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MICROLITES IN GLASSY VOLCANIC ROCKS[1]

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ABSTRACT

The study of silicic glassy volcanic rocks indicates that they are rarely without the minute crystals known as microlites. Pyroxenes are the characteristic type of microlite, but a few rocks contain abundant sanidine; amphibole and biotite are rare, and small amounts of magnetite are nearly always present. The pyroxenes are of two distinct types, one having formed previous to emplacement and the other after emplacement.

INTRODUCTION

A detailed study of glassy volcanic rocks has yielded information about the mineral identity, physical properties, and genetic history of the minute crystals known as microlites and trichites which characterize these rocks. The minerals identified include pyroxenes, amphiboles, biotite, sanidine, and magnetite. Pyroxenes are present in a very large proportion of such rocks, and fall into two distinct types. One occurs as slender prisms, which in general show a parallel distribution that must have been imposed during emplacement. The other type is without systematic arrangement, occurs as loops, spirals, and helices, as complexly twisted spiderlike groups, or as beadlike strings of minute segments. The complexity of the groups and their fragile character indicates that they would have been disrupted by any movement during emplacement. Also, some of the curved and looped microlites have formed in pumice fragments which collapsed and welded after emplacement. The prismatic microlites are absent in the quickly chilled glass of explosive eruptions, but developed during the interval between eruption and the emplacement of the enclosing glass. Thus pyroxene microlites have developed during two distinct stages in the cooling history of glassy volcanic rocks.

The sanidine type of feldspar has been observed in only a few obsidians but is commonly present in partly glassy flow rocks (vitrophyres). The individual grains vary greatly in size, and seem always to have hopper-like or forked terminations of the prisms. Biotite is rare in glassy rocks, and seems to be commonly associated with feldspar microlites. Amphiboles occur sparsely in fresh glassy rocks and in other glasses which seem to have been very slightly hydrothermally altered.

Magnetite is ubiquitous in glassy rocks, being very abundant in some, but so sparse as to be rarely directly observable in others. In some glasses magnetite forms streamlike clouds of magnetite dust, and in many rocks it has formed the locus for the development of groups of pyroxene or amphibole microlites, and hence in these rocks is an early

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crystallization product. In some densely welded tuffs which have remained glassy, magnetite has developed on the welding contact and so is a late product in the cooling history of the rock.

General Considerations

The background for any study of microlites is provided by two classical papers, one by Zirkel (1876) and the other by Iddings (1899). King (*in* Zirkel, 1876, p. xiii) states "I am sure that American men of science will welcome the present volume from the distinguished pen of Professor Zirkel, as one of the most important contributions to our geology." This statement is as true today as it was 84 years ago, and it is a very real pleasure to here reemphasize this outstanding contribution by Zirkel. Some of the descriptions by Zirkel are so pertinent that they are quoted in subsequent parts of this paper, and two of his hand-drawn illustrations are reproduced, as photomicrography cannot improve upon them.

Iddings, in his study of the rocks of the Yellowstone region, also had occasion to describe a number of minute crystals which he called globulites, microlites, and trichites, and some of Iddings' observations are also cited. This study has been greatly benefited by the availability of the thin sections used by Zirkel in the study of the rocks of the "Fortieth Parallel," and also by about 40 thin sections used by Iddings in his studies of the Yellowstone region. Fries has contributed an unusually significant group of obsidians from Mexico. The mineral identity and relationships of these microlites are presented by descriptions and microphotographs of representative occurrences, and the results of examination of a total of 60 occurrences are summarized in Table 1.

The glassy rocks included in this study comprise the more silicic types —rhyolite, dacite, quartz latite, and latite. Andesitic rocks are less commonly glassy, but a few with a glassy groundmass have shown the same mineral relations as the more silicic ones. Basaltic rocks have not been included.

The minute minerals that have developed in glassy rocks are included under the general term "microlites," that is, "minute crystals visible only under the microscope, usually affecting polarized light" (Webster, 1933, p. 1366). However, a subgroup of these microlites would correspond to "trichite" which is defined as "a kind of crystallite resembling a bunch of hairs, common in obsidian" (Webster, 1933, p. 2196).

Microlites in glassy rocks apparently do not include a large variety of minerals, and those identified in the course of this study are pyroxenes, amphiboles, feldspars, biotite, and magnetite.

With only a few exceptions the glassy rocks included in this study are entirely unaltered. Some of the obsidian studied (the so-called marekanites) was associated with perlite, which has been shown to be the result of hydration of the obsidian (Ross and Smith, 1955). However, this hydration is not accompanied by observable alteration of the microlites. Two of the glasses had been altered, as shown by the gray-green color. In one of these, from the Bear Springs area, Valles Mountains, New Mexico, accompanying prismatic pyroxenes were not altered. In the other glass, discussed in the section on amphiboles, the microlites are believed to be alteration products. No direct alteration of pyroxenes to amphiboles or of amphiboles to pyroxenes has been observed. In one specimen pyroxene appears to have altered to magnetite, and that in part to hematite. In other specimens magnetite has altered to hematite.

The sparsity (of the order of a few tenths of one per cent), the minute size, and difficulty of concentrating adequate amounts of microlites free from the glassy matrix, have precluded the application of chemical analysis or *x*-ray methods. For these reasons this study has depended essentially on optical examination of thin sections, showing the microlites embedded in glass. The small size demanded the use of an oil-immersion system involving high magnification. Very intense illumination has permitted the measurement of angles of extinction in grains as small as 0.003 mm. in diameter.

Prismatic Pyroxenes

Most of the microlites included in this study occur in typical obsidian, or in roughly rounded nodules embedded in perlite known as marekanite (Judd, 1886). A few occurrences are in flow rocks, commonly characterized by phenocrysts in a glassy groundmass which carries microlites. In general, prismatic pyroxene microlites have a distinct parallel arrangement. In some specimens they have a nearly even distribution, but commonly they occur in distinct swarms. A very large proportion of the prismatic pyroxenes studied has marked similarity of size and crystal habit, and therefore only a few occurrences need be described in detail.

In most of the glasses studied, identification depended upon determination of the optical properties of the pyroxenes while embedded in glass. The size of the pyroxene microlites varies within narrow limits, and the elongation along the *c* axis is commonly about 10 times the diameter of the prisms. The very small depth of focus given by an oil-immersion lens helps in the selection of microlites suitable for study. Only those crystals with the *c* axis approximately parallel to the thin section are in sharp focus throughout their length, and are in a position suitable for optical determination or for photography. The minute size and very low apparent birefringence with normal illumination, and the necessity of using an oil-immersion system, poses a problem in microscope technique. How-

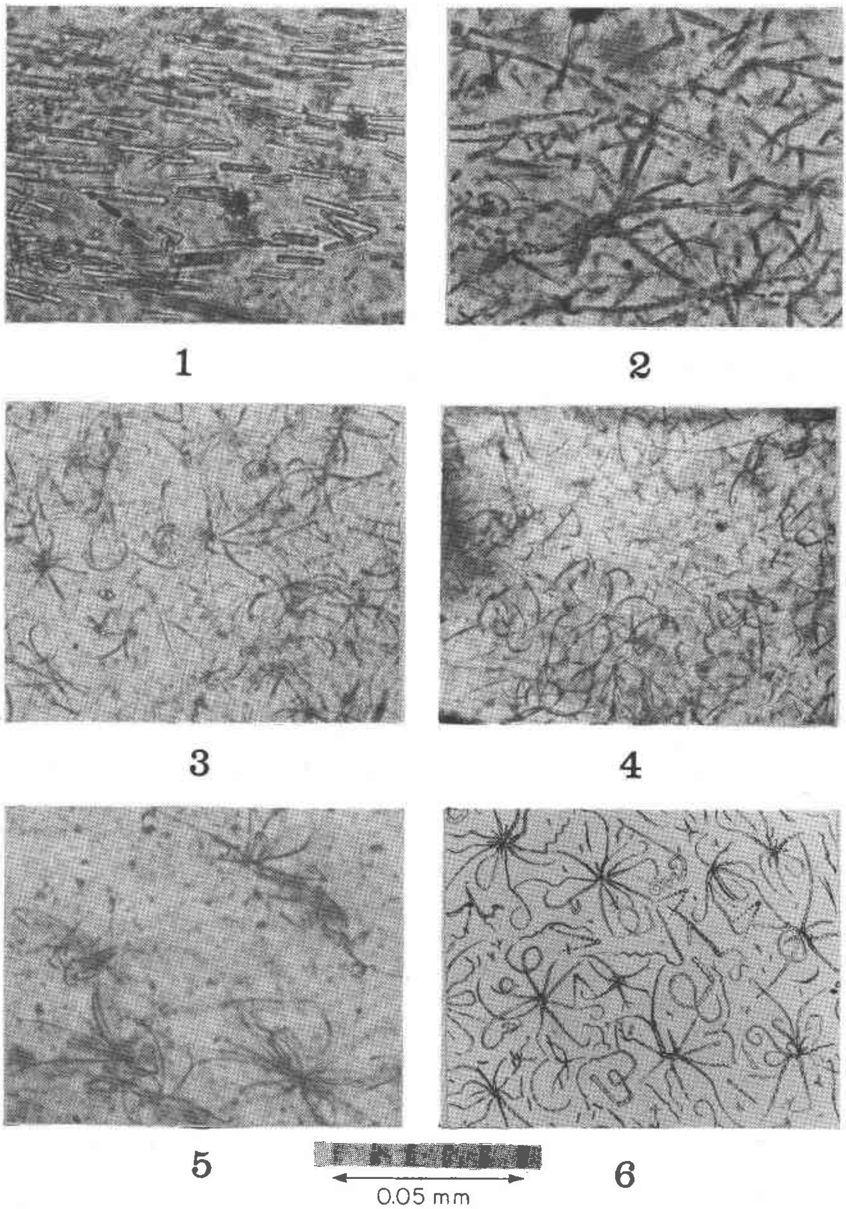

FIG. 1. Microlites in glassy rocks.

No. 1. Obsidian from Arroyo Hondo, Valles Mountains, N. Mex. Prismatic type of pyroxene microlites showing alignment imposed during emplacement.

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ever, with the full intensity of a 500-watt bulb the diagnostic angle of extinction may be determined.

Prismatic pyroxene microlites in rocks from Arroyo Hondo, Valles Mountains, New Mexico, are representative of a large proportion of those studied. This rock was previously studied by Ross and Smith (1955, p. 1081). This obsidian forms masses (marekanites) as much as 6 to 8 cm in diameter. The microlites in this rock are illustrated in Fig. 1, No. 1, and are similar to those from Water Canyon (Fig. 2, No. 6).

The prismatic microlites in both rocks are dominantly 0.01 to 0.02 mm in length, and 0.002 to 0.004 mm in diameter, and many of them show pyramidal terminations. In a few occurrences the pyroxenes are dominantly equidimensional grains associated with a few stubby prisms.

An interesting group of specimens from Metztitlán Barranca on the road to Zacualtipán, Hidalgo, Mexico, was collected by Carl Fries. One specimen contains unusually abundant pyroxene microlites with parallel orientation. Most of these are of the normal prism type, but a few are segmented. The prisms are exceptionally minute, being approximately 0.005 mm in length by 0.0005 mm in diameter. In another specimen the prisms are dominantly segmented and are illustrated in Fig. 1, No. 2. It is believed that commonly segmented pyroxenes belong to the group discussed in the following section, but it is probable that those in the Metztitlán Barranca are related to the prismatic type in time of origin.

A porphyritic flow rock from the Water Canyon area in the Valles Mountains contains pyroxenes which are more nearly equidimensional than are the prismatic forms. A large proportion of these occur as grains about 0.02 to 0.004 mm in diameter. Others are short prisms of the same

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No. 2. Obsidian from the north side of Metztitlán Barranca on the road to Zacualtipán, Hidalgo, Mexico, collected by Carl Fries. Abundant pyroxene microlites made up of beadlike segments with disordered arrangement.

No. 3. Obsidian from Lower Lake, Calif. Spiderlike and looped groups of pyroxene trichites, some of them radiating from magnetite grains.

No. 4. Welded tuff from Ammon quadrangle, southeastern Idaho, collected by G. R. Mansfield. Spiderlike and looped groups of pyroxene trichites which have formed in collapsed pumice in a glassy welded tuff. Note the identity with those in the obsidian of No. 3.

No. 5. Obsidian from Big Glass Mountain, Calif. Spiderlike groups of pyroxene trichites. Some of these show segments of the elbow type. Black dust is magnetite.

No. 6. Reproduction of a drawing by Zirkel (1876, Pl. IX, Fig. 1) of a glassy rock from the Truckee Range, Nev., represents spiderlike and looped trichites made up of beadlike segments.

Fig. 1 magnification 680X, except in No. 6. (Magnification for No. 6 not given by Zirkel.)

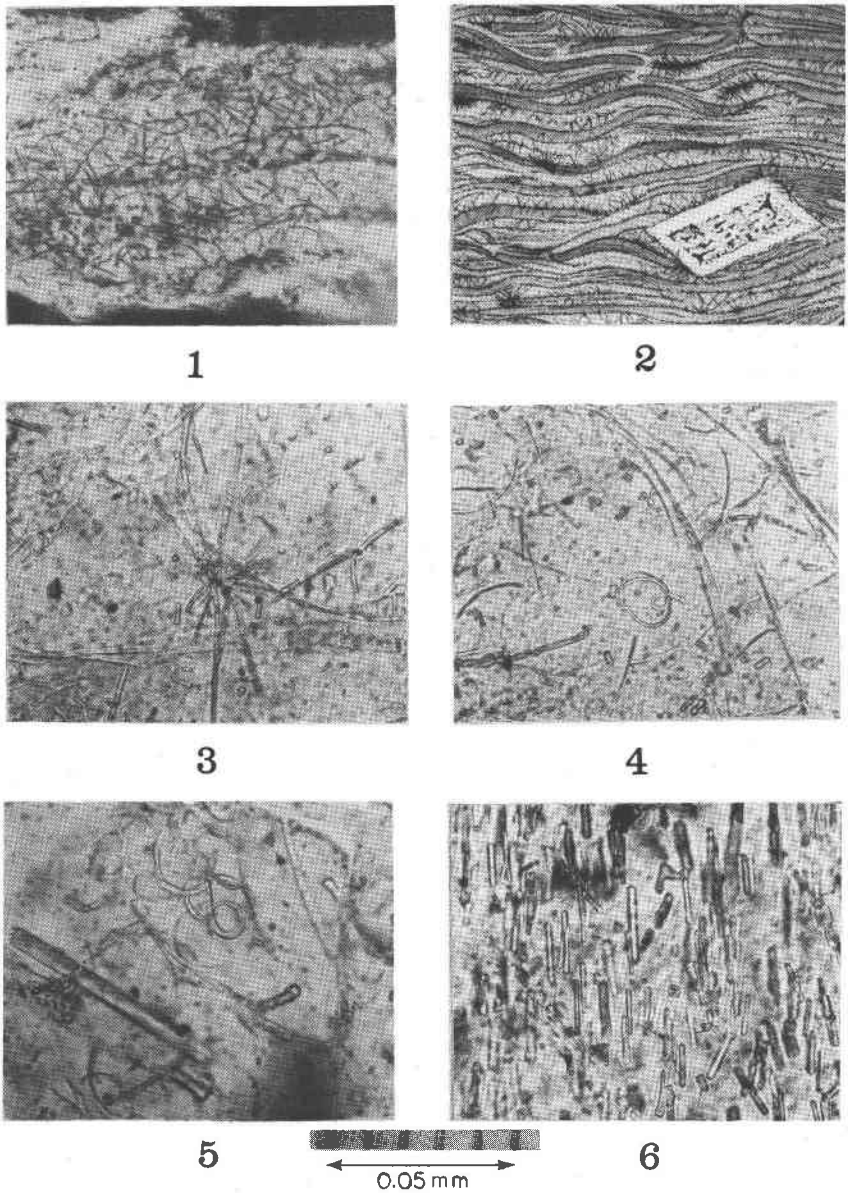

FIG. 2. Trichites in glassy rocks.

No. 1. Collapsed pumice in welded tuff from Los Américas quarries about 3 km west of Tlacotepec, Michoacán, Mexico, collected by Carl Fries. Spiderlike trichites in a collapsed pumice fragment in a glassy welded tuff.

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diameter but about twice as long, and in which the extinction angle is determinable.

Curved and Segmented Pyroxenes

The pyroxene microlites of the second type (the trichites) have extremely complex and varied forms. The various types of trichites have been so aptly described by Zirkel that some of his descriptions may be quoted. Zirkel (1876, p. 211) mentions "pellucid globulites, dark grains, globulitic needles, spikes, tendrils and cilla, screw-like and spider-like formations of black trichites." Zirkel (1876, Pl. IX, Fig. 1) presented a very good illustration of a rock from the Truckee Range, Nev., that shows spiderlike groups of beaded trichites and which is reproduced in Pl. 1, Fig. 6, of this paper. In his discussion of this rock, Zirkel (p. 207) states that " . . . they [the segments of the globulites] are strung out in lines, like pearly strings, an interval between the grains being usually distinctly visible, but in rare cases they touch one another. Towards the end, the globulites gradually grow smaller so the needles seem to be pointed. This [the arrangement of segments] is occasionally repeated three or four times, producing manifoldly kneeformed objects. In other cases, the aggregation of globulites takes the form of the most perfect curved and twinning tendrils. Sometimes a number of these radiate from a center, suggesting a spider with many legs." Zirkel recognized augites, hornblendes, biotite, and sanidine among the "globulites" in the materials studied.

An obsidian from Lower Lake, Calif., is an excellent example of the spiderlike groups of trichites and is illustrated in Fig. 1, No. 3. These groups have formed around tiny loci which were probably magnetite

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No. 2. Specimen from "Chataya Peak, Pah-Ute Range," Nev., illustrated by Zirkel (1876, Pl. VIII, Fig. 2). This represents a generalized drawing of a welded tuff. The light-colored areas show trichites and along the margins is dustlike material which must represent magnetite.

Nos. 3, 4, 5, and 6. A glassy flow rock from the Water Canyon area, Valles Mountains, New Mexico.

4. Near the center of the figure is a very perfect double loop of a pyroxene trichite. The large curved crystals show pyroxene trichites which vary greatly in diameter.
5. A complexly looped pyroxene trichite in the upper center. The large crystal lower left is an amphibole.
6. An area from the same thin sections as Nos. 3, 4, and 5 in which abundant prismatic pyroxenes have formed. Note that trichites have not formed in the presence of pyroxene prisms in No. 6, but have developed in Nos. 3, 4, and 5 in the essential absence of prismatic pyroxenes.

Fig. 2 magnification 680× except in No. 2 (Magnification for No. 2 not given by Zirkel).

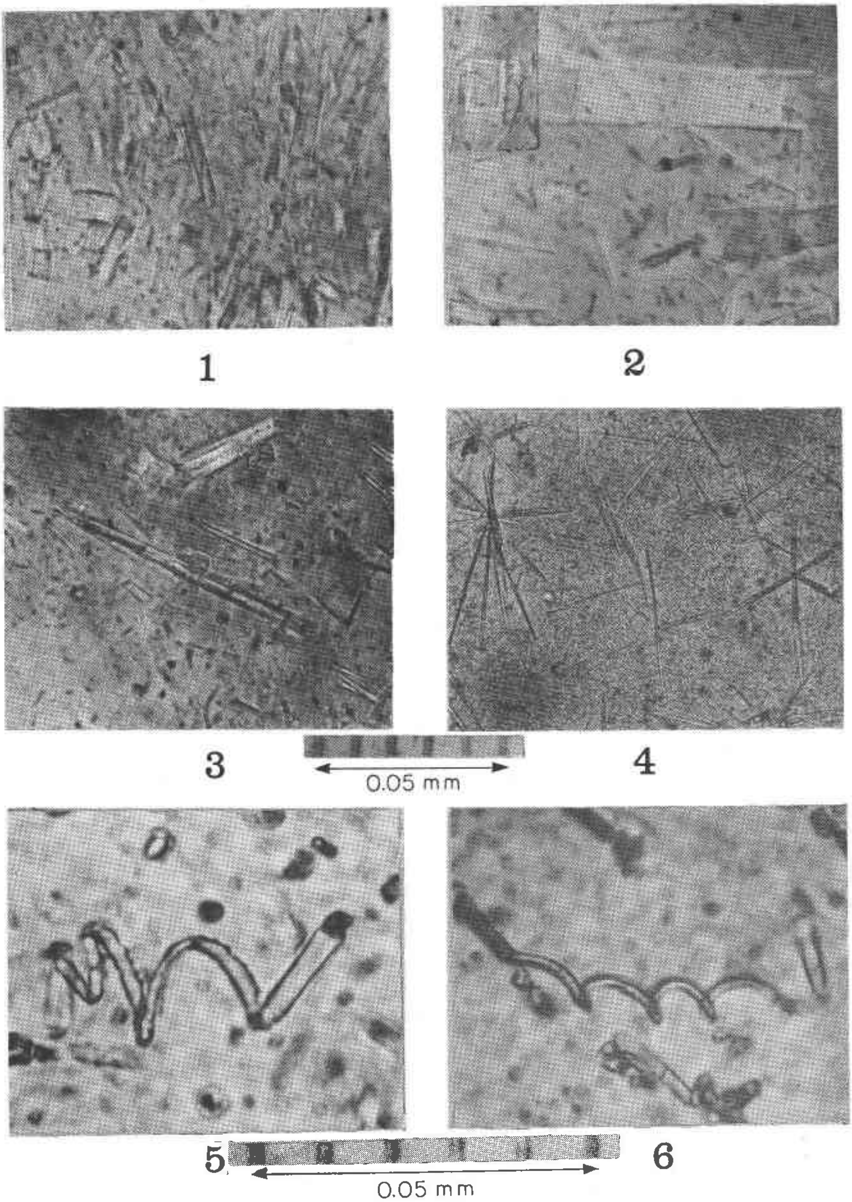

FIG. 3. Sanidine and amphibole microlites.

No. 1. Obsidian from a volanic center at Xalpazquillo, Puebla, Mexico, collected by Carl Fries. Typical occurrence of sanidine microlites. Magnification 580×.

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grains. The filaments of these groups are strongly curved, and many are circular loops, some being composed of two spirals. The filaments are very slender and are commonly 0.002 to 0.0004 mm in diameter. In the same occurrence are larger individuals with a well-developed segmented structure. The filaments resemble minute hairs with ordinary illumination, but with the phase microscope segments were observable.

An obsidian from Big Glass Mountain, California, contains twisted spiderlike groups of pyroxene trichites, as illustrated in Fig. 1, No. 5. The members of the groups tend to radiate from magnetite grains which formed loci for their development. Note the similarity to the spiderlike groups illustrated in Fig. 1, No. 6, which are reproduced from an illustration by Zirkel.

The segmented microlites described in the preceding paragraphs and the illustrations in Figs. 1 and 2 indicate that in general they are without orientation. However, those in another specimen from Metztitlán Barranca, on the road to Zacualtipán, Hidalgo, Mexico, collected by Fries, are sharply aligned. In these there is a very slender prismatic core and the beadlike segments, many of which are very short prisms, have formed as overgrowths on these cores. Thus there is evidence of two episodes of pyroxene formation: first the slender aligned prisms formed, and a beadlike overgrowth developed after emplacement.

Mineral identity posed a major problem in the study of the curved and segmented pyroxene microlites. A large proportion of these range in diameter from 0.001 to 0.003 mm and some are even smaller; hence they are in general too small for direct identification. Thus most of the looped trichites in Fig. 1, Nos. 3–5, are unidentifiable, although rare units in some such rocks permit observation of the large extinction angle characteristic of pyroxenes.

Fortunately, the Water Canyon rocks from the Valles Mountains, New Mexico, present a series of trichites with a very complete range in size.

No. 2. Obsidian from about 5 km NNE of Tulancingo, Hidalgo, Mexico-Tuxpán Highway, collected by Carl Fries. Illustrates a large sanidine grain with hopperlike walls showing at the right end and dimly at the left. Immediately to the left of this crystal is a sanidine crystal oriented in a position looking into one of these hopperlike depressions. Magnification 580×.

No. 3. Another specimen from the Tulancingo locality. Near the center of the figure is a fairly large amphibole crystal. Immediately above this is a prismatic pyroxene microlite and near the top a sanidine microlite. Magnification 580×.

No. 4. Amphibole crystals in a gray-green partly altered glass from an unknown locality. Magnification 280×.

Nos. 5 and 6. Glassy flow rock from Water Canyon, Valles Mountains, New Mexico, showing pyroxene microlites having the form of a coiled spring. Magnification 1180×.

The slender loops illustrated in Fig. 2, Nos. 4 and 5, and in Fig. 4, Nos. 1–4, are so slender that the identifying angle of extinction is not determinable. In contrast, the loops illustrated in Fig. 4, No. 5, and in Fig. 5, Nos. 1, 4, and 5, all from the same thin section, are made up of distinct segments of prisms which are identifiable as pyroxenes. Figure 5, No. 5, is made up of three large prisms, which continue into a loop with a faint trace of prisms. The large spiral in a specimen from 5 km NNE of Tulancingo, Hidalgo, on the Mexico-Tuxpán Highway, shows faint traces of segments in part of the loop. The very slender looped microlites shown in Fig. 1, Nos. 3–5, do not differ greatly from those from the Water Canyon rock.

The type of spirals resembling coiled springs illustrated in Fig. 3, Nos. 5 and 6, and doubly looped spirals as in Fig. 4, No. 4, are abundant in the Water Canyon rocks. A spiral and a helix occurring in the obsidian from 5 km NNE of Tulancingo, Hidalgo, Mexico-Tuxpán Highway are illustrated in Fig. 5, Nos. 2 and 3, and also occur in the glasses from other regions. They were also observed and illustrated by Zirkel, as shown in the upper part of Fig. 1, No. 6.

Pyroxene Relations

The previously mentioned parallel arrangement seems to be a general characteristic of the prismatic pyroxenes in glassy rocks. This orientation must have been imposed by movement during emplacement of the lava and indicates that the prismatic pyroxenes were formed before emplacement.

Examination of volcanic ash, pumice, and ash-flow tuffs of silicic composition shows that all those which have escaped modification, subsequent to explosive volcanic eruption, are without microlites. This relation has also been observed by Iddings (1899, p. 403). That is, the microlites seem to have been absent in the magma at the time of eruption, and therefore must have formed during the interval between eruption and emplacement.

The fragile character of the trichites (Figs. 1, 2, and 4) indicates that they would have been fragmented and dispersed by any movement of the emplacing magma. The filamental trichites occurring in some welded tuffs, and illustrated in Fig. 1, No. 4, and Fig. 2, No. 1, must have formed after deposition, collapse, and welding. Thus two distinct periods of formation must be represented by the prismatic pyroxenes and the curved and looped trichites. These differences in habit and time of formation of the pyroxene microlites must reflect a marked difference in the environment of formation. The relationships presented are inadequate for determining all the factors which may have played a part in their forma-

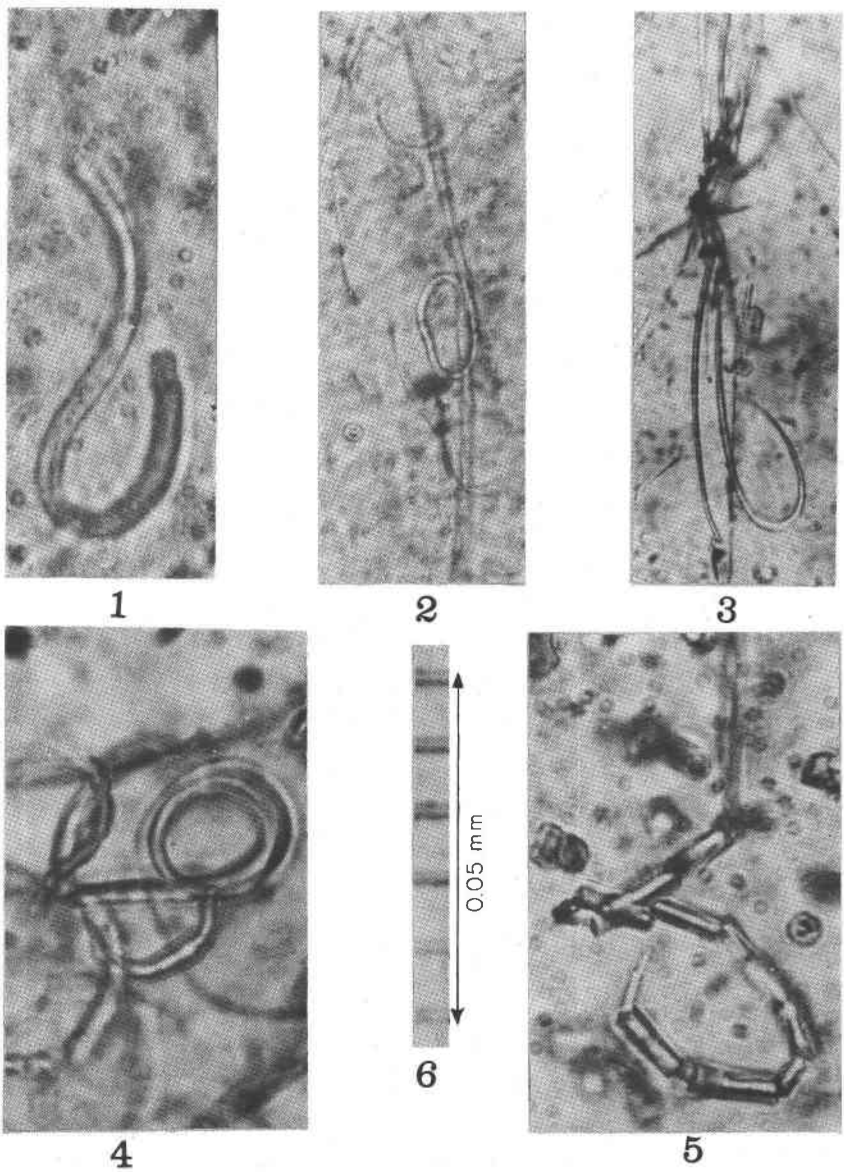

FIG. 4. Pyroxene microlites from a glassy rock, Water Canyon, New Mexico.

No. 1. A pyroxene microlite hook with continuity of structure, and unusually large diameter.

No. 2. Long slender pyroxene microlite with a loop near the center.

No. 3. A group of pyroxene microlites showing curved and looped form. The black grains at the center are magnetite.

No. 4. Looped pyroxene microlites. Note the double loop at the lower left, with one loop slightly out of focus below the other.

No. 5. Loops made up of prisms readily identifiable as pyroxenes.

Magnification 1180×.

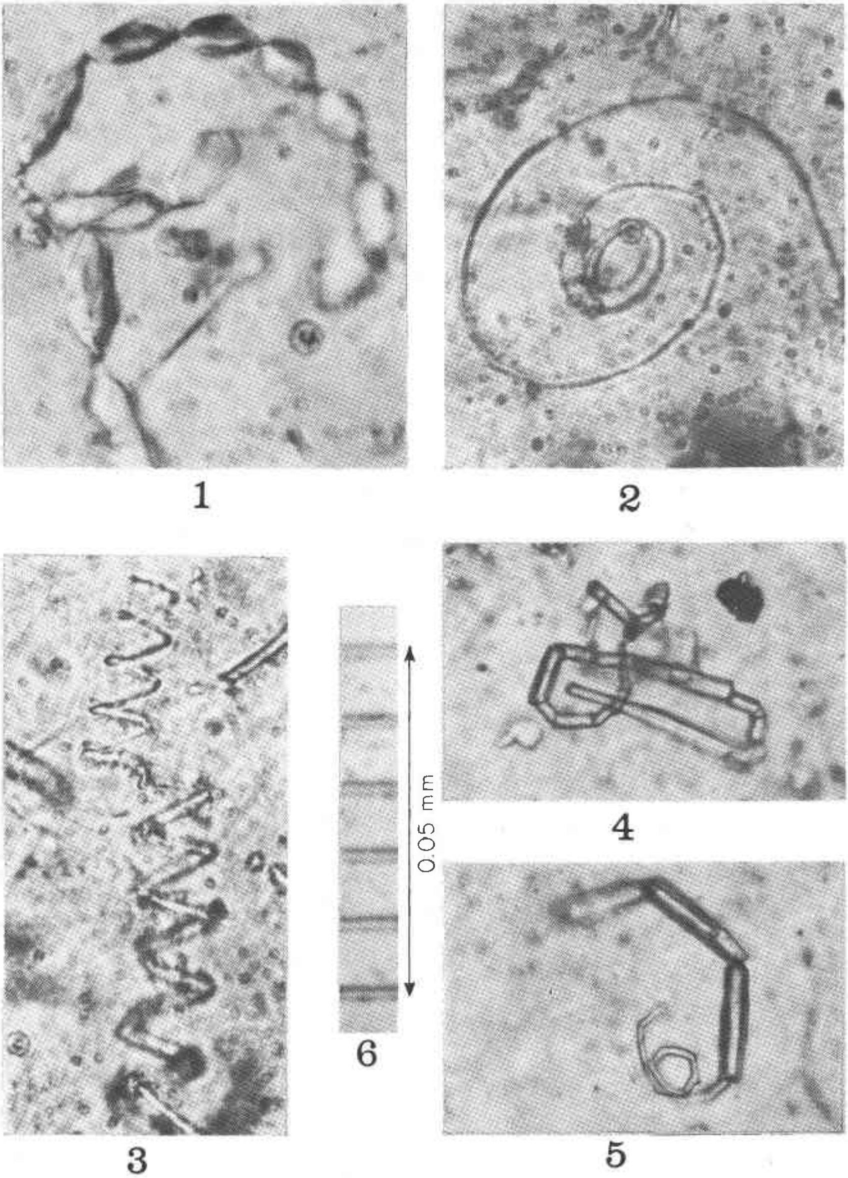

FIG. 5. Pyroxene microlites of varied form.

Nos. 1, 4, and 5 from a glassy rock Water Canyon, Valles Mountains, New Mexico. Nos. 2 and 3 from 5 km NNE of Tulancingo, Hidalgo, on the Mexico-Tuxpán Highway. Magnification 1180×.

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tion, but a lowering of temperature and a very high viscosity were probably major factors in the development of the trichites with their distorted crystal form. The very perfect spiral forms have a symmetry which must reflect some systematic anomaly in the crystal structure.

Some of the thin sections from Water Canyon present an interesting relationship. Numbers 4 and 5, Fig. 2, show the presence of looped pyroxenes, but no prismatic ones. Number 6 of the same figure represents another area in the same thin section with abundant prismatic pyroxenes, but without the looped type. This segregation of the two types seems explainable if the formation of the early-generation pyroxenes depleted the glass in magnesia and iron, the elements critical for the formation of pyroxenes. As a result these elements were not available in adequate amounts for the formation of second generation pyroxene in that immediate area. In areas without the earlier generation of pyroxenes there had been no such depletion and the second generation was free to form.

A count of the number of prismatic pyroxenes in a typical obsidian allowed a rough estimate of 3×10^5 in one cu mm of glass. Their size, however, is so small that this number would represent the order of about 0.5 per cent of the rock.

Amphiboles

Amphibole microlites have been observed in only a few of the many glassy rocks examined, and this has handicapped comparisons which would have clarified relationships. However, it seems evident that some amphiboles have been the product of deuteric or hydrothermal alteration, whereas others have developed in rocks having no evidence of alteration. In general, the amphibole microlites are larger than the pyroxene microlites and this, together with the different angle of extinction, has aided in identification.

Amphiboles from an unknown locality are illustrated in Fig. 3, No. 4, from a rock which is gray-green in color, indicating alteration of the glass. The groundmass glass is finely granular, as shown in the illustration, and contains minute prisms too small for identification, but which may be pyroxenes or altered pyroxenes. The amphiboles occur as stellate groups

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1. Loop made up of short pyroxene prisms. Pyramidal terminations are recognizable in the prism in the lower left. Crystal thickness greater than the depth of focus.
2. A remarkable microlite in the form of a helix showing four loops.
3. Pyroxene microlite in the form of a coiled spring.
4. A microlite with a double loop of pyroxene prisms.
5. A microlite with four large pyroxene prisms continuing into a loop of much smaller prisms.

which radiate from magnetite grains that formed loci of crystallization. Most of the crystals range from 0.02 to 0.08 mm in diameter and from 0.04 to 0.15 mm in length. The needles tend to taper to a very slender point and many of them are branched at their termination.

A specimen from Ongaroto (North Island), New Zealand, collected by Roy A. Bailey, contains amphibole prisms about 0.002 mm in diameter which range from 0.01 to 0.02 mm in length. With these are swarms of typical oriented pyroxene prisms.

An obsidian from Tulancingo, Hidalgo, Mexico, which is discussed in the section on feldspars, contains hornblende crystals, one of which is illustrated in Fig. 3, No. 3.

Biotite

Biotite seems to occur but rarely among microlites and is sparse even where it is present. The best examples are mentioned in connection with the discussion of feldspar with which the biotite seems to be commonly associated.

A group of rocks from Xalpazquillo, Puebla, Mexico, collected by Fries contains typical biotites which occur as very thin plates about 0.01 mm in diameter and with a small axial angle, and are similar to those in the rocks from Obsidian Knob, Valles Mountains, New Mexico, and Newberry Crater, Oregon. Those from Tulancingo, Hidalgo, on the Mexico-Tuxpán Highway, differ in that some of the biotites occur with a smaller plate symmetrically stacked on a larger one.

Feldspars

Feldspars seem to be exceeded only by pyroxenes among microlite minerals. They are abundant in a few of the obsidians observed, but seem to occur more generally in flow rocks with phenocrysts in a glassy groundmass. These feldspar crystals from a number of occurrences were separated and identified as sanidine by the index of refraction. The uniformity of habit suggests that sanidine is the characteristic feldspar of glassy rocks. These sanidines commonly show a secondary growth at the prism termination, which gives them a forklike appearance or more rarely a well-developed rectangular hopperlike depression.

A group of specimens collected by Carl Fries from a volcanic center at Xalpazquillo, Puebla, Mexico, is an excellent example of sanidine in glassy rocks and is illustrated in Fig. 3, No. 1. The sanidine crystals vary greatly in size, as they do in most of the rocks examined. Many of the more slender individuals appear to be nearly equidimensional in cross section and form slender prisms, but the larger ones are more blocky in habit.

A gray obsidian from Obsidian Knob, Valles Mountains, New Mexico, contains abundant sanidine, very sparse biotite, and rather abundant magnetite. Many of the sanidine grains appear to represent tabular crystals 0.002 to 0.004 mm in thickness, 0.01 to 0.03 mm in width, and 0.03 to 0.1 mm in length. Nearly all grains show the spurlike extensions at the corners.

A group of obsidian specimens from about 5 km NNE of Tulancingo, Hidalgo, on the Mexico-Tuxpán Highway, collected by Fries, contain an unusually varied group of microlites. These comprise sanidines, amphiboles and looped pyroxene trichites in some of the specimens. The sanidines vary greatly in size, some being slender prisms as small as 0.001 mm in width and others as large as 0.15 by 0.6 mm in size. Many of these are terminated by a very perfect hopperlike depression as illustrated in Fig. 3, No. 2. One specimen from Tulancingo contains large amphibole microlites, one of which is shown in the center of Fig. 3, No. 3. A sanidine grain lies near the upper part of the figure and a pyroxene prism between the sanidine and the amphibole.

The group of porphyritic rhyolites from Water Canyon, Valles Mountains, which has been described in the section on pyroxenes, also contains abundant sanidines. In general, these are smaller and more slender than those in typical obsidians and show the secondary growths at the corners of the prisms.

Magnetite

Magnetite is present in nearly all glassy rocks. In some of these it forms irregular grains as much as 0.003 mm in diameter, but it also occurs as clouds of minute dustlike grains and in a few rocks it is too sparse to be observable. Magnetite cannot be directly determined under the microscope, but any appreciable amount may be identified if the glass is ground to a very fine powder, this suspended in heavy solution and placed in direct contact with a powerful magnet. Magnetite becomes localized as a magnetic clot on the edge of the tube.

A specimen from "Norwikakat," Alaska, contains only dustlike magnetite grains, which are less than 0.001 mm in diameter. These occur in streaklike zones which must have formed during emplacement. Some of these are stringers of single grains and other zones are ribbonlike and only a few grains in thickness.

During the differential stress developed in a highly viscous glass during flowage, there is a tendency for the formation of incipient shear zones. These may heal or partly heal, and crystals tend to develop along such zones—probably promoted by the release of volatiles into the zone. A specimen for the Arroyo Hondo locality contained such a sharply localized zone, along which abundant pyroxene and magnetite microlites had formed.

A specimen collected by Fries from 5 km north of the Metztitlán Barranca on the road to Zacualtipán, Hidalgo, Mexico, is obsidianlike but has a red-brown color. Study with the microscope indicates that it represents the upper surface of a lava flow, which vesiculated and later collapsed and welded into a compact glass. Vestiges of the vesicular structure are retained in complexly twisted and swirl-like patterns. The areas that were originally most vesicular are now golden yellow; those of denser structure tend to have red borders and lighter-colored cores. The phase microscope and an oil-immersion objective reveal exceedingly abundant dustlike magnetite particles less than 0.0005 mm in diameter. In the redder areas the dust can be recognized as hematite by its color and birefringence. Under the microscope, large areas of the thin section appear blue, the intensity of the blue depending on the conditions of illumination. The red and golden areas and the blue overcast combine into a remarkable color pattern. The blue color must represent an optical effect, and evidently the magnetite grains are of the proper size to selectively reflect the shorter blue light waves.

Another specimen from the same locality in Mexico is composed of irregular subrounded black fragments 1 to 30 mm in diameter, in a matrix of finer-grained red material. This aggregate has been welded into an even-textured obsidian. The black fragments contain microlites of magnetite which retain the form of the pyroxene prisms that characterize normal obsidian from the same locality. In the bordering red areas the same prismatic forms are present, but a red color and birefringence indicates that magnetite has been oxidized to hematite. In the zones along which welding has occurred, secondary magnetite or its oxidation product has developed.

A number of thin sections used by Iddings (1899) in his report on the rocks of Yellowstone National Park have been available for comparison. In one of these, nearly colorless areas contain dustlike magnetite which produces a blue-gray color with transmitted light. Other areas are red owing to oxidation of the magnetite to hematite. The Yellowstone rocks seem in general to be characterized by abundant magnetite.

The discussion of microlites in welded tuffs points out that at least part of the dustlike material on the welded contact of the individual shards is magnetite. The reproduction in Fig. 2, No. 2, of an illustration by Zirkel (1876, Pl. VIII, Fig. 2) shows dustlike material which must represent magnetite which has developed along the contacts of the welded shards.

The ubiquity of magnetite in glassy rocks is also indicated by the studies of Senftle and Thorpe (1959), who report only one occurrence of obsidian—that from Mayor Island, New Zealand—which showed very low magnetic susceptibility. Commonly magnetite is the locus for the formation of microlites of amphiboles or pyroxenes. Such magnetite and that occurring in oriented streaks must represent early formation. Conversely, magnetite in welded tuffs must have formed after emplacement.

Microlites in Welded Tuffs

Some welded tuffs have undergone complete collapse of the shard and pumice structures and thorough welding, but retain the glassy character, and resemble obsidian in hand specimen. The trichite type of microlites have been observed in a number of such rocks.

Welded tuffs from the Ammon quadrangle, southeastern Idaho, were collected by G. R. Mansfield and described by Mansfield and Ross (1935). A restudy of some of this material has revealed pyroxenes of the trichite type which have developed within the collapsed shards as illustrated in Fig. 1, No. 4. Note the similarity to the trichites in the obsidian from Lower Lake, Calif., and represented in Fig. 1, No. 3.

A group of specimens from the quarries at Los Américas, about 3 km west of Tlacotepec, Michoacán, Mexico, collected by Fries includes several types of welded tuffs. Some of these contain collapsed pumice fragments, and in these trichites have developed as shown in Fig. 2, No. 1. Other areas in the same thin sections are made up of red-brown material which represents the finer-grained ash of the welded tuff, which is pigmented by red dust, probably oxidized magnetite. However, some shards are bordered by strongly refractive areas with parallel extinction and a pleochroism that seems to indicate biotite.

Trichites have been observed in welded tuffs from Redondo Peak and Battleship Rock in the Valles Mountains. They have also been observed in one of Iddings' thin sections of welded tuffs from River Basin, Yellowstone National Park, and from an obsidianlike welded tuff from near Taxco, Morelos, Mexico.

Zirkel (1876) in his studies of the rocks of the "Fortieth Parallel" pictured five specimens which evidently represent welded tuffs, although, of course, welded tuffs were not recognized at that time. One of these represented a rock from "Chataya Peak, Pah-Ute Range," Nevada, and was illustrated by a drawing in his Plate VIII, Figure 2, of his paper and is reproduced herein in Fig. 2, No. 2. The much flattened shards are represented as light-colored areas with darker material between them. Trichites have developed in the light-colored areas and magnetic dust along the borders. Compare these with the higher magnification of the trichites in the welded tuff represented in Fig. 2, No. 1.

Summary of Studies of Microlites

Table 1 lists the types, associations, and proportions of microlites in the 60 specimens of glassy volcanic rocks examined in the course of this study. These were dominantly from the Valles Mountains, New Mexico, and various localities in the western United States. Mexican localities are well represented and a few specimens from Iceland, Japan, New Zealand, and South America are included.

The number of specimens and the localities represented are inadequate for a full representation of microlite populations, but the following table gives a rough idea of the relative proportion of microlite types and of association relationships.

Table 1. Types, Proportions, and Relations of Microlites in Glassy Volcanic Rocks

	No. of specimens
Prismatic pyroxenes (total number)	22
Containing only prismatic pyroxenes	10
Trichite type of pyroxenes (total number)	19
Containing only trichite type pyroxenes	3
Prismatic type and trichite type of pyroxenes	6
Sanidine (total number)	12
Pyroxenes and sanidines (rare)	3
Biotite associated with sanidine	3
Amphiboles	6
Amphiboles and sanidine	3
Pyroxene trichites in welded tuff	6
Obsidian without observable microlites	8

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