PETROGRAPHY OF THE TROCTOLITE OF THE WICHITA MOUNTAINS, OKLAHOMA*

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ABSTRACT

This paper presents a detailed description of the petrographic nature of the pre-Cambrian troctolite of the Wichita Mountains, Oklahoma. The troctolites are composed essentially of bytownite (An_{75}), olivine, Fo_{75-80}, small amounts of diallage, hypersthene, and many accessory and secondary minerals. Development of coronas about olivine and plagioclase is described. The presence of spinel (pleonaste) in troctolite and sillimanite in the associated anorthosite indicates assimilation of aluminous material. The magma had a temperature somewhat above 1100° C. at the time of intrusion as evidenced by the occurrence of diopsidic lamellae in hypersthene.

INTRODUCTION

Though early in 1899, Vaughan (p. 47–48) reported troctolite in Iron Mountain of the Wichita Mountain System, Oklahoma, the rock has been neglected in subsequent investigations except for brief petrographic notes by Chase (1950), and a petrofabric study by Huang and Merritt (1952).

Field work was carried on during the academic years of 1949–1950, and 1950–51, when all outcrops of troctolite were studied and extensive collections made. The microscopic examinations of representative sections occupied the academic year of 1951–52. It is hoped that the present study may contribute to the petrographic and related character of the troctolite problem, and may shed light for the future investigation of the igneous complex of the Wichita Mountains.

The writers wish to express their appreciation to Gerald W. Chase of the Oklahoma Geological Survey for discussions on the troctolite problem and permission to use his unpublished geologic map of the Raggedy Mountains, Wichita Mountain System, Oklahoma, and for the loan of several thin sections of the rock under investigation.

FIELD OCCURRENCE

The Wichita Mountains of southwest Oklahoma are composed of a series of pre-Cambrian igneous rocks, beginning with basic and ending with acidic composition. The troctolite is interpreted as formed by gravity settling of crystals as some outcrops show a downward gradation

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from an anorthosite through an olivine gabbro to a troctolite. Bands of anorthosite, feldspathic pyroxenite, pyroxenite, and diallagite may occur in any horizon of the basic rock series, while younger offshots of troctolite occurring as dikes also cut across the stratified igneous rocks. Except for the dikes, the boundaries between the rock types are indefinite, and there is always a gradual passage from one to another of the roughly horizontal layers.

Though the base of the igneous complex is not exposed, it is believed that the mass attained a great thickness from data revealed by drilling on the flanks of the Wichitas. Also, the form of intrusion is conjectural, but it seems likely that it may have been a sheet or lopolithic body similar to the stratified gabbro-anorthosite and periodotite sheets of other parts of the world.

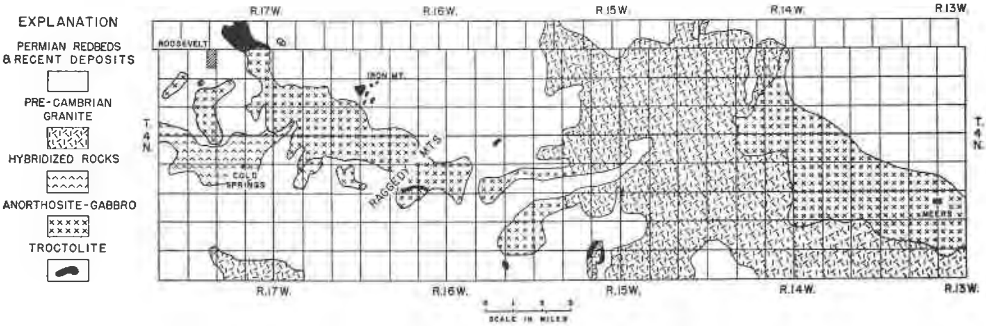

FIG. 1. Sketch map showing location of troctolite in the Wichita Mountains, Oklahoma.

Most troctolites occurring at the lower portion of this rock series crop out as scattered low hills near Roosevelt and other vicinities of the Raggedy Mountains (Fig. 1). Small sporadic outcrops also occur near Meers in the eastern Wichitas. Some outcrops are inliers surrounded by Permian Red Beds; others underlie granite, and still others underlie gabbroic rocks and anorthosite. One troctolite dike attains almost one mile in length and 150 feet in thickness. Small aplitic and pegmatitic dikes, not always mapable, cut across the troctolite outcrops. Within the troctolite exposures are many small local gradations into other rock types. For example, north of Roosevelt, the troctolite, with gradual decrease of olivine, laterally changes to olivine gabbro, which with absence of olivine, passes into labradorite and bytownite gabbros; in Iron Mountain a concentration of iron ores gives magnetite gabbro, which appears as an iron-rich differentiate.

Textures of troctolite range from medium to coarse-grained with feldspar tablets as much as 5.2 cm. in length and 3 cm. in width, and with olivine crystals as large as 4 cm. in diameter, the average grain size being about 4 mm. by 3 mm. Some phases show mafic minerals which form interstitial grains between blocky plagioclase crystals. Others, generally medium grained and relatively high in olivine crystals, are markedly saccharoidal. Olivine is evenly distributed in the rock, but local concentration is common. It is commonly altered to iron minerals, which stand out on the surface of the outcrop. Marked irregularities in grain size, some zonal arrangement of minerals in the coarsest phases, and occurrence of massive mafic minerals suggest that at least a part of the excessively coarse-grained material is pegmatoid in character.

In the Cold Springs area of the Wichita Mountains, Walper (1951, p. 51) described the gabbro-anorthosite as having a structure similar to schistosity and he ascribed it to magmatic flow. The banding of the troctolite is commonly conspicuous. Locally well-defined platy and linear parallelism of feldspar in the plane of the banding, were observed in several horizons. The bands, usually only a few cms. in thickness, continue with regularity for a few yards before they terminate by lensing out, or displacement by small faults. The contacts between adjacent bands are relatively sharp in some cases, and gradational in others. Within many of the bands there is a variation from an olivine-rich facies at the bottom to a feldspar-rich one at the top. Repetitions of this feature are common and reversals were observed. Hess (1938, p. 266) concluded that the factors responsible for primary banding in norite and gabbro are: (1) the relative density differences between each of the main constituents settling, plagioclase and pyroxene, compared to the density of the magma: (2) disturbance of the normal stage of quiescence in the magma by short epochs of gentle flow. This explanation is applied to the banding observed in some of the present igneous bodies in the Wichita Mountains by postulating that they were intruded in an approximately horizontal position, and were crystallized during the gentle magmatic flow. That the interpretation of the banding is the result of magmatic flow is further supported by local dimensional parallelism of the underformed plagioclase tablets in some places and by the tendency for elongated olivines to show dimensional parallelism in others.

Petrographic Nature of the Rock

1. *Methods of feldspar determination*

Orthoclase was recognized and determined. The optical properties are as follows: $\alpha = 1.514 \pm 0.002$, $\beta = 1.518$, $\gamma = 1.522 \pm 0.003$, $(-)2V = 58°–62°$, plane of optic axes $\perp(010)$, plane of optic axes $\wedge(001) = 4°$,

$(010) \wedge (001) = 90°$. These data are within the range of plutonic perthitic orthoclase as described by Spencer (1937, 1938).

The composition of the plagioclase was determined in each case by a combination of methods described by Winchell; especially valuable were extinction angles between Z or X and (001) or (010), in sections perpendicular to X and Z respectively (Winchell, 1951, p. 262). Selected sections were also examined with a universal stage, for the purpose of checking the composition of plagioclase (Turner, 1947). In all cases the composition of plagioclase as determined by the two methods agreed reasonably well; further, the axial angles of plagioclase as determined by the universal stage measurement were found to correspond closely with the curve given by Winchell (1951, fig. 148, p. 262).

TABLE 1. SELECTED MODAL ANALYSES OF THE TROCTOLITES, WICHITA MOUNTAINS, OKLAHOMA

	1	2	3	4*
Plagioclase	69.0	68.0	67.8	68.2
Olivine	26.0	29.8	26.4	26.8
Hypersthene	1.5	1.2	0.2	1.8
Diallage	1.5	1.0	1.1	0.5
Spinel	2.0	tr		1.5
Magnetite	tr	tr	4.5	1.2
Diopside	tr	tr		tr
Cummingtonite	tr		tr	tr
Lamprobolite	tr	tr	tr	tr
Hornblende	tr		tr	tr
Biotite	tr	tr	tr	
Muscovite	tr	tr		
Chrysotile	tr		tr	
Antigorite	tr	tr	tr	tr
Serpophite	tr	tr	tr	
Zircon	tr			tr
Apatite	tr	tr	tr	
Brookite		tr	tr	
Chromite	tr	tr	tr	tr
Ilmenite			tr	tr
Hematite	tr			tr
Range of anorthite content in plagioclase	70–75	76–78	72–74	72–75

tr = trace.

* Orthoclase and oligoclase occur in two sections.

1. One and one-half miles northeast of Roosevelt (SW$\frac{1}{4}$, SW$\frac{1}{4}$, Sec. 33, T. 5 N., R. 17 W.).
2. One mile northeast of Roosevelt (SE$\frac{1}{4}$, Sec. 32, T. 5 N., R. 17 W.).
3. Iron Mountain (SE$\frac{1}{4}$, NE$\frac{1}{4}$, Sec. 12, T. 4 N., R. 17 W.).
4. 13 miles southeast of Roosevelt (NE$\frac{1}{4}$, Sec. 9, T. 3 N., R. 15 W.).

2. *Detailed petrographic description*

Troctolites are holocrystalline, granular, medium-grained rocks, composed essentially of bytownite and olivine with diallage, hypersthene, minor accessories and secondary products. All the troctolites examined fall into Johannsen's family 2312P (1939, p. 225–226). Table 1 shows the selected modal analyses of the troctolites.

Plagioclase, generally lath-like, usually constitutes over half the volume percentage of the troctolite. Grains are occasionally very large, indicating a later pegmatitic development; otherwise, grain size averaging 4 mm.×3 mm., is comparable to the associated olivine. Occasionally the plagioclases occur as slender zonal laths, but most are unzoned, or occasionally as poikilitic crystals of more uniform composition. The laths were formed by crystallization in a magma undergoing movement. The unzoned and poikilitic habits are ascribed to crystallization in a quiescent magma. The zoned crystal has a core of An_{78} and mantle of An_{74}. Sharply defined zonings are wanting; the transition in composition from the core to the edge is commonly a gradual one. The total variation in composition is from $Ab_{30}An_{70}$ to $Ab_{22}An_{78}$, but the great majority falls in $Ab_{25}An_{75}$.

The plagioclases represented are bytownite. Twinning is universally developed, and twinning laws were determined with the migration curves (Turner, 1947). Relative abundance of plagioclase twinning laws is indicated in Table 2. In general, the more calcic plagioclases tend to twin according to the so-called less common laws. Albite law is universally present.

TABLE 2. RELATIVE ABUNDANCE OF PLAGIOCLASE TWINNING LAWS

Twinning Laws with Anorthite Content			Relative Abundance
Normal twin law:	Albite	An_{25-38}	Abundant
		An_{70-78}	Abundant
Parallel laws:	Ala B	An_{25}	Rare
	Carlsbad	An_{72}	Present
	Pericline	An_{72-75}	Present
	Acline	An_{78}	Rare
Complex laws:	Albite-Carlsbad	An_{76}	Present
	Albite-Ala	An_{78}	Rare

Remark: sodic plagioclases, An_{25-38}, were introduced.

Well developed dust-like and needle-shaped magnetite enclosures were seen in plagioclase. The needles occupy the center of the crystals;

the exterior of the crystals is generally free from inclusions. Not infrequently, the acicular bodies are altogether absent, and then the minute dots are arranged in lines which indicate the position of the twinning lammelae, twinning planes, and cleavages. Pseudo-zonal structure is occasionally produced by inclusions. Fine reddish brown rods, possibly hematite, trending parallel to the intergrowth planes of the lamellae were observed. Zircon and apatite appear as inclusions; while long apatite needles, too long to be entirely enclosed, intersect the plagioclases. Olivine is rarely enclosed, possibly because it invariably occurs in large crystals.

Evidences of syncrystalline deformation are absent and the plagioclases are usually fresh. Alteration when present is restricted to the incipient development of clayey minerals too small to permit identification. The feldspar is also patchily replaced by the invading serpentine.

Orthoclase and sodic plagioclase, An_{25-38}, occur in small quantities in the troctolite collected from outcrops, 13 miles southeast of Roosevelt. It is believed that they were introduced by contamination of the adjacent granitic rocks in a manner similar to that leading to the formation of granodiorite and other hybrids in the Wichita Mountains (Walper, 1951).

Olivine is the second most abundant mineral in the troctolite; it never shows a well-defined crystal nor it is corroded. The olivine also occurs in ramifying and wormy shapes giving the rock an ophitic-like texture. In size it varies from 0.8 mm. to 3.4 mm., and it is colorless to a greenish tint in thin section; it has an imperfect cleavage parallel to (100). In some olivines this plane of mechanical weakness is well shown by the presence of minute rod-like opaque and semi-opaque schiller inclusions, which tend to sharply orient in (100) of the host crystal. Twinned olivine was also noted.

The olivine is partly older, but mostly contemporaneous with plagioclase, and always older than the pyroxenes, for the latter commonly surrounds it.

The olivines were determined with the curves of Winchell (1951, p. 500–501). Optical properties are shown in Table 3.

Over 75 per cent of all determinations fall in Fo_{75-80}, and no exceptional relations are shown by the composition of the olivines in the troctolite. Generally, the olivines show a slight range in composition within one thin section, though individual crystals are of uniform composition.

Zoning of olivines was observed only in two slides from an outcrop one mile northeast of Roosevelt. The zoned olivines are surrounded by numerous minute granules of olivine. According to Walker and Polder-

TABLE 3. OPTICAL DATA ON OLIVINES

Specimen Number 2V and Optic Sign	Beta Index	Per Cent Forsterite
H24 (+)83°	1.662	96
H31 (+)84°	1.682	92
H36 (−)87°	1.694	89
H45 (−)87°	1.698	80
H28 (−)86°	1.710	75
H37 (−)81°	1.712	70

vaart (1949, p. 663), the zoning is ascribed to a local acceleration in the crystallization of olivine, presumably caused by magmatic reaction with a quartzite xenolith. Though not conclusive in the present case, it is strongly supported by the widespread occurrence of the stoped material, both igneous and sediments of various composition in the Wichita Mountains igneous complex. The scarcity of the zoned olivines may be due to alteration of the crystals, destroying any evidence of the phenomenon.

Feathery reaction rims are developed sporadically between the olivine and plagioclase. Some olivines are surrounded by coronas built against anhedra of plagioclase feldspar, and the olivine is forsterite in composition. The reaction minerals are small; few grains are larger than 0.1 mm. The reaction products are composed of two shells. Close to olivine occurs a shell, approximately 0.07 mm. in width, of pinkish hypersthene; this shell passes outward into a second shell commonly 0.2 mm. in width, composed of minute dark grains. The shell appears cloudy in many places. The small grains prevent precise determination, but the mineral has the optical properties of a diopsidic-spinel symplektite (Fig. 2).

Another type of corona was recognized. The kelyphite of greenish amphibole prisms (hornblende), commonly 0.1 mm. in width, is almost continuous, and it has a uniform width indicating that the amphibole rim was formed largely from olivine. Spinel rarely appears in this rim. It is logical to consider that the amphibole was formed from the original olivine grain just as the diopside-spinel symplektite replaced plagioclase.

The contact between plagioclase and iron ore is marked by a corona, especially when the ores are large in size. The reaction product appears to be greenish amphibole prisms so small and so closely packed, that precise identification is difficult (Fig. 3). The coronas between plagioclase and iron ore were originally formed between plagioclase and olivine that was selectively replaced by iron ore; for incomplete replacement of olivine by iron ore can be clearly recognized. A similar description is given by Sclar (1951, p. 1477). Thus some iron ores are late in development.

Coronas are an intriguing feature of many basic rocks (Buddington, 1930, p. 290). In his recent studies of the coronas and coronites, Shand (1945) concluded that the coronas are the result of thermal metamorphism, and that the instability of olivine, probably because of its tenor of iron, has caused the rims to form by a process of ionic migration. The troctolites of the Wichita Mountains contain olivines of Mg-rich variety as shown by optical properties (Table 3). Shand's conclusion that ferrous iron is important in corona formation is not supported by the troctolite in the Wichita Mountains. Osborne (1949, p. 94) believes that Shand's conclusion may help to explain the reaction rims formed against plagioclase and iron ores. The writers find their opinion irreconcilable with Osborne's explanation in the present corona-bearing troctolite. For, as already noted, olivines with corona structures were selectively replaced by late iron ore. Field evidence, from the corona-bearing troctolites in the Wichita Mountains, lends support to Shand's conclusion that thermal metamorphism acting upon rocks of suitable mineralogical composition, seems to offer the most likely solution for the corona problem, for the corona-bearing troctolites collected are commonly cut by pegmatitic dikes.

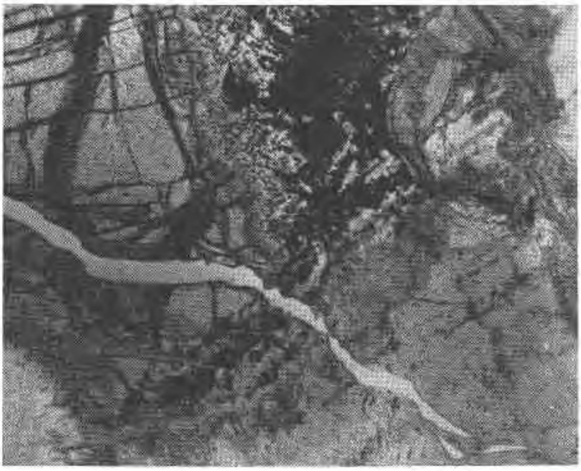

FIG. 2. C-142, plane light ×58. Olivine is surrounded by a corona built against anhedra of plagioclase An_{75}. The reaction products are composed of two shells. Close to the olivine is a shell of hypersthene. This shell passes outward to a diopside-spinel symplektite. Note a part of the olivine is selectively replaced by iron ore.

Location: One mile northeast of Roosevelt (SE$\frac{1}{4}$, SE$\frac{1}{4}$, Sec. 32, T. 5 N., R. 17 W.).

Olivine is the mafic mineral most susceptible to alteration. This is in the form of serpentinization, beginning along cleavage cracks and margins of the crystal, and always present to some degree. The serpentines are fibrous antigorite, chrysotile veinlets and isotropic serpophite. Coincident with this serpentinization are developments of ilmenite and magnetite.

FIG. 3. C-164, plane light, ×58. In the upper left, olivine is surrounded by a kelyphite of greenish hornblende prisms, and is selectively replaced by iron ore. In the lower right, a corona is built about iron ore and plagioclase upon completion of replacement of olivine. Location: Thirteen miles southeast of Roosevelt (NE $\frac{1}{4}$, Sec. 9, T. 3 N., R. 15 W.).

Orthopyroxene, though in small quantities, presents an interesting petrographic study; it forms narrow shells from 0.02 mm. to 0.08 mm. in width, around the olivine grains, indicating a younger age than the olivine in the course of crystallization. Most orthopyroxenes, however, occur as oblong-shaped crystals which average about 0.2 mm. by 0.8 mm. in dimensions. The orthopyroxene was determined using Hess and Phillips' curve (1940). Optical properties of orthopyroxene are: $(-)2V=64°$, $\gamma=1.700\pm0.002$, faintly pleochroic: X=pinkish, Y=colorless, and Z=pale to greenish. These data indicate hypersthene with enstatite content $En_{73}Of_{27}$.

Some hypersthenes contain schiller inclusions, which are composed of fine needles arranged parallel to the *c*-axis, and of small plates of a reddish-brown color lying parallel to (010) or (110). The exact nature of these minute inclusions cannot be determined; the unusual high relief suggests brookite. Other hypersthenes are marked by lamellation, often parallel to (010), which at first suggests multiple twinning. The petrogenetic significance of this mineralogical feature will be discussed later.

The hypersthene is commonly fresh, but not infrequently shows alteration into various minerals. Serpentines not only fill the cleavage cracks of the hypersthene, but also those of the adjacent plagioclase, and occur as marginal films between the grains of those two minerals. The mineral is composed of fine fibers, which are characterized by weak pleochroism: X = greenish tint, Z = green, birefringence of about 0.01, and is most likely a variety of antigorite. The alteration of hypersthene not only produces serpentine minerals, but also develops magnetite grains.

Another interesting type of alteration of hypersthene is the production of cummingtonite. The process takes place along the cleavages and margins of the hypersthene. Commonly the alteration is incomplete, giving the impression of patchy intergrowth of the two minerals. In an advanced stage, the hypersthene changes to cummingtonite and greenish amphibole. The amphibole occurs along the margins, and was obviously formed as a reaction product between hypersthene and plagioclase in a manner similar to that described by Asklund (1925, p. 23). The cummingtonite borders both the hypersthene and the iron ore: the deepest brown cummingtonite is seen where the mineral is in contact with the hypersthene. The pleochroism of cummingtonite is: X = colorless to pale, Y = yellowish brown, and Z = chestnut brown. On the universal stage every crystal proved to be optically positive with $2V(+) = 82°–84°$ and a maximum extinction angle of 20°, indicating molecules of 64 per cent of grünerite $Fe_7Si_8O_{22}(OH)_2$ (Winchell, 1951, p. 428).

Alteration of hypersthene into cummingtonite has been recorded by several workers. Asklund (1925, p. 20–25) described it in a noritic gabbro in Stavajo at Kolmarden, and he listed a number of other authors. Lundegårdh (1943, p. 340) found similar alteration rims of colorless fibrous amphibole surrounding hypersthene remnants in the ultra-basic gabbro (hypersthene eucrites) in the Grovstanas region, Sweden, and agreed with Asklund's identification of cummingtonite. Heitanen (1947, p. 1042–1043) and N. F. M. Henry (referred by Stewart, 1947, p. 483) also describing the similar alteration and illustrating it by the following chemical equation:

$$\begin{array}{c} 7(\mathrm{Fe, Mg})\mathrm{SiO_3} + \mathrm{SiO_2} + \mathrm{H_2O} \rightarrow \mathrm{H_2O(Fe, Mg)_7Si_8O_{24}} \\ \text{7 Hypersthene} + \text{Quartz} + \text{Water} \rightarrow \text{Cummingtonite.} \end{array}$$

In view of the intensive hydrothermal activity in the area studied, the above reaction can be equally applied to the present mineral alteration.

Lastly, the hypersthene is also altered to biotite. The brown mica wisps are intimately associated with hypersthene having marked pleochroism from brown to almost colorless, and with almost parallel extinction, thus differing from the cummingtonite.

Clinopyroxenes occur in small amounts in troctolite, but it increases in amount giving diallage gabbro. The clinopyroxene is rarely twinned; occasionally it is zoned. The presence of parting on both (100) and (001) in some of the mineral makes the variety name diallage appropriate. Clinopyroxene appears colorless throughout and is always optically positive, with the optical plane parallel to (010). The optical angle, extinction $Z \wedge c$, and beta refractive index were determined. The method of composition determination suggested by Hess (1949, p. 636) was used, i.e. the intersection of the beta value with the crystallization curve is a check on the composition inferred from 2V and the beta index. Table 4 shows the optical properties and composition of the clinopyroxenes in the troctolites. The petrologic significance of the composition of clinopyroxenes cannot be deduced, until the investigation of the basic igneous rocks of the Wichita Mountains is completed. It is hoped, however, that the present data may aid in the interpretation of the clinopyroxenes in the basic igneous rocks in that area.

TABLE 4. OPTICAL PROPERTIES AND CHEMICAL COMPOSITION OF CLINOPYROXENES

Nomenclature (after Hess, 1941)	2V	Beta Index*	$Z \wedge c$	Composition Inferred	Specimen
Augite	46° 53°	1.702 1.688	43° 46°	$Wo_{36}En_{37}Fs_{27}$ $Wo_{41}En_{44}Fs_{15}$	In troctolite outcrops near Roosevelt
Ferroaugite	45° 46°	1.721 1.724	52° 48°	$Wo_{27}En_{21}Fs_{52}$ $Wo_{31}En_{20}Fs_{49}$	Iron-rich differentiate in Iron Mountain

* The limits of error of the indices of refraction are 0.003.

Strongly pleochroic biotite, X = pale brown, Y = Z = reddish brown, occurs in small amounts. According to Hall (1941, p. 30), the red brown biotite is due to the high titania and low magnesia content: magnesia masks the color. Pleochroic lamprobolite, X = yellowish brown to Z = brown, was noticed in several slides. Muscovite threads occur in clusters, but in negligible amounts. Euhedral apatite crystals are invariably enclosed in olivine and plagioclase crystals. Chromite was recorded and commonly associated with magnetite in a fine granular habit; it is also seen in serpentinized olivine cracks and cleavages. Under the microscope, the center of the grains appears opaque and the edge translucent brown.

Primary ilmenite is practically absent from many slides in widely scattered outcrops, but it becomes increasingly prominent in some layers and in Iron Mountain. The crystals tend to be skeletal or idiomorphic, but are also intimately intergrown with magnetite crystals. Merritt (1939, p. 277–278), also observed the intergrowth of the magnetite and ilmenite in the iron ores of the Wichita Mountains. Examination of polished sections of these iron ores in reflected light reveals that the ilmenite consists of a typical exsolution intergrowth of lamellae of ilmenite, in the octahedral planes of magnetite. Some of the ilmenite lamellae are quite broad, but others can be detected with only high magnification. Diffusion and segregation of the ilmenite has led to a separation of irregular shaped areas of ilmenite at the margins of some of the magnetite crystals. According to Edwards (1938, p. 48–52), this indicates a moderately slow rate of cooling. The amounts of ilmenite vary considerably. In some cases, the mineral constitutes as much as 2 per cent of the rock.

Finally, considerable amounts of spinel were found in several slides in addition to those described in connection with the formation of corona. The occurrence of this mineral bears an important petrogenetic significance, and it will be discussed in a later section.

3. *Petrogenetic significance of some mineralogical features*

Several mineralogical features have important petrogenetic significance. These are discussed as follows:

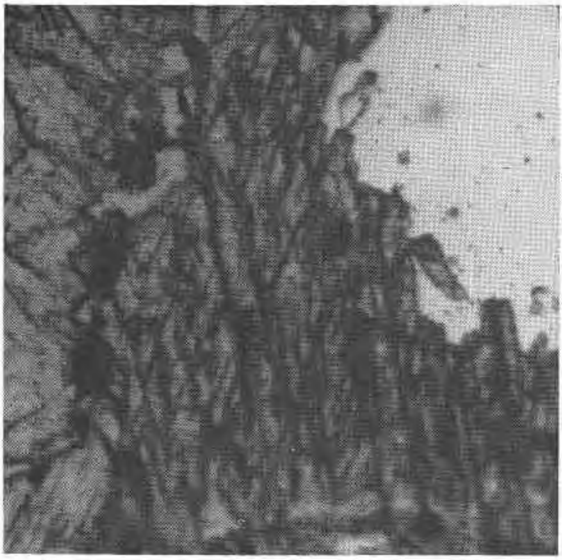

FIG. 4. H-36 plane light ×56. Intergrowth of diopsidic lamellae and hypersthene. Location: One mile northeast of Roosevelt (SE $\frac{1}{4}$, Sec. 32, T. 5 N., R. 17 W.).

First, some hypersthenes are marked by lamellation (Fig. 4) often parallel to (010), resembling multiple twinning. Such lamellation has, however, been considered by Hess and Phillips (1938) as due to inversion of pigeonite to orthopyroxene, with the segregation of diopside in the form of an intergrowth, orthopyroxene being able to hold $CaSiO_3$ in solution to the extent of about 9 per cent, but unmixed on further cooling. Hess further clarified the pigeonite and orthopyroxene stability relations in a diagram (1941, p. 583). In the present rocks where the lamellation is not continuous across the crystal, it has the appearance of an exsolution effect rather than one due to twinning. The lamellae have lower indices of refraction than the enclosing hypersthene, low birefringence and extinction angles 40°–46°. Measurements of this intergrowth on a universal stage was plotted in Fig. 5. The lamellae (En_{75}) are almost parallel to the parting plane (010) in the hypersthene. The optical angle of the hypersthene is of $(-)2V=64°$, while that in the lamellae was measured as $(+)2V=68.5°$. One of the optical axes of both minerals almost coincides.

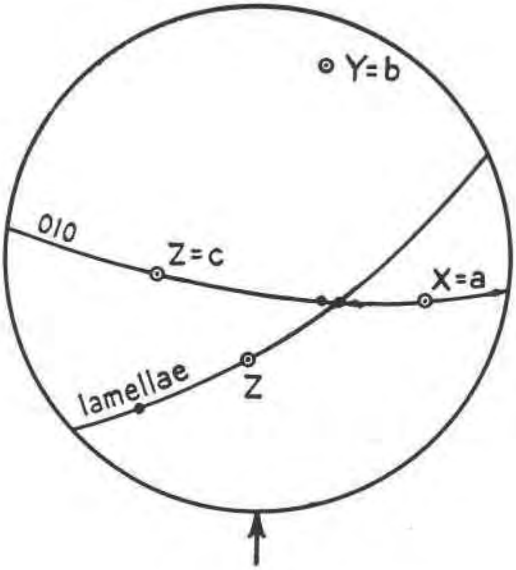

FIG. 5. Stereographic projections showing orientation of the optic axes and axial planes of the hypersthene and the diopside lamellae.

Edwards (1942, p. 587–590, 593–602) observed similar intergrowths of diopside and hypersthene in dolerites of Tasmania, and considered it as due to exsolution of clinopyroxene attending an inversion of pigeonite to hypersthene. Recent studies in the inversion of pigeonite to orthopyroxene by Walder and Poldervaart (1949, p. 635–638) in the Karroo dolerites, South Africa, confirm, and in part extend Hess's explanation.

The occurrence of these diopside lamellations gives a valuable geologic thermometer. The inversion temperature of pyroxene of this composition (En_{75}) has been determined experimentally as about 1100° C. (Hess, 1941, p. 582–583). The intergrowth of diopsidic lamellae in hypersthene found in the troctolite indicates that the magma had a temperature slightly above 1100° C. at the time of intrusion.

Second, troctolite and associated melanocratic rocks frequently contain small amounts of a brownish to vivid green spinel (pleonaste). Spinel was first noted in the melanocratic rocks collected two miles south of Roosevelt near Cold Springs area, where the stoped material and assimilation are most prominent (Walper, 1951). At first, it was believed that spinel represented excess Al_2O_3 thrown out in the process of metasomatism of xenoliths of aluminous sediments.

Later, spinel was found among the mafic constituents of the troctolite and associated rocks. This suggests that the spinel is rather a product of crystallization from a magma, or a result of unmixing during later stages of crystallization. Bowen (1928, p. 277, et seq.), discussed the reactive crystallization of spinel and showed that under certain conditions of falling temperature it would eventually disappear, but has been preserved in some rocks by envelopment in cloaks of silicates which has protected it from the surrounding magma. Bowen also pointed out that partial replacement by clinopyroxene might be expected with falling temperatures. In such circumstances, more or less complete coronas of spinel in contact with olivine might sometimes be expected, surrounded by other silicates without spinel. In the present troctolite, however, olivine may have disappeared through reaction and the spinel is scattered through the outer shell in dactylic growths. Some spinels are enclosed in olivine, others in clinopyroxene, and still others occur in the interstitial space between feldspars. It seems possible that much of it has been developed consequent to the reactive replacement by clinopyroxene of magma containing excess Al_2O_3. As already noted, the corona-bearing troctolites are commonly cut by pegmatitic dikes. Olivine is unstable in contact with alumina-rich hydrothermal solutions, and reacts metasomatically according to the following scheme (Barth, 1952, p. 329):

$$\begin{array}{c}(Mg, Fe)_2SiO_4 + Al_2O_3 \rightarrow (Mg, Fe)SiO_3 + MgAl_2O_4 \\ \text{olivine} + \text{alumina} \rightarrow \text{hypersthene} + \text{spinel.}\end{array}$$

When the spinel is enclosed in olivine, it is assumed that it has precipitated during decreasing temperature, and the olivine has protected the spinel from reaction. It should be stated that most spinels do not assume crystal forms, and the grains between feldspars are perhaps accidental inclusions. The foregoing discussions lead to the conception that the magma, or a portion of it, is abnormally rich in Al_2O_3, perhaps due to incorporation of aluminous sedimentary material at levels far below the present emplacement. A similar conclusion has been reached by Prider (1940, p. 378–379) in his studies on the constitution of the spinel-olivine-hypersthene xenoliths in granite gneisses from Toodyay, western Australia. That the magma is abnormally rich in Al_2O_3, is further supported by the occurrence of sillimanite in the associated anorthosite in the Wichita Mountains. There can be no doubt that the original sediments were aluminous, for the Meers quartzite now occurring as roof pendents (Taylor, 1915, p. 32; Hoffman, 1933, p. 31; Merritt 1948) in the eastern Wichita Mountains contains small amounts of sillimanite. The incorporation of older igneous country rocks, widespread occurrence of stoped igneous materials, metasomatism and transfusions of quartzitic sediments are common phenomena in the Wichita Mountains igneous complex. Whether the feeble development of muscovite in the troctolite, and in the associated gabbro and anorthosite throughout the Wichita Mountains, represents an arkosic element in the sediments is a matter of further research. The apparently sporadic nature of the development of spinel, too, needs further consideration, though it may be explained by irregular distribution of aluminous stoped sediments, followed by convection and restrained diffusion.

The presence of some aqueous fluids throughout much of the igneous cycle, is evident because of the presence of muscovite, biotite, and lamprobolite in the troctolite and melanocratic rocks. Some of the fluids may have been provided by sedimentary xenoliths absorbed by the magma.

Finally, several of the troctolites are characterized by ideal reaction groupings. Even in those corona structures, isolated crystals of the minerals forming the coronas are usually found sporadically among the feldspars. Not infrequently the mafic minerals are present in well-defined clots composed of various minerals. The association is apparently random, and there is no indication of reaction zoning in mafic mineral aggregates.

The reaction zoning is in accordance with Bowen's reaction principle. Starting with the core minerals with successive zones to the right, the following groups were noticed:

1. Olivine———hypersthene———amphibole with spinel.
2. Hypersthene———diopside———hornblende———magnetite.
3. Hypersthene with a little spinel———diopside with spinel.
4. Hypersthene———biotite.
5. Iron-ore———hornblende

It is clear that during the magmatic stages of crystallization, concentration of potash in the magma was low in the troctolite, and biotite appears as an end member of the reactions. Potash in excess of that in a normal troctolite magma must have been present, as it is evidenced by the sporadic and minute muscovite in the rock.

SUMMARY AND CONCLUSIONS

Field occurrence of the rock types, leucocratic on the higher parts, and melanocratic in the lower parts of many outcrops and at the apparent base of the intrusion in the Wichita Mountains, Oklahoma, strongly suggests that development to a great extent is due to gravitational differentiation. The troctolite facies of the basic igneous rocks is produced by accumulation of olivine crystals by gravity settling. Other petrologic features such as the indication of incorporation of quartzite xenolith, banding of the rocks, and occurrence of the spinel in several rocks, demand the invocation of other petrogenetic factors.

The troctolites are composed essentially of bytownite, An_{75} and olivine, Fo_{75-80}, with small amounts of diallage, hypersthene, and many accessory and secondary minerals. The formation of corona-bearing troctolite accords with Shand's conclusions, i.e. due to instability of olivine under thermal metamorphism, though Shand's conclusion that ferrous iron is important in corona formation is not supported by the present study. The occurrence of diopside lamellae in hypersthene indicates that the magma had a temperature slightly over 1100° C. at the time of intrusion. Two kinds of feldspars are present in the troctolites: namely, calcic plagioclase An_{70-78} and orthoclase accompanying sodic plagioclase An_{25-38}. The bytownite is primary whereas the latter is introduced by contamination from adjacent granitic rocks.

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