given along with brief descriptions of the rock types. For the exact relation between modal composition and rock number, consult Johannsen (1939) Chapter XIV.

The analyses in Table I were made by point counts consisting of 200 to 425 points. Patton made 15 traverses across each thin section with a Wentworth recording micrometer. He thus measured about 2,000 grains in each thin section. Patton's data not only provide additional information about the intrusives, but also supply a means for estimating the accuracy of the point count measurements.

Both Patton's and my Carrizo Mountain specimens were collected in Powell Canyon (see fig. 4). Except for the quartz contents, our modal compositions agree quite well. The close agreement of his two quartz values of 3.7% and 3.8%, and the grouping of my values between 5.7% and 7.5% suggest a systematic error in one of the analysis methods rather than a quartz concentration variation between the Patton specimens and those which I collected.

Estimates of the amounts of minerals present in concentrations of less than 1% were made by finding the smallest field in which at least one grain of the mineral would be observed in most views of the thin section. The estimates are indicated by x's in Table I.

The amount of magnetite in an intrusive specimen was computed from the weight of material magnetically separated from a certain amount of specimen (generally 1-2 kg). One-half the weight percent of magnetite was used for volume percent in Table I. The hematite in a specimen is considered to have been magnetically separated with the magnetite because most of the hematite observed in polished section seems to be a magnetite oxidation product with more or less magnetite remaining.

Plagioclase compositions were determined by the Michel-Levy method as described by Rogers and Kerr (1942, p 241). The method requires that the maximum angle between albite twin extinctions be measured. Most specimens had so little plagioclase that the largest angles were probably not observed. The determinations made on the low plagioclase specimens were oligoclase or calcic albite. The relatively abundant plagioclase of specimens A47, A60, and A61 is andesine.

The compositions of the Capitan, Carrizo, and Lone Mountain intrusives are fairly uniform for each intrusive. Most specimens from the three intrusives are characterized by a high content of K-feldspar, and a low content of minerals which contain calcium, magnesium, and iron. The Jacks Peak specimens, on the other hand, have considerable plagioclase, mafic minerals, and magnetite, and thus the intrusive is relatively rich in calcium, magnesium, and iron. Specimen A47 is anomalous relative to the other Lone Mountain specimens because of its high content of plagioclase, mafic minerals, and magnetite.

The quartz content of the Capitan specimens is high, relative to the other intrusive rock specimens. The Capitan near-contact specimen A30, however, has only 1.6% quartz, and Carrizo near-contact specimen A62 has 14% quartz, an amount nearly equal to the quartz content of some of the Capitan specimens. The 16% quartz content of Lone Mountain specimen A49 is considerably higher than that of the other specimens of the same intrusive, whereas near-contact specimen A11 is somewhat low in quartz.

Carrizo near-contact specimens A69 and A62 differ from the other Carrizo specimens in mafic and accessory mineral composition. A69 and A62 both have sphene, whereas the interior specimens have little or none. On the other hand, A69 and A62 both lack hornblende and biotite and the other specimens have as much as several percent of these two minerals. The magnetite content of all the Carrizo specimens, however, is fairly uniform (except for Patton's P8).

The two specimens from the Jacks Peak area, A60 and A61, are texturally different and come from outcrops separated by sedimentary rock (fig. 8), but the similarity of their mafic mineral and quartz contents suggests that they may be crystalline products of the same magma. The total feldspar content of each specimen is similar, but the proportion of plagioclase to K-feldspar differs in each. This difference may not be a real difference, however, but may instead result from the difficulty of identifying the very fine-grained groundmass feldspars in A60.

Minute zircon euhedra (.01 to .03 mm long) are very minor constituents in many of the thin sections examined.

Textures - General There is considerable textural, as well as compositional, similarity among the four intrusives studied. Table II contains a summary of the textures. The intrusives are porphyritic, holocrystalline, and anhedral to subhedral. The average grain sizes of phenocrysts and groundmass are nearly the same in most of the specimens. Feldspar phenocrysts range in size up to 5 or 6 mm in greatest dimension. The groundmass grain size averages are .1 to .2 mm. Phenocrysts compose 5 to 35% of most specimens.

Plagioclase occurs in more or less elongate rectangular anhedra which range from groundmass to phenocryst size. Most of the plagioclase is zoned and much of it has overgrowths of orthoclase. The irregularity of the outline of the plagioclase grains within the orthoclase suggests some replacement of plagioclase by orthoclase. Orthoclase occurs in some specimens along fractures in the plagioclase and also as rounded, cloud-like patches throughout the plagioclase. Separate patches of orthoclase in an individual plagioclase grain are usually optically aligned with each other. All degrees of development of this texture are observable, and in

TABLE II INTRUSIVE ROCK TEXTURAL SUMMARY

	Specimen	Class.	Textural Features
Capitan	A30	n-c	por., bimodal groundmass grain size.
	A37	int	por.
	A36	int	por.
	A33	int	por.
Carrizo	A69	n-c	por., trachytic, lathlike groundmass grains, few phenocrysts.
	A68	n-c	por., imperfect trachytic, lathlike groundmass grains predominate over equant grains, subparallel orientation of elongate grains (both phenocryst and groundmass).
	A67	int	por., subparallel orientation of elongate grains.
	A65	int	por., no preferred orientations, equant groundmass grains.
	A64	int	por., subparallel orientation of elongate grains.
	A62	n-c	por., trachytic, lathlike groundmass grains.
Lone Mountain	A11	n-c	por., groundmass grain size smaller than that of other Lone Mountain specimens.
	A41	int	por.
	A12	int	por.
	A14	int	por.
	A42	int	por.
	A44	int	por.
	A45	int	por.
	A47	int	por.
	A49	int	por., micrographic quartz-feldspar intergrowth.
	A5	int	por.
	A4	int	por.
	A3	int	por.
	A2	int	por.
Jacks Peak	A60	n-c	por., imperfect trachytic, subparallel orientation of hornblende phenocrysts, small groundmass grain size.
	A61	int	granular, seriate grain size.

Explanation

n-c	<u>near-contact</u>
int	<u>interior</u>
por.	porphyritic

many orthoclase grains a few small plagioclase remnants can be seen.

Orthoclase phenocrysts almost invariably occur in aggregates of equant individuals. These phenocrysts have sutured boundaries with one another and tend to have euhedral outlines against the groundmass. Much of the orthoclase of both phenocryst and groundmass size is microperthitic. A few microcline grains are present in most sections.

The groundmass feldspar grains are subhedral to anhedral elongate, and equant or irregular. The proportion of elongate grains relative to equant grains varies from one intrusive to another and from specimen to specimen of the same intrusive, but both shapes are present in most specimens.

Quartz is interstitial to the groundmass feldspar and thus appears to have crystallized after the feldspar. Single pieces of quartz are not usually much larger than the average groundmass grain size, but the optical alignment of several separate pieces shows that in some cases, the quartz individuals are close to the phenocryst size.

There has been some kaolinization and sericitization of the feldspars in all of the specimens, but in none of them is this alteration intense. In general, the alteration is localized along fractures, Plagioclase grains are less altered than are orthoclase grains, and the groundmass grains are more altered than are the phenocrysts.

Pyroxene and hornblende are commonly associated in textures that indicate a close genetic relationship. Attached hornblende and pyroxene grains have paralled crystallographic directions and irregular mutual boundaries. Because color difference is subtle in some cases, a grain may appear homogeneous except for the difference in the extinction angle from some parts of the grain to other parts. Patches of pyroxene with a common orientation occur in hornblende grains. This texture suggests that hornblende has formed at the expense of the pyroxene.

In some cases, biotite occurs in intimate association with hornblende. The trace of the biotite cleavage and of the hornblende cleavage directions are parallel. This mutual texture may be observed in all degrees of development from patches of hornblende in biotite to strips of biotite lying along hornblende cleavage traces.

In most thin sections, the hornblende pleochroism is moderate and the colors are yellowish-green (X), bluish-green (Y), and green (Z). The exceptions are the somewhat darker greens of the Carrizo Mountain hornblende which have no bluish coloring, and the hornblendes of Jacks Peak specimen A60 in which the hornblende is pleochroic from pale yellow (X) to medium green (Y) to dark green (Z).

Magnetite occurs as rectangular subhedra and as irregular anhedra, and is generally closely associated with hornblende, biotite, sphene, apatite, and zircon when these minerals occur in an intrusive rock specimen. Magnetite grains commonly are enclosed by larger hornblende and biotite grains. Magnetite grains also penetrate the edges of these two minerals and are concentrated near them as well. Magnetite and sphene grains are attached to, penetrate, and enclose one another. Small apatite and zircon grains are attached to and enclosed by magnetite grains.

Polished sections were made of eight intrusive rock specimens in order to identify the opaque minerals and to study the textural relationships of these minerals with one another. The eight specimens are Capitan A30, Carrizo A62, A65, and A67, Lone Mountain A2, A5, and A47, and Jacks Peak A60. The minerals recognized in these specimens are magnetite, hematite, and pyrite. Pyrite occurs as very few, minute (0.02 mm) blebs in several magnetite grains in Lone Mountain specimen A2, and in Jacks Peak specimen A60. No ilmenite could be discerned in any of the magnetite at a magnification of 360 times.

Most opaque grains in these eight intrusive specimens are combinations of more or less hematite with magnetite. In all cases in which the two minerals compose one grain, the hematite is concentrated at the grain boundaries and along fractures. Hematite plates (laths in section) penetrate the interior of magnetite grains along magnetite octahedral planes, and taper away from grain boundaries and fractures. This texture undoubtedly results from the oxidation of magnetite grains from their exterior inward.

The degree of oxidation of the accessory magnetite is somewhat greater in the smaller grains than in the larger. The proportion of a grain that is composed of hematite, however, does not appear to be related to the minerals with which the grain is associated.

Ore Specimens Polished sections were made of six of the ore specimens; Tide A31, House A10 and A13, Stoddard A52, Ferro A1, and Jack No. 1 A59. Magnetite and hematite were the only opaque minerals observed. The mutual texture of the two minerals is the same as that described above for the accessory opaque grains. In the ore specimens, the degree of oxidation of the magnetite seems less uniform than in intrusive rock specimens as observed from one part of a polished section to another. An extreme example of this variability of degree of oxidation is observable in a polished section of ore specimen A59. Part of the section is composed of magnetite which is 10 to 20% oxidized to hematite. The other part of the section is hematite which either contains a few shreds of magnetite or no magnetite at all. The grain size in the two parts is the same. The transition from the one part ot the other occurs over several grains in which the amount of oxidation of magnetite increases toward the hematite part of the section. The boundary between the magnetite-rich and hematite-rich parts is a fairly straight line on the section. In a polished section of specimen A52 from the Stoddard mine, however, the magnetite and hematite grains are intermingled. Grains of pure hematite are distributed among the more numerous grains of magnetite which contain very little hematite themselves.

Capitan Near-contact specimen A30 has a groundmass composed of about equal amounts of larger and smaller orthoclase grains. The smaller sized grains average .02 mm and are anhedral and equant. The larger grains have the same average size (.2 mm) as do the groundmass grains of the three Capitan interior specimens. The small groundmass grain size and the specimen location (see fig. 2) are the reason for classifying A30 as *near-contact*. The larger groundmass grains in A30 are elongate and subhedral. The orthoclase groundmass grains of the three interior specimens are predominantly equant and anhedral with somewhat sutured intergranular boundaries. Orthoclase phenocrysts compose 20 to 25% of each specimen.

Magnetite is similar in appearance and in textural relationships in the four Capitan Mountain specimens that were studied in thin section. Rectangular subhedra of magnetite reach .5 mm in size and are usually arranged in small clusters with other magnetite grains. Magnetite is also found as small grains disseminated in the groundmass and as irregularly shaped interstitial grains or grain aggregates (fig. 9). The feldspar phenocrysts are generally free of magnetite grains.

Apatite and sphene grains usually are attached to and also concentrated near magnetite grains. Patches and discontinuous rims of magnetite within the euhedral outlines of sphene grains are frequently observed and are evidence for the replacement of at least some sphene by magnetite (fig. 10). A polished section of A30 provides several instances in which irregularly shaped blebs of magnetite are concentrated in the outer parts of euhedral sphene grains. In the same polished section, magnetite grains contain randomly distributed, angular grains of sphene.

Carrizo Mountain The specimens from this intrusive are characterized by flow textures. The *near-contact* specimens A62 and A69 have groundmasses composed entirely of anhedral orthoclase laths which are arranged in a well-developed trachytic texture. The laths average .1 to .2 mm in length, which is about the average greatest dimension of the groundmass grains in the interior specimens. The *near-contact* specimen groundmass grains are slender, however, and consequently have less volume than the broader groundmass grains of the interior specimens.

Specimens A68 and A67 are transitional from the *near-contact* to the *interior* facies. A68 has a predominance of lathlike grains in the groundmass, and these are arranged in an imperfect trachytic texture. This specimen is included in the *near-contact* classification because

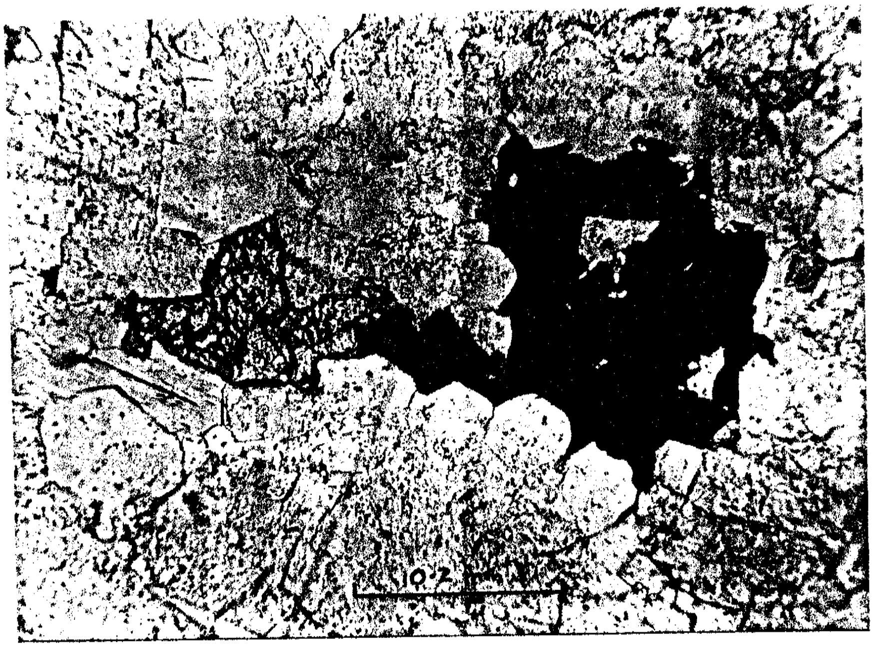

Figure 9 Specimen A36, Capitan Mts. Magnetite grains and a sphene grain are interstitial to groundmass feldspar and quartz (equant grains with no alteration). To the left and below the sphene is a bleached biotite grain (with cleavage). Minute high relief sphene and apatite grains attached to and included within the magnetite.

Figure 10 Specimen A30, Capitan Mts. Partial replacement of a euhedral sphene grain by magnetite. An irregularly shaped magnetite grain at left.

its groundmass texture is similar to those of *near-contact* specimens A69 and A62. Some of the A68 groundmass is composed of equant grains and also broadly elongate grains. The broad and equant grains predominate in A67. There are no slender laths in the groundmasses of A65 and A64, and the groundmass grains in these two specimens are either equant, or rectangular and somewhat elongate.

The flow texture of specimens A68, A67, and A64 is manifested by the subparallel orientation of all elongate grains. The elongate grains include biotite, hornblende, the elongate groundmass orthoclase grains, and phenocryst plagioclases (which are thickly overgrown with orthoclase). Specimen A65 seems to have a texture identical to the other Carrizo *interior* specimens except that its elongate grains show no preferred orientation.

Phenocrysts, predominantly orthoclase, form only 5 to 10% of the Carrizo specimens. Compared to the other Carrizo specimens, *near-contact* specimens A69 and A62 seem to have somewhat fewer phenocrysts, about 5%.

Magnetite has two modes of occurrence in the Carrizo Mountain thin sections. The greatest part of the magnetite is present in more or less uniformly disseminated grains in the groundmass. In the Carrizo *interior* specimens, minor amounts of magnetite are present as concentrations of grains which outline the missing parts of hornblende and biotite grains.

Magnetite grains are not found in the feldspar phenocrysts except along fractures and at grain boundaries within phenocryst aggregates.

The disseminated magnetite grains in all specimens are eqant and range from euhedral to anhedral in outline. In *near-contact* specimens A69 and A62, the disseminated grains average .03 mm in size, and in the *interior* specimens they average .1 mm. The grain size of the magnetite which forms pseudomorphic concentrations after hornblende and biotite is smaller than that of the disseminated magnetite in the same specimens. The magnetite in the concentrations average about .03 mm, nearly the same average size as the disseminated magnetites in the *near-contact* specimens.

Near-contact specimen A69 contains several grains of phenocryst pyroxene, which is the only mafic mineral in the specimen. A few of the larger magnetite grains are in ahd near some of these pyroxene grains. Near-contact specimen A62 contains no mafic minerals other than a few shreds of altered biotite(?) and several patches of amorphous yellow to black material. None of the alteration material has an outline which suggests the former presence of a mafic mineral. No magnetite is associated with the alteration material.

The larger magnetite grains in A62 are associated with sphene. In A69, however, the magnetite grains do not show strong association with sphene.

In the interior specimens, the magnetite grains which outline hornblende and biotite grains are concentrated between the remnants and also within some of the remnants themselves. The magnetite grain concentrations are very elongate and lathlike where they outline hornblende grains (see fig. 11), and where they outline biotite grains the concentrations are either lathlike or broadly elongate.

Some biotite grains are zoned and exhibit two shades of color when oriented in the direction of maximum absorption. The interior zone is very dark brown to black, but the exterior zone is a medium brown color. The interior zones of these biotite grains contain no magnetite, but there are concentrations of magnetite in the exterior zones, especially near the zone boundaries.

In a few instances, rod-shaped (in section) magnetite grains lie between biotite cleavage traces.

A polished section of specimen A67 shows that the opaque grains, seen in thin section, are either composed predominantly of hematite, or almost entirely of magnetite. Magnetite and hematite grains occur together, and preferred associations of the magnetite or hematite grains with other minerals oculd not be discerned.

The Carrizo Mountain hornblendes are somewhat more deeply colored than the hornblendes of all other specimens (except A60 from the Jacks

Figure 11 Specimen A67, Carrizo Mt. Concentration of magnetite is pseudomorphous after a lath of hornblende. Hornblende remnants (with cleavage) occur along the magnetite concentrations. A biotite grain (no cleavage) is crossed by the magnetite grains. The hornblende lath had a length of 4 mm, the left half of which is shown.

Figure 12 Specimen A4, Lone Mt. Magnetite grain interstitial to plagioclase grains. Sphene grain attached to the lower left corner of the magnetite. Orthoclase composes most of the surrounding material. Holes in the thin section are dark gray, magnetite is black. Crossed nicols.

Peak area), and they also do not have the usual blue-green color, but are pleochroic from yellowish-green to medium green.

Lone Mountain   A11 is the only near-contact specimen from the Lone Mountain intrusive. Its groundmass grain size average, .03 mm, is about one-tenth that of the other Lone Mountain specimens. Most of the quartz in A11 occurs as .5 mm subhedra rather than as interstitial anhedra.

In many of the interior specimens, there are a few grains with a crude micrographic intergrowth of quartz and orthoclase. In A49, however, this texture is well developed, and about one-fourth of the quartz in the specimen is part of a micrographic intergrowth. The quartz intergrowth usually occurs in only a part of an orthoclase grain. The 16% quartz content of A49 is anomalously high among the Lone Mountain specimens, and this fact is probably related to the development of micrographic intergrowths.

The Lone Mountain specimens can be divided into a pyroxene-dominant group and a hornblende-dominant group. The pyroxene group comprises the specimens from the northeast side of the mountain (specimens A11 through A45 in table I). The hornblende group comprises the specimens from the west side of the mountain (specimens A47 through A2 in table I).

The pyroxene in the pyroxene-dominant group was identified as aegirine-augite because of its pale yellow green to green pleochroism, and $Z \wedge C = 50 - 73^\circ$ (Rogers and Kerr, 1942, p 269). It occurs as anhedral equant or slightly elongate grains which are usually in aggregates. Although some magnetite is found with pyroxene, the magnetite grains are commonly distributed throughout each thin section. Some of the magnetite subhedra are contained within feldspar phenocrysts. Specimens in the pyroxene group are all low in magnetite.

The pyroxene (aegirine-augite) and magnetite of specimens A11 and A14 are confined to fractures which cross the thin sections. Many intrusive rock outcrops on the northeast part of the mountain are crisscrossed by green veinlets, but A11 and A14 were the only specimens collected which contain these veinlets.

The hornblende which occurs in the pyroxene-dominant group appears to be genetically related to the pyroxene because adjoining grains of the two minerals have parallel c axes.

In the hornblende-dominant group of specimens, much of the magnetite is within and near hornblende grains. Sphene and apatite are usually attached to and included within magnetite grains, although each of the three minerals also occurs in separate grains.

There is textural indication within this group of specimens that magnetite has partially replaced some euhedral sphene grains. Polished sections of A2 and A5 show a few textures in which magnetite appears to have filled cracks which cross sphene grains. In thin section, several instances occur in which magnetite seems to be pseudomorphous after part of a sphene grain, but this texture is not as well developed as the same texture shown in Figure 10 (photomicrograph of specimen A30, Capitan Mountains).

Most hornblende grains are in contact with groundmass feldspar only, but several textures were observed that suggest that hornblende crystallization preceded the crystallization of orthoclase phenocrysts. In specimen A3, two hornblende patches are in perfect crystallographic alignment but are separated .5 mm by a feldspar phenocryst. Because of the amount of separation, it seems unlikely that the hornblende patches were connected out of the plane of the thin section. The orthoclase phenocryst probably replaced the center part of the earlier-formed hornblende grain. In specimen A2, the presence of two .4 mm-long hornblende grains within a large orthoclase phenocryst suggests that some orthoclase crystallization succeeded that of the hornblende.

A few plagioclase phenocrysts have been broken and the pieces slightly rotated with respect to one another. This texture, not observed for any other of the minerals in Lone Mountain specimens, indicates that plagioclase crystallized before the magma stopped moving. The interstitial relationship of irregularly shaped magnetite grains or aggregates to plagioclase grains (fig. 12) suggests that this magnetite formed later than the plagioclase.

Megascopically, specimen A13 resembles a conglomerate composed of rounded intrusive rock pebbles within a magnetite martix. In thin section, the magnetite appears to be a replacement of certain feldspar grains or parts of grains, rather than a filling of fractures or of open spaces. There is no evidence of brecciation and the parts of phenocrysts which are separated by magnetite have not been rotated relative to one another.

Jacks Peak Area The phenocrysts of the near-contact specimen A60 consist of euhedral hornblende grains and a few euhedral plagioclase grains. The phenocrysts average 1 to 2 mm in size, but a few hornblende phenocrysts are considerably larger. The groundmass is composed of lathlike and equant feldspar anhedra which average .05 mm in size. The groundmass laths are arranged in a crude trachytic texture, and the elongate hornblende phenocrysts tend to conform to the orientation of the groundmass laths. Of all the rock specimens studied, A60 is the only one that does not contain orthoclase phenocrysts.

The hornblende in A60 is more intensely colored than the hornblende in any other specimen and is pleochroic from light green to dark green. The zonal growth of some hornblende grains is shown by different shades of green color and by dusty inclusions within particular zones or at zone boundaries. The hornblende grains are unusually intact and few of them are much embayed or corroded by the groundmass feldspars.

There is no marked hornblende-magnetite association in A60, and many of the hornblende phenocrysts are nearly free of magnetite. In other hornblende grains in this specimen, there is a concentartion of very fine-grained magnetite just within the outer margins.

Small magnetite grains (.02 mm average size) are rather uniformly distributed throughout the groundmass. These small magnetite grains do not occur in the hornblende or in the plagioclase phenocrysts (fig. 13). The fine-grained magnetite, then, probably crystallized after the phenocrysts.

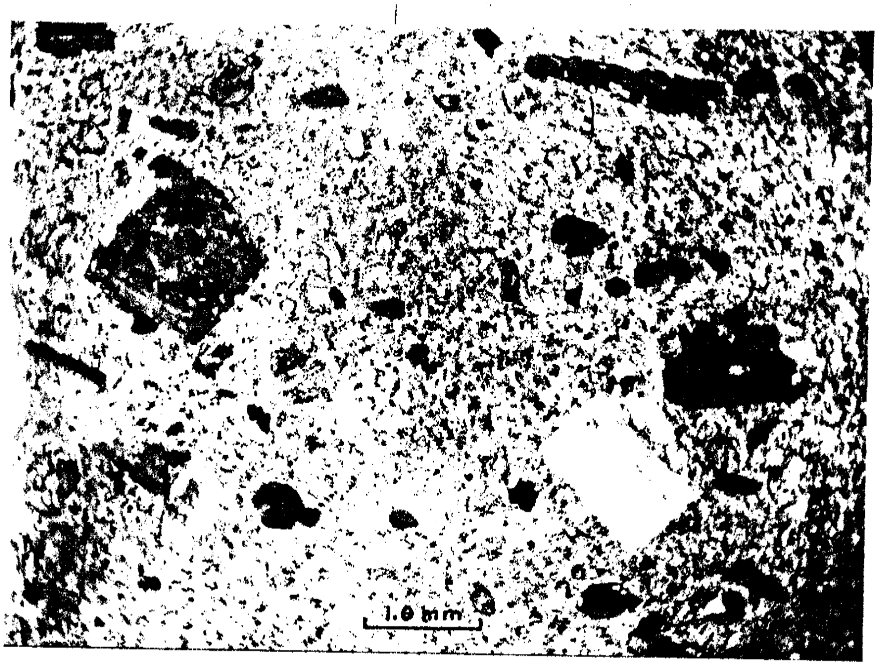

Figure 13 Specimen A60, Jacks Peak area. Magnetite grains (black) disseminated through the groundmass, but not preferentially concentrated in or near hornblende phenocrysts (various shades of gray). A euhedral plagioclase phenocryst (white) contains no magnetite.

Larger-grained magnetite (sizes from .1 to .3 mm) is neither as plentiful nor as evenly distributed as the smaller-sized variety in A60. The angular subhedral magnetites are found as individuals in the groundmass, as loose aggregates, and within or attached to some hornblende grains.

Interior specimen A61 has a seriate grain size. The larger of its orthoclase grains, which reach 6 mm in diameter, have a mesostasis composed of plagioclase laths, mafic minerals, and smaller orthoclase grains. The plagioclase grains, which average about 1 mm in length, are contained within the larger orthoclase grains. Some of the mafic minerals are also contained within large orthoclase grains.

Some mafic mineral grains, particularly hornblende, have magnetite grain concentrations nearby and within them, but many hornblende, biotite, and pyroxene grains are nearly free of magnetite. Hornblende and pyroxene are closely associated in attached grains with a common c axis orientation, and some hornblende and bitotie grains are attached to one another, but the location of magnetite concentrations does not seem to be related to either of these hornblende associations.

Hornblende and bitotie grains are corroded and embayed by orthoclase and plagioclase. Unlike the hornblende in A60, the hornblende in A61 is not strongly colored, and it has the pale yellowish-green to pale bluish-green pleochroism that characterizes the hornblende in most of the other specimens.

A61 contains a little calcite, which is interstitial and seems to be associated with the mafic minerals.

Quartz is also intersititial. The optical alignment of a number of separate pieces, however, shows that one quartz individual is 4mm across.

Magnetite Associations in the Igneous Rocks In most of the specimens studied in thin section, the association of magnetite with sphene, hornblende, biotite, and apatite is quite evident. These preferred associations of magnetite and other accessory minerals with hornblende and biotite, common in some igneous rocks, are the subject of a study by Moorhouse (1956). Moorhouse defines a parameter called the association ratio by means of which the relative degrees of closeness of association of one mineral with others may be evaluated quantitatively. Using the association ratio criterion, Moorhouse demonstrates the preferred associations of magnetite, sphene, apatite, and zircon with one another and with hornblende and biotite for several rock types. The preferred mineral associations in the specimens of this study, however, are sufficiently well developed that quantitative analysis seems unnecessary.

Possible explanations for the development of preferred mafic-accessory mineral associations are:

1. Early crystallization of magnetite and the accessory minerals and subsequent scavenging of these minerals by growing mafic minerals.

2. Late crystallization of both mafic and accessory minerals in pockets of residual melt.

3. Formation of accessory minerals from components released by the mafic minerals through resorption or other reactions. The accessory minerals may also have reaction relationships with one another.

1. In a discussion of Moorhouse's (1956) paper, Schermerhorn (1958) concluded that early crystallized magnetite and other accessory minerals are collected and incorporated by growing grains of mafic minerals which move through the melt. One objection to this proposed process is that, if mafic minerals are able to move through the melt, there should also be gravitational settling of the heavy accessory minerals, particularly the magnetite. Evidence of gravitational concentration of heavy minerals was not observed in this study, and, because of the high viscosity of acidic melts, is not to be expected.

2. Moorhouse (1956) explains the commonly observed mafic-accessory mineral associations as being the result of the late crystallization of all these minerals from pockets of residual melt. In support of this explanation, Moorhouse notes the erratic distribution of the mafic-accessory mineral aggregates and contends that this sort of distribution

is unlikely in a predominantly molten magma where the early crystallizing phases would nucleate and grow in loci of rather uniform distribution. Moorhouse also argues (without going into detail) that minerals, whose main constituents are minor or trace elements, should be late in the sequence of crystallization even though the melting point of these minerals may be relatively high. Prince (1943) makes this same point in the report on his experimental studies of the system albite-anorthite-sphene. He emphasizes that, if titanium is a minor component, much of the melt will have crystallized before sphene will start to crystallize, even though sphene has a relatively high melting point.

Within pockets of residual melt, the magnetite of this study might either have crystallized first and then been engulfed by the hornblende, or it might have crystallized with the hornblende and been included by it. The random distribution of magnetite both in and near hornblende in the Capitan and Lone Mountain specimens suggests that the two minerals crystallized independently of one another and that magnetite could either have preceded the hornblende or have been contemporaneous with the hornblende. In the Carrizo specimens, the location of concentrations of magnetite in hornblende and biotite suggests that the magnetite crystallized preferentiall on the growing hornblende and biotite.

If the hypothesis of mafic-accessory mineral crystallization from residual melt is to be compatible with the specimens of this study, it is necessary that these minerals should have crystallized after most of the groundmass grains. Several textures (each observed in one specimen only) are indications, however, that hornblende crystallized before the groundmass grains. In Carrizo near-contact and adjacent specimens, flow of the partially crystalline magma is evidenced by the trachytic texture of the groundmass and by the parallel orientation of the phenocryst grains. In specimen A65, however, only the phenocrysts (hornblende included) have any preferred orientation. The magma from which the rock of this specimen formed, then, had moved after the hornblende had crystallized, but had stopped before the groundmass crystallized.

In Capitan *near-contact* specimen A30, hornblende crystallization prior to at least part of the groundmass crystallization is deduced from the similarity of the hornblende of this specimen to the hornnblende of th other Capitan specimens. Much of the groundmass grain size in A30, however, is smaller than that in the *interior* specimens. The change in the crystallizing conditions which affected the groundmass grain size did not affect the size of the hornblende grains which thus crystallized before the change in conditions occurred.

The hypothesis of crystallization from pockets of residual melt cannot be accepted as an explanation for the associations observed in this study because the mafic minerals do not appear to have crystallized as late as most of the groundmass mineral grains.

3. In the Carrizo Mountain *interior* specimens, the formation of magnetite through the resorption of hornblende and biotite is strongly suggested by the magnetite grain concentrations that are pseudomorphous after these minerals. Resorption of biotite and hornblende to form iron oxides, plagioclase, and pyroxene is a common phenomenon in volcanic rocks and has been described and pictured by a number of petrographers (e. g. Larsen et al., 1937, or Williams, Turner, and Gilbert, 1958, pp 96 and 125). In the resorption texture described, the iron oxides form a fine dust (opacite) which outlines the destroyed mafic mineral grains. In a hornblende grain that has been only partly destroyed, the iron oxide dust is most densely concentrated at the outside of the hornblende grain where the most resorption has taken place.

The magnetite-mafic mineral textures in the Carrizo specimens differ from the common resorption texture in two ways. First, the grain size of the Carrizo magnetites in the pseudomorphous concentrations is much greater than that of the iron oxide dust of the common resorption texture. Second, the density of the magnetite concentrations does not seem to be closely dependent on the degree of destruction of the mafic mineral with whose remnants the magnetite concentrations are associated. Figure 11 shows the typical magnetite grain size and the relationship of magnetite concentrations to the hornblende remnants. The pseudomorphous concentrations of magnetite shown in Figure 11 are not much more densely concentrated between the remnants of the hornblende than they are within these remnants.

In the case of the Carrizo specimens, at least, there is little doubt that resorption has taken place and that the hornblende and biotite grains are not parts of skeletal growths which now show the fullest extent of their growth. This conclusion is based on the fact that the mafic mineral pseudomorphs and remnants show preferred orientations (flow textures) from which fact it follows that while the magma was still movin these mafic minerals were integral individuals with a degree of strength not likely to be attained by skeletal crystals.

When the resorption took place, some iron would certainly be released and thus give rise to the formation of magnetite. A slow rate of breakdown of hornblende and biotite due to gradual release of water press and oxidation of the iron produced might be the reason for development of the larger than usual (for resorption) magnetite grain size. The lack of close correlation of the density of magnetite concentrations with the deg of resorption could also be ascribed to a slow resorption rate which woul permit more migration of iron.

The occurrence of magnetite grains distributed within mafic grains is a texture common to the specimens of the Capitan, Carrizo, and Lone Mountain specimens. This inclusion of magnetite grains within mafic mine is the most difficult to reconcile with a resorption hypothesis for the origin of the magnetite. Possibly some magnetite may nucleate on the surface of growing hornblende grains and thus become incorporated with them.

Besides the decomposition of mafic minerals to produce magnetite, other reactions may be involved in the development of the observed mineral associations. The decomposition of the mafic minerals to release titanium is proposed as an origin of sphene. On page 55, a chemical equation sugge a possible reaction relationship among a calcium silicate, titaniferous magnetite, and sphene. There are probably other reaction relationships among the associated mafic and accessory minerals. Incomplete reactions would increase the number of associated minerals.

The hypothesis of mineral reaction relationships seems to be the most applicable explanation of the mafic-accessory mineral associations observed in this study.

MAGNETITE SPECTROCHEMICAL AND X RAY DIFFRACTION STUDIES

Spectrochemical Analyses   Table III contains the analyses of magnetites which were separated from the specimens collected for this study. The analyses were made by means of a 1.5 meter grating type D.C. arc spectrograph.

Quantitative analyses were made for aluminum, calcium, magnesium, and titanium, because these elements were detected in the magnetite from most specimens. An estimate of the relative silicon content was made as a check on the extent of silicate contamination in the analyzed magnetite. An estimate of the relative vanadium content is also given in Table III. All spectrograms were examined in the wavelength region from 2535 Å to 4400 Å, but no elements other than iron and the six elements given in Table III were positively identified.

Lines of the iron spectrum were used as internal standard lines for each of the analysis elements. Hasler et al. (1943) describes this use of the many-lined iron spectrum as a multiple internal standard for samples in which iron is the predominant element.

Table IV contains a list of the spectral lines used.

Six standard samples were prepared in the concentration range .007% to 2.2% for each of the four analysis elements. The element concentration ranges in Table IV indicate the range over which the standardization curves are approximately linear. The standardization curves* for each element were constructed on log-log paper by plotting element concentration versus the ratio of the analysis line intensity to the standard line intensity.

Spectral line intensity is obtained from film calibration curves* (one for each wave length region) which are log-log plots of the intensity versus the microphotometrically measured density of a spectral line on the film. For this study, the Seidel function (Ahrens and Taylor, 1961, pp 142, 143) which is a function of density, was used for the calibration curve rather than density itself. A graded series of intensities was obtained

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* Examples of these curves are contained in the appendix.

TABLE III MAGNETITE ANALYSES AND UNIT CELL DIMENSIONS

	Specimen	Classification	percent of magnetite				estimated		unit cell(A)		est. % hem
			Al	Ca	Mg	Ti	Si	V	(220)	(311)	
		accessory									
Capitan	A26	?	.6	1.1	.7	.4	-	-	8.36	8.36	40
	A30	n-c	.1	1.1	.1	1.0	xx	x	.41	.40	55
	A37	int	.5	.1	.6	.6	xx	xx	.42	.35	75
	A36	int	.4	.4	.2	.6	xx	x	.42	.35	80
	A33	int	.1	.05	-	.1	xx	xx	.42	.35	90
Carrizo	A69	n-c	.3	.1	-	2.8	xx	-	8.41	8.38	75
	A68	n-c	.4	.04	.08	2.4	xx	x	.42	.37	70
	A67	int	.4	.04	.08	2.8	xx	xx	.40	.36	75
	A66	?	.4	.05	.08	2.4	xxx	x	.40	.40	30
	A65	int	.4	.05	.1	1.4	xx	xxxx	.41	.39	55
	A64	int	.2	.04	.05	3.1	xxx	xxx	.40	.39	35
	A63	?	.5	.03	.07	2.1	xxx	xx	.40	.39	40
	A62	n-c	1.0	.8	.2	3.5	xx	-	.36	.36	-
Lone Mountain	A41	int	.2	1.0	.5	.4	x	-	8.42	8.39	55
	A12	int	.2	.2	.4	.1	x	xx	.40	.40	35
	A42	int	.1	.1	-	.4	-	xxxx	.40	.40	30
	A43	?	.1	.1	.04	.7	x	xxxx	.41	.40	50
	A44	int	.1	.2	.08	.3	x	xx	.40	.40	45
	A45	int	.3	2.1	.4	1.1	x	xxx	.40	.40	25
	A47	int	.2	.3	.2	.9	-	xxx	.40	.40	-
	A49	int	.2	.4	.08	.4	xx	-	.41	.40	35
	A5	int	.08	.05	.04	.2	-	xxxx	.40	.40	35
	A4	int	.1	.05	.06	.3	-	x xxxx	.40	.40	50
	A3	int	.08	.08	-	.4	x	xxx	.40	.40	25
	A2	int	.04	-	-	.2	xx	xxx	.40	.41	15
Jacks Peak	A60	n-c	.3	1.0	.3	1.4	xxx	x xxxx	8.40	8.40	35
	A61	int	.3	.7	.2	.8	xxx	xxxx xxxx	.40	.40	-
		ore									
Tide	A27	in sed	.8	.06	1.8	.1	x	xx	8.43	8.36	80
	A28	in sed	2.4	.2	2.1	.3	xx	xx	.43	.36	85
	A29	in ig	.6	.06	1.4	-	x	-	.40	.40	35
	A31	in ig	.06	.02	.3	.1	x	x	.40	.39	45
House	A10	in sed	.08	.03	.1	-	xxx	xxx	8.41	8.40	30
	A22	in sed	.2	.06	.8	-	xx	x	.40	.40	50
	A24	in ig	.6	.1	.4	.4	x	xx	.40	.40	-
	A13	in ig	.08	.04	-	-	xxx	x xxxx	.41	.40	50
	A14	in ig	.1	.06	.06	.1	xx	x xxxx	.40	.40	50
Stoddard	A51	in sed	.2	.02	1.1	-	-	xx	8.40	8.40	20
	A52	in sed	.2	.04	1.8	-	xx	-	.41	.41	-
	A53	in sed	.2	.02	1.1	-	x	-	.40	.40	35
	A1	in sed	.08	.02	1.8	-	x	?	8.41	8.35	80
Ferro	A54	in sed	.1	.06	1.1	-	?	-	.39	.39	-
	A55	in sed	1.4	-	4.2	-	-	x	.39	.38	-
	A56	in sed	.1	.06	.1	.2	x	xxxx	.40	.40	30
Jack No.1	A57	in sed	.2	.06	1.4	-	x	xxxx	8.40	8.38	65
	A58	in sed	.5	.03	1.3	-	x	x	.40	.38	70
	A59	in sed	.2	.02	1.3	-	xx	-	.40	.39	30

Explanation - see Table V explanation.

TABLE IV SPECTROCHEMICAL ANALYSIS LINES AND STANDARD LINES

Element	Wavelength (A) element	Wavelength (A) iron	Element concentration range
Aluminum	3961.5	3997.4	.02 - 3.5%
Calcium	3968.5	3969.3	.02 - 3.5
Magnesium	2802.7	2813.3	.04 - 1.4
Titanium	3372.8	3370.8	.2 - 2.1
Titanium	3372.8	3407.5	.2 - 3.5
Titanium	3371.5	3407.5	.7 - 3.5
Silicon	2881.6	-	relative conc. only
Vanadium	3185.4	-	relative conc. only

TABLE V ANALYSES OF REPEAT MAGNETITE SOLUTIONS

Specimen-Solution	% Conc. in magnetite Al	Ca	Mg	Ti		Si
A2-1	.04	-	-	.21		xx
2	.13	.10	.08	.24		?
3	.08	.03	-	.28		xx
A3-1	.08	.08	-	.42		x
2	.10	.08	.04	.33		?
A4-1	.14	.07	.06	.39		-
2	.10	.05	.06	.28		?
A14-1	.10	.06	.06	.14		xx
2	.10	.10	.10	.14		?
A64-1	.49	.08	.13	.24		xxx
2	.24	.04	.05	3.1		xxx
A47-1	.18	.28	.21	.98		-
2	.18	.08	.13	.70	3.18 hours*	xxx
3	.18	.35	.18	1.1	6.58	xxx
4	.18	.49	.24	.98	21.76	x

Explanation (for tables III and V)

*	time in contact with hot concentrated HCl.
n-c	<u>near-contact</u>
int	<u>interior</u>
-	concentration below limit of measurement (table IV)
xx	relative amount.
in sed	<u>in sedimentary</u>
in ig	<u>in igneous</u>

by the step sector method (Ahrens and Taylor, 1961, p 149).

For the magnetite analyses, the rock and ore specimens were ground to -50 mesh, and the magnetites were concentrated by means of a hand magnet. The magnetite concentrates were first treated with dilute HCl in order to dissolve any carbonates or apatite present. The concentrates were then washed with water, and the magnetites were taken into solution with concentrated HCl. These solutions were filtered from the silicate residues and were analyzed.

Spectrograms were obtained from the solutions by applying a drop to a graphite electrode, and then by arcing the electrode after the drop had soaked in. Sloviter and Sitkin (1944) carefully evaluate various factors involved in this method for the arcing of solutions.

Nine spectrograms were produced from each magnetite solution. For each of these spectrograms, a different percentage of the radiation produced by the arc was allowed to reach the film. For each analysis element in solution, it was thus possible to obtain a measurement of the densities of from one to six analysis-internal standard line pairs. Values obtained from different spectrograms of the same solution are generally in close agreement with one another and have been averaged to give the concentration values for the solution. Fewer than 5% of the element concentration values for the solutions are based on only one spectrogram.

The analyses of repeat solutions of magnetite from the same specimens are given in Table V. Most of the values show fair agreement with one another, but several values disagree markedly. The titanium content of the first solution of magnetite from specimen A64 is low relative to the other Carrizo Mountain magnetites, but analysis of a second magnetite solution, A64-2, gave a titanium content comparable to the other Carrizo Mountain magnetites. A possible explanation for this disparity between solutions of magnetite from the same specimen is that titanium may have been inadvertently precipitated in some manner from the A64-1 solution before filtration. The possibility of titanium loss reduces confidence in the validity of the titanium analyses because no precautions were taken to prevent this loss.

To determine the degree to which silicates were going into solution with magnetite in concentrated HCl, three solutions (A47-2, -3, -4) were prepared from the magnetite of specimen A47. Study of the A47 thin section showed that magnetite was intimately associated with hornblende, pyroxene, biotite, sphene, and apatite. Table V gives the periods of time that the magnetite concentrates were left in contact with concentrated HCl before separation of the solution from the solid residue. Solution A47-2 was filtered from the residue when all the magnetite appeared to be dissolved. The increase in calcium and magnesium concentration with time of exposure of the residue to the acid suggests that some silicate was dissolving.

The data from the three solutions are insufficient for reliable extrapolation of concentrations of calcium and magnesium to zero time of contact with concentrated HCl. Possibly more extensive studies of the sort made on the magnetite from specimen A47 would allow accurate extrapolated determinations of the concentration of an element in the magnetite itself. For the specimens from which repeated solutions were made, the solution analyses with the lowest aluminum, calcium, and magnesium values were chosen for the magnetite analyses which appear in Table III.

For most specimens, a part of the material analyzed as magnetite is actually hematite. Polished section textures (pages 26 and 27) strongly indicate that magnetite was the original mineral, and that more or less hematite developed later from this magnetite. The data in Table III suggest that the minor element concentrations in the magnetites were not affected by partial oxidation to hematite. The estimated percent hematite in the Carrizo Mountain magnetites varies considerably, but the concentrations of aluminum, calcium, magnesium, and titanium obtained for these magnetites are nearly uniform. Further, among all the magnetites analyzed, it is not possible to correlate percent hematite with the concentration variation of any element. The oxidation of the magnetite to hematite thus seems to have taken place without appreciable gain or loss of minor elements relative to iron, and the analyses obtained from the mixed iron oxides may be considered to be valid for the original unoxidized magnetite.

The close grouping of most of the element concentrations in magnetites for the same type of ore occurrence or from the same intrusive supports the belief that these values are approximately the true concentrations of the elements in the magnetites of the particular paragenesis. Concentration values which are markedly different from the values for most of the magnetite from the same occurrences must be evaluated individually to determine their significance. Some of these anomalous values may be due to analytical errors or to mineral contamination of the magnetite. Others may be real differences. Except for the anomalously low titanium value at first obtained for the magnetite of specimen A64 (Table V), however, the anomalous values have not been reinvestigated. Without verification of the anomalous values, speculation about these values is not justified.

The aluminum concentrations for most of the accessory magnetites vary from about .1% to .5% and there do not seem to be any significant differences among the four intrusives or any trends within a particular intrusive. No explanation is apparent for the anomalously high value for A62 (1.0% Al) or the low value for A2 (.14% Al).

The aluminum concentrations of the ore magnetites have about the same range as those of the accessory magnetites . There appear to be no consistent or significant differences either between the in sedimentary and in igneous specimens, or among magnetites from different deposits. Anomalously high aluminum values were determined for ore specimens A28 and A55, which also have the highest concentrations of magnesium. Because of local conditions in the sediments, the destruction of the sedimentary minerals by the iron-bearing solutions may have released greater amounts of aluminum and magnesium when the magnetites of A28 and A55 were forming than when the other ore magnetites were forming. As a result of the higher concentrations, more magnesium and aluminum was incorporated into the A28 and A55 magnetites than in the other ore magnetites.

The calcium values for most of the accessory magnetites are less than .5%. The few magnetites with relatively high calcium values, if these values are accompanied by substantial titanium concentrations, suggest some contamination by sphene. In Table VI, the high calcium and titanium analyses are reproduced from Table III along with an estimate of the amount of silicon and the modal content of sphene (from Table I) for each specimen from which the magnetite came. Except for the magnetite of specimen A62 (which contains no sphene) all the calcium content of the magnetites shown in Table VI could be due in part to sphene contamination.

TABLE VI MAGNETITE ANALYSES POSSIBLY AFFECTED BY SPHENE CONTAMINATION

Specimen	Ca	Ti	Si(est)*	sphene**
A26	1.1	.4	-	1%
A30	1.1	1.0	xx	xx
A41	1.0	.4	x	xx
A45	2.1	1.1	x	1%
A60	1.0	1.4	xxx	-
A61	.7	.8	xxx	xx
A62	.8	3.5	xx	xx

* from Table V

** from Table I except A26 which is estimated from the hand specimen.

Corrections for silicate contamination in the analyses of magnetites are possible if quantitative determinations of silicon have been made. The silicon is combined with the necessary amounts of elements, deducted from the magnetite analyses, to form the silicates which have been identified as accompanying the magnetites (Vincent and Phillips, 1954). Because the silicon analyses are only semi-quantitative, this correction is not possible for the data of this study. Nor is it possible to combine the calcium and titanium in the stoichiometric proportions of sphene and then to deduct them from the magnetite analyses, because, in most cases, the amount of calcium exceeds the amount of titanium. Thus, not all the calcium could have come from sphene.

None of the ore specimens yielded a calcium analysis greater than .2%, and most gave calcium values of less than .06%. There must have been a considerable concentration of calcium in solution at the time of formation of the *in sedimentary* magnetites, and so the low calcium contents of these magnetites show that calcium does not readily substitute for iron in magnetite.

Most of the magnesium analyses for the *accessory* magnetites are low. The highest magnesium values were obtained for two of the Capitan specimen magnetites (.7% and .6% Mg). The magnesium contents of the other Capitan magnetites and of the magnetites from the other intrusive rock specimens range from .5% Mg to below the limit of measurement (.04% Mg). No trends or correlations could be established for the variations of magnesium concentration in the *accessory* magnetites.

All but three of the *in sedimentary* ore specimen magnetites gave magnesium values of greater than 1%. It is likely that the magnesium in the magnetite of these specimens was furnished by dolomite in the replaced sediments. The low calcium values for the same specimens show that the presence of magnesium does not result from carbonate contamination of the analyzed magnetite.

Nine of the fourteen *in sedimentary* magnetite specimens have magnesium concentrations in the 1.1 to 1.8% Mg range. This grouping of concentrations indicates that a condition common to these specimens at the time of the magnetite formation was the dominant factor in the determination of the amount of magnesium substitution for iron. The ionic radius of Mg^{2+} is less than that of Fe^{2+} (0.78 vs .83 Å, Mason, 1952, p 68), and so the enthalpy of the substitution of magnesium for iron is probably negative. Therefore, the availability of magnesium rather than temperature should determine the amount of magnesium in magnetite. It is easier to conceive, however, that the temperatures of the formation of the *in sedimentary* magnetites were somewhat uniform, rather than that the replaced sediments had a uniform magnesium content at the different deposits.

The relatively low magnesium contents of the *in sedimentary* specimens A10, A22, and A56 suggest either that these magnetites formed by replacement of sedimentary rocks that had little magnesium, or that the magnetite may have been emplaced in previously silicated rock, or that the magnetite came from bodies with less close associations with limestone than the specimens from which the magnetite with more magnesium came. Specimen A10 came from a magnetite body next to a thin porphyry body (fig. 6), specimen A22 came from an outcrop which is near limestone outcrops (fig. 6), and specimen A56 was in contact with limy quartzite. Most of the relatively high magnesium in sedimentary magnetites came from outcrops directly in contact with limestone (for example, A1, A54, and A55, the Ferro mine, fig. 7).

In contrast to the relatively high magnesium content of most in sedimentary ore specimens, four of the five in igneous ore specimens have magnesium contents of less than .5%. This lower magnesium content most likely reflects lack of available magnesium at the time of magnetite formation. In igneous specimen A29 furnished magnetite with 1.4% Mg. This specimen came from a pod of magnetite in a porphyry outcrop which is within ten feet of a limestone outcrop (fig. 3). At the time of formation of the magnetite pod, limestone could have been even closer and the solution from which the magnetite deposited could have contained magnesium which had been dissolved through attack on the limestone.

As discussed above, determination of the titanium content of accessory magnetites is subject to uncertainty owing to possible contamination of the analyzed samples by sphene. In the case of the Carrizo accessory magnetites, however, the low calcium concentrations and the lack of correlation of sphene content with titanium concentrations (some specimens have no sphene) indicates that there has been little contamination of these magnetites by sphene. Furthermore, the grouping of the Carrizo analyses around 2.5% Ti suggests that the actual titanium contents in magnetite are somewhat uniform throughout the intrusive and have an average titanium concentration not far from this value. Because precipitation of titanium may have occurred before the analysis of the solutions, however, the uncertainty of the analysis is great enough that the recognition of actual trends in titanium among the magnetites from different Carrizo specimens is not justified.

The titanium contents of magnetites from specimens of the Capitan, the Lone Mountain, and the Jacks Peak intrusives are between .1% and 1.4%. Contamination of the magnetite by sphene may be responsible for some of the higher titanium values, but the magnetite with the highest titanium concentration comes from Jacks Peak specimen A60 which contains no sphene.

The titanium in most of the ore specimen magnetite is below the limit of measurement (.1% Ti), but the .3% Ti value for in sedimentary specimen A28 and the .4% Ti value for in igneous specimen A24 suggest that titanium can be transported with iron in ore-forming solutions. Determination of the conditions under which titanium is incorporated into the manetite pods and veins would require more study of these occurrences.

The vanadium content is relatively high in the accessory magnetites from the Jacks Peak specimens, and in the magnetites from in igneous specimens A13 and A14. The vanadium content is uniformly low in the accessory magnetite from the Capitan specimens and in the ore specimens from the Tide deposit. In the remaining intrusives and ore deposits, the vanadium content of magnetite does not seem to be uniform for each occurrence, because the magnetite from each intrusive and ore deposit gives a range of vanadium contents. Among all the specimens, the vanadium content of the magnetite does not seem to correlate with either the minor element content of the magnetite or with the type of magnetite occurrence.

X-Ray Diffraction Study Accompanying the spectrochemical data in Table III are the magnetite unit cell sizes computed from two inter-planar spacings, and also an estimate of the amount of hematite with the magnetite.

A North American Philips x-ray diffractometer and unfiltered iron radiation were used in the x-ray studies. Magnetite was mixed with a silicon internal standard, and the mixture was applied as a smear to a glass slide for the measurements. The goniometer of the diffractometer traversed from $2\theta = 35.5°$ to $2\theta = 45.5°$ at a rate of 1/4° per minute. Measurements of the magnetite (311) and (220) reflections (at $2\theta = 45°$ and $38°$ respectively) were made from the silicon (111) reflection (at $2\theta = 35.95°$). The 2θ angle of a reflection was taken as the center at two thirds of peak height above background.

Two measurements of the 2θ angle of each reflection for a magnetite specimen were obtained by traversing the 2θ region of interest in both directions. The two values thus obtained never differed by more than .05° 2θ, and usually agreed to within .03° 2θ. In the 2θ region used for this study, a $\Delta 2\theta$ of .05° gives a Δ unit cell dimension of .01 Å. The unit cell dimensions in Table III are therefore given to .01 Å.

X-ray powder photographs were made of magnetite from specimens A55, A61, and A62 in order to derive a unit cell size from a number of high angle reflections. A 114.6 mm diameter Straumanis mount camera was used with iron K-alpha radiation. The results are presented in Table VII with the diffractometer results reproduced for comparison.

TABLE VII MAGNETITE UNIT CELL SIZES AS DETERMINED BY TWO METHODS

Specimen	method	a (220)	a (311)	a_o
A55	diffractometer	8.388	8.382	
A55	powder camera	8.388	8.384	$8.388 \pm .009$
A61	diffractometer	8.399	8.402	
A61	powder camera	8.389	8.407	$8.395 \pm .005$
A62	diffractometer	8.358	8.359	
A62	powder camera	8.349	8.331	$8.352 \pm .008$

Because of the scatter of unit cell values, a, computed from each reflection, and plotted against functions of θ, no extrapolation could be made to the unit cell value a_o for $2\theta = 180°$. The a_o values given in Table VII are estimated averages of the a values. The spread of the a values is indicated with the a_o values. The a values computed from the diffractometer (220) reflections agree with the a_o powder photograph values to within .01 Å.

The estimate of the percent hematite in the magnetite (table III) was obtained by dividing the peak height of the hematite (401) reflection (the strongest hematite reflection) by the sum of the heights of the hematite (401) and magnetite (220) peaks, and multiplying the quotient by 100.

For all specimens with less than 50% hematite, the magnetite unit cell dimensions computed from the (220) and (311) reflections differ by no more than .01 Å. For most specimens with greater than 50% hematite with the magnetite, the unit cell size computed from the (311) reflection is .02 to .07 Å less than the unit cell size computed from the (220) reflection. This discrepancy occurs because of the broadening of the peak of the magnetite (311) reflection (d = 2.53 Å) by the adjacent strong hematite (110) reflection (d = 2.51 Å).

Unlike the magnetite (311) reflection, the magnetite (220) reflection has no adjacent hematite reflection, and so the unit cell measurement derived from this reflection is considered to be the more accurate. The unit cell size obtained from the magnetite (311) reflection is corroborative for the specimens in which the amount of hematite in the magnetite is less than 50%.

Almost all the magnetites that contain less than 55% hematite have unit cell sizes of 8.40 Å. This value is within .01 Å of Basta's (1957) determination of the magnetite unit cell size as 8.3963 Å, the value used by the American Society for Testing Materials for x-ray card 11-614 (starred to indicate data of high reliability).

Most of the magnetites with greater than 50% hematite have unit cell sizes, computed from the magnetite (220) reflection, which are greater than 8.40 Å. These expanded unit cells range from 8.41 Å to 8.43 Å. The magnetite unit cell may expand as a preliminary stage in the oxidation of magnetite to hematite. A large portion of hematite with magnetite indicates that considerable oxidation has taken place, and suggests that much of the remaining magnetite has the expanded structure of the hypothetical intermediate stage in its conversion to hematite.

Differences in the unit cell sizes of the magnetites appear to be unrelated to variations in the concentrations of aluminum, calcium, magnesium, and titanium. Basta (1959) points out that substitution of aluminum and magnesium for iron in magnetite causes contraction of the unit cell, but he shows that magnetites with relatively high contents (several percent) of these elements have unit cell sizes within .01 Å of the unit cell size of pure magnetite. Titanium in magnetite causes an increase in unit cell size and the titanium in some of the magnetites studied by Basta (1959) apparently counteracts the contraction effects of the magnesium and aluminum. The effect of calcium on the magnetite unit cell size is not discussed by Basta, but from its position in the periodic table relative to iron, one would infer that calcium in magnetite causes an increase in unit cell size. In any case, the concentrations of aluminum, calcium, magnesium, and titanium in the magnetites of this study are probably too low to be the cause of detectable unit cell size variation.

The small cell sizes (8.36 Å) of the accessory magnetites from specimens A26 and A62 are not explainable on the basis of the minor elements in them or the percent of accompanying hematite. These magnetites may be partially oxidized to maghemite (gamma Fe_2O_3) which has an inverse spinel structure and is magnetic (Basta, 1959). Basta maintains that magnetite may oxidize continuously to maghemite and that the unit cell size of solid solutions of the two minerals varies continuously from that of pure magnetite (8.369 Å) to pure maghemite (8.335 Å).

Specimen A26 was not studied microscopically, but specimen A62 was examined both in thin and polished section. Much of the magnetite in specimen A62 is fine grained (average .03 mm) and is disseminated in the groundmass. Possibly this fine grain size facilitated oxidation of the magnetite to maghemite rather than directly to hematite. This proposition is supported by the work of Lepp (1957) who, by grinding the magnetite to -250 mesh (.06 mm), was able to produce maghemite as an intermediate phase in differential thermal analyses of the oxidation of natural magnetites to hematite. Previous investigators were able to obtain maghemite only from synthetic magnetite and not from natural magnetites. Lepp's work showed the importance of fine grain size for the production of maghemite and that the failures to produce maghemite from natural magnetites were due solely to the coarse grain size of the magnetite used.

Davies and Evans (1956) found that x-ray identification of maghemite is possible if maghemite composes more than 80% of the maghemite-magnetite solid solution because maghemite has six reflections which are not produced by magnetite. For my study, a Debye-Scherrer powder photograph of A62 was made using Fe K-alpha radiation. The Fe K-beta reflection from the strongest magnetite reflection (311) interferes with the Fe K-alpha reflection from the (221) plane which gives the strongest reflection that is exclusive to maghemite. Thus the x-ray identification of maghemite in magnetite would require the use of cobalt radiation.

The unit cell size measurements suggest that magnetite may oxidize in two ways, one of which produces an expanded magnetite unit cell as an intermediate stage, and the other way is through conversion to maghemite which is manifested by a decrease in cell size.

Discussion of the Titanium Content of the Accessory Magnetites The concentration of titanium in accessory magnetites probably depends on several factors, any of which may be dominant depending on the given situation. The factors are concentration of titanium in the melt, temperature of formation of the magnetite, and oxygen pressure in the melt. The saturation concentration of titanium in magnetite is a function of the temperature of formation of the magnetite. The increase in the saturation concentration of titanium in magnetite with temperature is the basis for the use of this concentration as a geologic thermometer (Buddington et al., 1955). In order to use the titanium concentration in magnetite as a geologic thermometer, however, it is necessary to demonstrate that the magnetite was saturated with titanium. Buddington considers that the presence of separate ilmenite grains with the titaniferous magnetite is proof that saturation of the magnetite with titanium was attained. No ilmenite was detected in the rocks of this study, however.

The partial pressure of oxygen, Po_2, may be important in the determination of the amount of titanium in magnetite because of the manner in which the titanium is dissolved in the magnetite. Verhoogen (1962) suggests that the titanium may be in magnetite in the form of ulvospinel, Fe_2TiO_4. It has also been suggested that the titanium may be in the form of gamma $FeTiO_3$ (which has a defect spinel structure and so is analogous to gamma Fe_2O_3, maghemite). In either case, the solution mechanism involves the addition of iron(II) to the magnetite. A reaction which involves the solution of iron(II) in magnetite along with the titanium and which is dependent on the Po_2 is:

$$3CaSiO_3 + (3FeTiO_4)|_{\text{in magnetite}} + O_2 = 3CaTiSiO_5 + 2Fe_3O_4,$$

in which $CaSiO_3$ represents any calcium-bearing silicate, or the calcium in the melt. The presence of magnetite, of course, restricts the range of the Po_2 at a given temperature. From this equation, it appears that higher Po_2's would result in lower titanium concentration in magnetite.

It is now of interest to see how the influence of temperature, titanium concentration in the magma, and Po_2 might help to explain the observed behavior of the titanium concentration of the magnetites from the intrusive rocks of this study. The specific problems are: 1. the reason why the titanium concentration in the magnetites of an intrusive remains fairly constant from specimen to specimen while the total content of titanium in the specimens varies considerably owing to the presence or lack of sphene in the specimen; 2. the reason why the magnetites of the Carrizo intrusive have a higher concentration of titanium than the magnetites in the other intrusives studied.

An estimate of the amount of titanium in most of the igneous rock specimens was obtained by using the rock modal analyses. Table VIII contains these estimates. The mafic minerals (hornblende, biotite, and pyroxene) were each estimated to have 1% Ti, the analysis titanium content was used for the magnetite, and the stoichiometric titanium content was used for the sphene. Because of its relatively high content of sphene, Lone Mountain specimen A47 has the highest estimated total titanium content, which is .7% Ti. Most of the other rocks that contain sphene have about .3% Ti. Rocks that do not have sphene generally contain less than .1% Ti.

TABLE VIII DISTRIBUTION OF TITANIUM IN THE IGNEOUS ROCKS

	Specimen	sphene	magnetite	mafics	total	magnetite	% Ti in magnetite
		(amount of titanium in % of rock)				(modal %)	
Capitan	A26	?	-	?	?	.01	.4
	A30	.25	.006	.01	.27	.6	1.0
	A37	.25	.002	.01	.26	.4	.6
	A36	.25	.002	.01	.26	.4	.6
	A33	.25	.001	.04	.29	.6	.1
Carrizo	A69	.25	.028	.002	.28	1.0	2.8
	A68	-	.021	.07	.09	.9	2.4
	A67	-	.028	.045	.07	1.0	2.8
	A66	?	.05	?	?	2.1	2.4
	A65	-	.028	.056	.08	2.0	1.4
	A64	.05	.084	.043	.18	2.7	3.1
	A63	?	.05	?	?	2.4	2.1
	A62	.25	.084	-	.35	2.4	2.5
Lone Mountain	A41	.25	-	.01	.26	.02	.4
	A12	.25	-	.01	.26	.02	.1
	A42	.38	.001	.01	.39	.15	.4
	A43	?	.001	?	?	.1	.7
	A44	.25	-	.04	.29	.04	.3
	A45	.25	-	.045	.30	.005	1.1
	A47	.625	.04	.045	.71	4.5	.9
	A49	.05	.001	.002	.05	.15	.4
	A5	.38	.002	.01	.39	1.0	.2
	A4	.38	.004	.035	.42	1.5	.3
	A3	.25	.004	.025	.28	1.0	.4
	A2	.25	.002	.05	.30	1.0	.2
Jacks Peak	A60	-	.182	.155	.34	12.7	1.4
	A61	.25	.072	.190	.51	9.0	.8

The amount of sphene essentially determines how much titanium there is in a rock because the other titaniferous minerals (mafic minerals and magnetite) not only are minor constituents of most rocks of this study, but also (probably) have low concentrations of titanium. Errors in the modal analyses of these minerals and poor estimates of the amounts of titanium in the mafic minerals should not greatly affect the estimates of total titanium content of the rocks.

The concentration of titanium in the accessory magnetites appears to bear no relation to the amounts of magnetite, mafic minerals, or sphene in the rock. Lone Mountain specimens A45 and A47 have very different amounts of magnetite (.005% and 4.5% respectively), but the titanium content of the magnetites is .9 and 1.1% respectively.

The lack of correlation of the amount of titaniferous mineral in a rock specimen with the titanium content of the accessory magnetite is most evident in the Carrizo specimens. As pointed out in the section on modal analyses, near-contact specimens A62 and A69 have sphene and little or no mafic mineral, whereas the other Carrizo specimens have mafic minerals and little or no sphene. Because the total titanium content of the rocks of this study seems to be strongly dependent on the sphene content of the rock, the Carrizo specimens with sphene appear to have about three times the total titanium content of the specimens without sphene. Yet the concentration of titanium in the Carrizo magnetites is fairly uniform regardless of whether or not the magnetite came from a specimen with sphene.

If the titanium concentration in magnetite is proportional to the titanium concentration in the melt from which the magnetite precipitated, then the titanium concentration in the liquid part of the Carrizo magma must have been uniform when magnetite was precipitating. The entire magma could have had a uniform titanium content as magnetite crystallized, and the titanium to form the sphene could have been introduced later, possibly hydrothermally. Nothing in the textures of the Carrizo near-contact specimens, which contain the sphene, suggests late introduction of material. Further, it seems unlikely that the two widely separated near-contact specimens would be the only rocks into which titanium would be introduced.

Even though the titanium concentration in the magma may not have been uniform, uniformity of titanium concentration in the melt while magnetite crystallized could have occurred through either early precipitation of sphene, or incorporation of titanium in early formed mafic minerals which, after the formation of the magnetite, were resorbed and released titanium to form the sphene. Early crystallization of sphene as a mechanism to obtain uniform titanium concentration throughout the magma in the melt is supported by the textures in the Capitan and Lone Mountain specimens that indicate that sphene preceded magnetite in formation. By analogy, the same sequence could have occurred in the Carrizo magma. As discussed on page 37, the crystallization of sphene would not be expected until much of the magma had solidified because titanium is only a minor element in the rock. Magnetite crystallization thus would have had to take place even later in the sequence.

The hypothesis of titanium incorporation in mafic minerals to explain the uniform concentration of titanium in the melt when magnetite precipitated is supported by the antipathetic relationship of the sphene and mafic minerals in the Carrizo specimens. The near-contact specimens have spehne, but few mafic minerals, and the interior specimens have mafic minerals and little or no sphene. An objection to this explanation is that if mafic minerals had once made up 6% of the volume of the magma where the near-contact specimens were obtained, these minerals would have had to contain 4% titanium in order to release enough titanium to produce 1% sphene. Four percent titanium is a rather high titanium content for mafic minerals, however (see the tables of Deer, Howie, Zussman, 1963, vol. 2 p. 274, vol. 3 p 58). Furthermore, no sphene seems to have been produced by the partial resorption of mafic minerals in the Carrizo interior specimens.

Formation of sphene before the formation of magnetite seems to be the most satisfactory explanation for the uniform titanium content of the magnetite in spite of variable total titanium content in the rock.

The high titanium content of the Carrizo magnetites relative to the magnetites from the other intrusives does not appear to be explainable by any differences in total titanium content of the rock. The modal compositions of the Carrizo specimens is also similar to those of the Capitan and Lone Mountain specimens (table I). The greater titanium content of the magnetite of the Carrizo specimens may be due to a difference in the crystallization-intrusion history of the Carrizo magma compared with the histories of the other magmas.

The Carrizo intrusive has fewer phenocrysts than the Capitan and Lone Mountain intrusives (less than 10% vs. 20 to 25%) which fact indicates that the Carrizo magma was emplaced at an earlier stage in its crystalliaation than the other magmas. If the higher titanium content of the Carrizo magnetites is related to the earlier emplacement of the magma, the magnetite in the Carrizo specimens would have had to form after the emplacement of the magma. Textural relations indicate, however, that most of the magnetite of the other intrusives also formed after intrusion. Thus the relatively low titanium content of the Capitan, Lone Mountain, and Jacks Peak magnetites did not result from the crystallization of their magnetite under greater pressure, i.e. intratellurically, than the more titaniferous magnetite of the Carrizo intrusive.

The magnetite of the Carrizo intrusive, nonetheless, may have crystallized under lower pressures than the magnetites of the other intrusives, even though the difference was not due to post- and pre-intrusion crystallization. The Carrizo resorption and trachytic textures, characteristic of some volcanic rocks, both suggest that the Carrizo magma crystallized at low total pressure after intrusion. If, as is likely, low total pressure resulted in low Po_2, more titanium could be taken into the magnetite because the entry of titanium into magnetite is accompanied by iron(II).

CONCLUSIONS

1. Textures indicate that magnetite formation was late in the crystallization sequence of the intrusive rocks studied.

2. Mafic and accessory minerals are preferentially associated with one another. These associations are probably due to reaction relationships.

3. The titanium content of the Carrizo magnetites is fairly uniform in spite of the fact that the total titanium content of the rock varies considerably from specimen to specimen. Crystallization of sphene before magnetite may have given rise to uniform titanium concentration in the melt from which the magnetite crystallized. The uniform titanium concentration in magnetite, then, would be a result of the uniform titanium concentration in the melt.

4. The higher titanium concentration in the Carrizo magnetites relative to the magnetites from the other intrusives studied may be the result of crystallization of the Carrizo magnetites at a lower Po_2.

5. The magnetite from most of the limestone replacement deposits has a narrow range of relatively high magnesium concentrations (1 - 2% Mg). It is likely that the dominant factor in the determination of the amount of magnesium in the magnetite is temperature rather than the concentration of magnesium in the replaced sediments.

6. The magnesium content of the in sedimentary magnetites suggests that magnetite precipitation was caused by a reaction between solution and carbonate minerals that resulted in a pH increase. The in igneous magnetite bodies that are near sedimentary contacts may also be the result of a pH increase. As a result of the pH increase of the solution in sedimentary rock, hydrogen ion diffusion through a slow-moving solution could increase the pH of the part of the solution still in igneous rock.

7. The small unit cell size of two accessory magnetites suggests that maghemite is the predominant iron oxide in the intrusive rock specimens

from which these magnetites were obtained. The maghemite may have formed preferentially to hematite as an oxidation product of magnetite because of the small grain size of the magnetite.

8. Expansion of the magnetite unit cell may be an initial stage in its oxidation to hematite as evidenced by the high content of hematite in samples of magnetites which have relatively large unit cells.

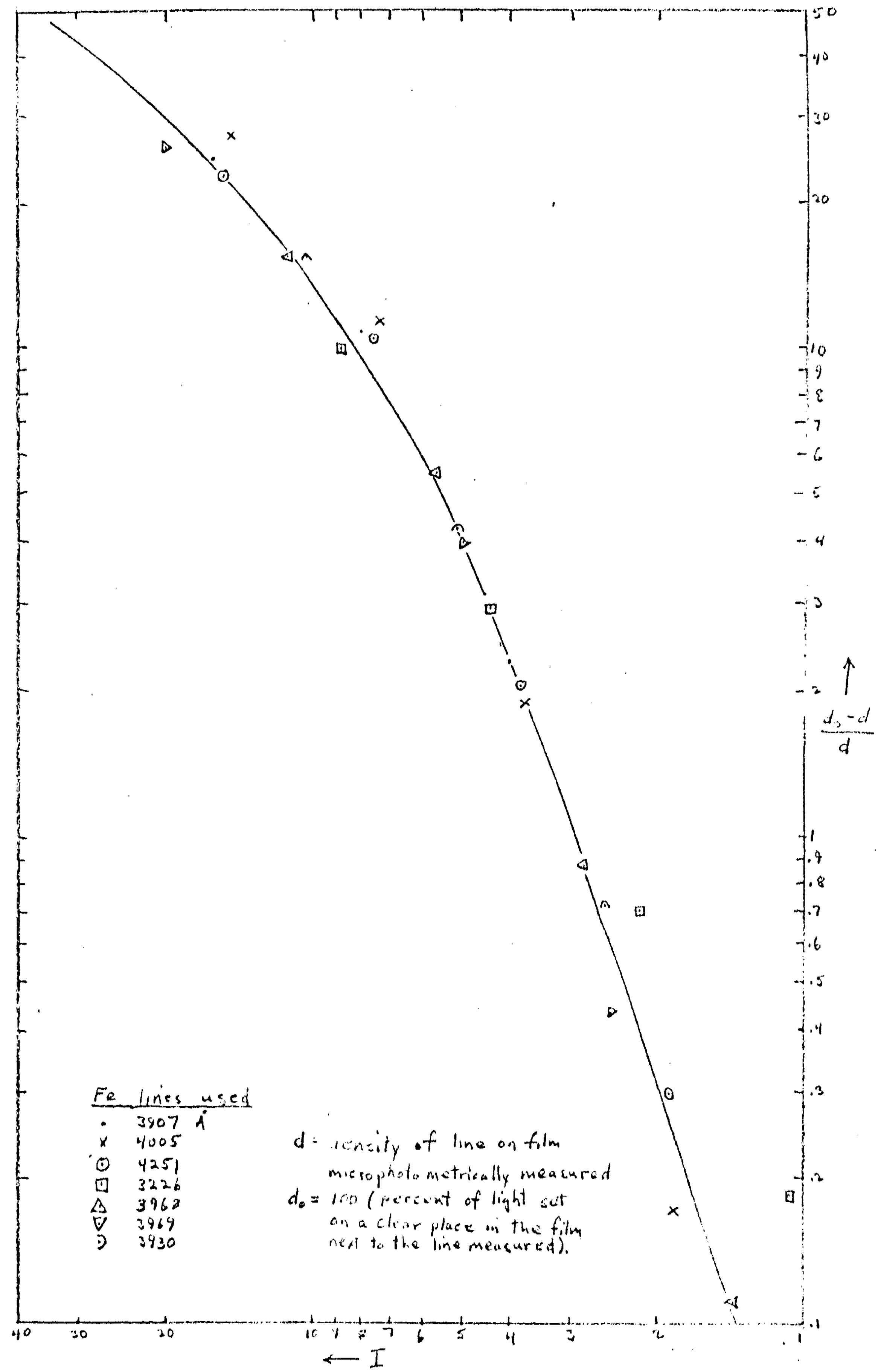

Figure 14. Representative film calibration curve. 4000 Å region. Intensity versus the Seidel function. See text page 41.

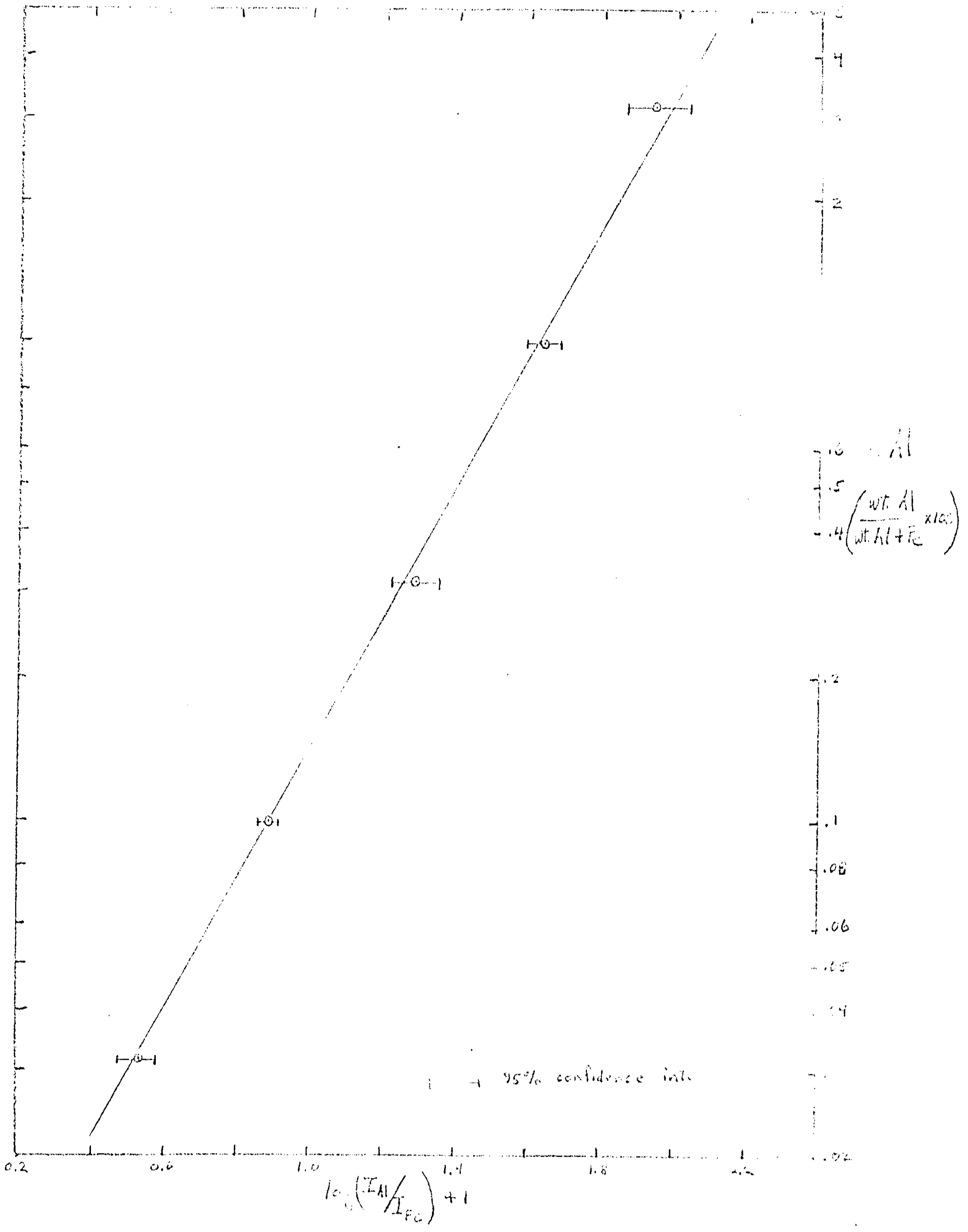

Figure 15. Aluminum standardization curve. The points for this curve show less scatter than the points for the Ca, Mg, and Ti standardization curves. These curves and further details on the analysis method are contained in a report (Spectrochemical Analysis of Magnetite for Calcium, Aluminum, Magnesium, Titanium. by Patrick Butler Jr, 1962) on file in the New Mexico Institute of Mining and Technology Library.

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Date: May 25, 1964