# 6. *Petrogenic Meaning of the Occurrence of Spinel in Xenoliths.**

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## I. Introduction.

Petrological study on xenoliths sometimes informs us of the events that might have taken place during the metamorphism of xenoliths due to magmatic action. Researches on the xenoliths in effusive or hypabyssal rocks are effective in ascertaining the facts that might have taken place at an intermediate stage of metamorphism brought about in xenoliths of which we cannot be informed otherwise. Modes of occurrence of the spinel in xenoliths, now in question, is one of the most characteristic phenomena that might have taken place at an intermediate stage of metamorphism of xenoliths with argillaceous composition.

Behaviour of foreign inclusions in igneous rocks ought to be influenced not only by the original composition of foreign rocks, but by the kind of an attacking magma, and also in general by the prevailing condition to which both host and guest are exposed. It may be conceived, however, that during the metamorphism of argillaceous xenolith, events of the same kind might have been brought about almost exclusively at an intermediate stage regardless of the kind of an attacking magma. It is needless to say that each xenolith, a record of the effects of magmatic action on pre-existing rock, represents respectively each step of metamorphism brought about by a magmatic action in xenoliths or in the pre-existing rock, from which each xenolith has been derived. But in nature, xenoliths showing every step of their metamorphism are not found in equal frequency. Xenoliths recording the evidence showing an earlier and an intermediate state of metamorphism are in general scanty, when compared with those informing us of the state of metamorphism at a later stage, for we are informed of these processes from the evidences recorded in rocks that are end products of the mutual action between foreign matter and magma.

* Dedicated to the memory of late Prof. Takeo KATO.

Final goal of the metamorphism of xenolith is represented by an aggregate of the minerals that are crystallized out from the hybrid magma highly contaminated by foreign material. And the mineral assemblage of such xenoliths that reacted with magma to highly advanced state should be determined by the properties of an attacking magma. It is pointed out here that before reaching these various goals given by the characters of contaminated magma, most of argillaceous xenoliths, however, must have passed through the same course, and that the formation of spinel in xenoliths indicates one of the characteristic evidences showing such same course.

Occurrence of the xenoliths containing spinel seems to be almost restricted to those found in volcanic or hypabyssal rocks, while they seem to be scarcely found in plutonic rocks. Metamorphism of xenoliths might have easily been checked by eruption or rapid cooling of host rock. On the other hand, xenoliths in plutonic rocks were favoured in promoting the interaction with their surrounding magma sufficiently. Thus, it is difficult for us to find spinel in the xenoliths included in plutonic rocks. Even if it had been formed in the xenoliths in plutonic rocks, it must have disappeared, as the mutual reaction between xenoliths and magma have proceeded to more advanced degree. In short, occurrence of spinel in xenoliths owes much to the geologic condition that checked the metamorphism of xenoliths due to magmatic action at a moderate stage. And such a geologic condition must have prevailed in the case of the xenoliths included in volcanic or hypabyssal rocks.

Chemical composition of the original rocks is, of course, one of the essential factors that facilitate the formation of spinel in the xenoliths derived from them. We must take into our consideration the fact that the xenoliths treated by the present writer were mainly derived from the metamorphic rocks such as biotite-schist which might had already been partially rich in alumina and poor in silica on account of its metamorphic differentiation before they were influenced by the magmas related to volcanic action. And such heterogeneity in original rocks may have been favourable to appearance of the spinel in their derivative xenoliths. The andalusite or sillimanite porphyroblasts fringed with spinel grains described in the succeeding chapters may also be considered as one of the remarkable petrographic features to be ascribed to such a polymetamorphism or repeated metamorphism as shown by the pyrometamorphosed xenoliths derived from mica-schist enclosed in volcanic rocks[1]. There is no need to mention here that in the spinel-bearing xenoliths the writer intends to describe in this paper, xenoliths not influenced by the surrounding rock *viz.* xenoliths which were caught up mechanically and do not indicate any

1) A. HARKER, *Metamorphism.*, (1932), 322–326.

evidences which may be ascribed to the effects of host rock are excluded.

## II. Mode of occurrence of the green spinel in the xenoliths in the garnet-biotite-andesite from Nijō volcano near Osaka.

During his petrological study on the inclusions in the garnet-biotite-andesite from Nijō volcano near Osaka, the writer pointed out the occurrence of green spinel as a common accessory constituent found in some argillaceous xenoliths. The original rock from which these spinel-bearing xenoliths are thought to have been derived is represented by such inclusions in the andesite that show no effect of magmatic action, or by those that have been only moderately metamorphosed, still with remnants of its original characters. Petrographically, these inclusions belong to so-called normal regional metamorphic rocks of the almandine-zone, staurolite-zone, and perhaps to sillimanite-zone, or to the diaphthorite derived from the former. The spinel in question is not found in these xenoliths. The first step of the metamorphism due to the attacking magma is indicated by the development of hornfelsic texture, characterized by mosaic aggregate of dark brown biotite and andesine-labradorite, among the original schistose or phyllitic texture (Fig. 1–4). Corresponding to this textural change, porphyroblasts of some aluminous minerals such as andalusite, sillimanite, and cordierite are formed. Corundum appears within the porphyroblasts of andalusite; fibrous sillimanite around the blastoporphyritic staurolite; and green spinel and calcic plagioclase around or along the cleavages of the porphyroblasts of sillimanite or of andalusite at this stage (Fig. 5–8). The appearance of corundum and spinel indicates the culmination of metasomatic action between the xenoliths or the pre-existing rock and the magma. At a further advanced stage of metamorphism which is characterized by glass invasion and by development of glomeroporphyritic aggregates of biotite and plagioclase sporadically formed in the general mass of the hornfels texture, the above-mentioned porphyroblasts of the preceding stage disappear, and are gradually replaced by andesine or sodic labradorite. Spinel is not found in such xenoliths. Metamorphism of the xenoliths is checked by effusion of the hybrid mash as a lava, and final stage of the metamorphism is represented by glomeroporphyritic aggregates of biotite and plagioclase. In other words, the xenoliths metamorphosed by the magma into an advanced degree have a mineral assemblage as if it were results from the crystallization of the contaminated magma under an intratelluric condition.

### III. Examples of occurrence of spinel in xenoliths.

Andalusite or sillimanite porphyroblasts fringed by spinel—an intergrowth of the two aluminosilicates is not rare, and as far as the writer has observed, the former always tends to be replaced by the latter—are common in the xenoliths included in volcanic or hypabyssal rocks, the xenoliths caught up into host rocks only mechanically or the xenoliths sufficiently reacted on with an enclosing magma, of course, being excluded. And their occurrence have been reported by many European petrographers since the last decade of 19th century[2]. H. H. Thomas[3] described the spinel-bearing rock as a hybrid derived from an argillaceous xenolith (sillimanite-buchite) in the tholeiite sill from Mull (Fig. 9). R. Brauns[4] mentioned in his memoir on the ejecta from Laacher Seegebiet, that spinel was newly formed from staurolite, sillimanite, and andalusite during the pyrometamorphism of mica-schist due to a volcanic magma. And the spinel-bearing xenoliths were reported by G. A. Bartrum[5] in the andesite from Auckland, New Zealand.

In Japan, K Sugi[6] found the biotite-andesine-rock containing corundum and spinel as an inclusion in the quartz-porphyry from Nikkō, Pref. Tochigi, and noticed that the corundum was fringed by spinel and the former was often replaced by the latter. As compared with the above-mentioned andalusite (or sillimanite) -spinel-assemblage, this corundum-spinel-assemblage may be considered as a more extreme case showing a characteristic trend of metamorphism of argillaceous xenoliths that a xenolith becomes poor in silica, at an intermediate stage of its metamorphism, and in consequence relatively rich in alumina. Corundum is found in the xenoliths from Nijō volcano, as was mentioned in the foregoing chapter. And T. Watanabe[7] also described a xenolith containing spinel and corundum in the porphyritic granite from Suan district, Korea.

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2) A. LACROIX, *Les enclaves des roches volcaniques*, (1893).
F. CORNU, *Beitr. zur Paläont. und Geol. Osterreich-ungarns und des Orients*, 19 (1906), 34-47.
A. BERGEAT, *Neues. Jahrb. Mineral.*, 33 (1910), 575 629.
S. RICHARZ, *Jour. Geol.*, 32 (1924), 685-689.
G. KALB, *Min. Petr. Mitt.*, 47 (1935), 185-210.

3) H. H. THOMAS, *Quart. Jour. Geol. Soc*, 78 (1922), 229 260.

4) R. BRAUNS, *Die kristallinen Schiefer des Laacher Seegebietes und ihre Umbildung zu Sanidinit.*, Stuttgart (1911). usw.

5) G. A. BARTRUM, *Trans. Roy. Soc. New Zealand*, 67 (1937), 251-280.

6) K. SUGI, "Contact metamorphic rocks." *Iwanami Kōza Geol. & Mineralogy* (1931), 39, (in Japanese).

7) T. WATANABE, *Jour. Fac. Sci. Hokkaido Univ.*, (ii), 6 (1943), 239.

Andalusite or sillimanite in xenoliths has often grown up to large porphyroblasts, several centimetres in their length, whose typical example was shown by a specimen collected by J. Masutomi[8] from the nevadite quarried at Shingū, Pref. Wakayama (Fig. 10). Remarkable large xenocrysts of andalusite scattered in the granite-porphyry were also described by T. Iwafune[9] from Owase, Pref. Mie.

Staurolite associated with spinel has been reported not only by Brauns in his above-mentioned memoir, but by T. Takeuchi[10] in the xenolith in the garnet-bearing andesite from Mt. Amataki, Pref. Kagawa (Fig. 11), and also by the present writer in the xenolith from Nijō volcano (Fig. 12).

## IV. *Desilication* as a remarkable phenomenon characteristic of the metamorphism of argillaceous xenoliths.

Relating to this metamorphism of argillaceous xenoliths, the present writer contemplates recapitulating here that at the intermediate stage of metamorphism, a decrease in $SiO_2$, and an increase in $Al_2O_3$ take place in the chemical composition of the xenoliths. This is shown by the results of his systematic observation on the argillaceous xenoliths that are same in their origin and only different in degree of their metamorphism, as was mentioned in the foregoing description (Chapter II). And this is also consistent with geological fact that the occurrence of spinel is common from the xenoliths found in volcanic or hypabyssal rocks, while it is rare from the ones contained in plutonic rocks. The trend of this chemical change of these xenoliths is observed as the temporary appearance of spinel, usually with calcic plagioclase, sometimes with corundum, around or within the porphyroblasts of sillimanite or of andalusite in the xenoliths representing an intermediate stage of metamorphism. At the present state of his study, it may be inconceivable for the writer to make clear how the decrease in silica takes place, for the mechanism of *desilication* has never yet been analyzed. In other words, it is only considered as a result of some uncertain metasomatic processes commonly found in xenoliths or at the contact portion between wall rock and igneous mass where geological condition favourable to such processes must have been prevailing. In spite of its obscurity, however, we cannot help recognizing an important rôle played by the *desilication* in petrogenesis. If we postulate this to be one of

8) J. MASUTOMI, *Our Mineral*, 9 (1940), 62-63, (in Japanese).

9) T. IWAFUNE, "Geology and Petrology of Kinomoto and Owase District (MS)," Geol. Inst., Tokyo Univ., (1939).

10) T. TAKEUCHI, *Jour. Jap. Assoc. Petrologists, Mineralogists, and Economic Geologists*, 26 (1941), 33-60, (in Japanese).

the most primal inclination of the metasomatism brought about in xenoliths or in wall rocks due to magmatic action, many evidences observed in such rocks may be reasonably interpreted.

Thomas[11] pointed out that the plagioclase formed in the xenolith had a composition similar to anorthite and was more calcic than the plagioclase (bytownite) in the cognate inclusion. And it is often observable that the plagioclase formed in xenoliths is more calcic than those in the surrounding rocks. Concerning the garnet-biotite-andesite from Nijō volcano, R. Ōhashi[12] and T. Sugimoto[13] wrote as follows: Plagioclase enclosed in the garnet phenocryst is anorthite, while compositions of the isolated crystals of plagioclase in the andesite are An 65–40%, and the plagioclase having the composition of An 90-65 is lacking in this lava. Therefore, these garnet crystals in the andesite must have crystallized out from the magma during the cyrstallization of the plagioclase having the composition of An 90-65%. As to these garnet crystals including calcic plagioclase, it may be considered that these calcic plagioclase had been included by the garnet crystals during the formation of garnet porphyroblasts in the xenoliths or in the wall rock under the influence of the attacking magma, and were scattered into the andesite at the time of disintegration of the xenoliths into the magma.[14] The fact noted by Ōhashi and Sugimoto, whose interpretation is different from the writer's, coincides with the trend of metamorphism of xenoliths emphasized in this paper. And some of the anorthite, often found in andesite or in tholeiitic basalt as conspicuous large porphyritic minerals, may be considered as a kind of the xenoliths derived from some argillaceous rocks concealed under the volcanoes.[15] Some of them may be the extreme examples showing this trend of metamorphism. Formation of the calcic plagioclase as well as of the spinel and the corundum in xenoliths may be ascribed to the mutual reaction between xenoliths and an enclosing magma. And other metasomatic processes which might have led to the introduction of CaO, MgO, FeO, etc., into xenoliths from the attacking magma must be taken into our consideration. It may be influenced also by the least change of femic contents in xenoliths, whether the spinel appears in them or not. Nevertheless,

11) H. H. THOMAS, *op. cit.* 245.

12) R. ŌHASHI, *Our Mineral*, 5 (1936), 20-22, (in Japanese).

13) T. SUGIMOTO, *Our Mineral*, 5 (1936), 10-20, (in Japanese).

14) R. MORIMOTO, *Jour. Jap. Assoc. Petrologists, Geologists, and Economic Geologists*, 32 (1944), 218-225, (in Japanese).

15) K. YAGI, *Jour, Jap. Assoc. Petrologists, Mineralogists, and Economic Geologists*, 33 (1949), 13, (in Japanese).

T. ISHIKAWA, *Jour. Geol. Soc. Japan*, 53 (1947), 64, (in Japanese).

S. KÔZU, *Sci. Rep. Tohoku Univ.*, (ii), 2 (1914), 7.

J. HARADA, *Bull. Vol. Soc. Japan*, 2 (1936), 330, (in Japanese).

the writer supposes, however, that the *desilication* must have played an important rôle in making a favourable condition to form these minerals in xenoliths. Recently, H. Yamada, who described the basic xenoliths in the quartz-diorite from Senmaya, Pref. Iwate, talked about this process and explained the genesis of those inclusions.[16] And it is of interest, relating to this problem, that silica mineral such as tridymite, rarely with cordierite,[17] are found conspicuously in some lava containing xenoliths.[18]

In conclusion, the present writer wishes to be given an opportunity to offer his cordial thanks to Prof. Seitarô Tsuboi of this Institute for his kind encouragement during this study, and his special thanks are due to Dr. Hisao Yamada of the Tokyo Institute of Technology for his kind instruction, also to Prof. Tsunehiko Takéuchi of the Tohoku University and to Mr. Junosuke Masutomi for gifts of specimens.

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## 6. 捕獲岩に見出される尖晶石の産状とその成因

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二上火山（大阪府南河内郡山田村，奈良縣北葛城郡二上村）産柘榴石黑雲母安山岩中の礬土質捕獲岩の變成過程に見られる尖晶石の消長と，各地火山岩，半深成岩中の捕獲岩中における尖晶石の産狀について記載し，礬土質捕獲岩の變成過程の特徴を述べ，特に脱珪酸作用の重要性を論じた.

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16) H. YAMADA, *Jour. Geol. Soc. Japan*, 55 (1949), 154.

17) R. MORIMOTO, *Bull. Earthq. Res. Inst.*, 25 (1947), 33-35.
R. MORIMOTO and H. MINATO, *Bull. Earthq. Res. Inst.*, 26 (1948), 41-44.

18) Washinoyama, (Yamanouchi-mura, Ayauta-gun, Pref. Kagawa), Ishigamiyama, (Kumamoto City, Pref. Kumamoto), etc.

## Explanation of Plates.

Fig. 1. Staurolite-bearing phyllite, a xenolith slightly metamorphosed by the magma. Microfolded phyllitic structure and the irregular grains of plagioclase are still reserved, though the recrystallized mosaic aggregate of plagioclase and biotite and invasion of glass are observed. Photomicrograph, polarizer only. ×ca. 20. (40IIIRM-$61_{29}$).

Fig. 2. Clomeroporphyritic aggregates of biotite and plagioclase (g) are formed among the matrix of the xenolith. The general mass of the rock consists of fine-grained mosaic aggregates of biotite and plagioclase, and the original schistose structure (sch) is still reserved. Photomicrograph, polarizer only. ×ca. 18. (40IIIRM-61s').

Fig. 3. Pockets of glomeroporphyritic biotite and plagioclase (g) developing in the matrix of hornfelsic texture (h). Photomicrograph of the andalusite-cordierite-biotite-plagioclase-xenolith, analyzer being inserted. ×ca. 12. (RM41123003).

Fig. 4. Hornfelsic texture reserved in the glomeroporphyritic aggregate of biotite and plagioclase. Photomicrograph of the garnet-bearing biotite-plagioclase-xenolith, analyzer being inserted. ×ca. 23 (RM41123048).

Fig. 5-6. Green spinel within and around the porphyroblast of andalusite which is partially replaced by sillimanite (s). Periphery of the porphyroblasts is embayed by the minute grains of spinel and calcic plagioclase intimately associated with each other (b), where spinel grains are arranged along the lines perpendicular to the crystal face of the andalusite. Euhedral octahedron of spinel (a) associated with clear homogeneous plagioclase is formed within the porphyroblast. Fig. 6 was photo., an analyzer being inserted. Spinel-sillimanite-andalusite-biotite-plagioclase-xenolith in the garnet-biotite-andesite from Nijō volcano. ×ca. 76. (40IIIRM-$17s_5$).

Fig. 7. Twinned sillimanite porphyroblasts fringed by green spinel (z), crystal x and crystal y penetrate each other perpendicularily. Spinel-sillimanite-biotite-plagioclase -xenolith, Nijō volcano. Polarizer only. ×ca. 35. (42 (II)-$322_{15}$).

Fig. 8. Relic of sillimanite porphyroblast (s) fringed by spinel (brown dirty glass) in the biotite-plagioclase-xenolith with glomeroporphyritic texture invaded by glass. Analyzer being inserted. ×ca. 19. (40IIIRM-17s).

Fig. 9. Spinel (S) forming a pseudomorph after sillimanite surrounded by anorthite (An), G being glass. A diagramatic sketch of a photomicrograph of the xenolith described by H. H. Thomas from Mull.

Fig. 10. Xenolith in the nevadite from Chihogamine, Shingū, Pref. Wakayama. Collected by J. Masutomi. Remarkable porphyroblasts are the parallel intergrowth of andalusite and sillimanite fringed by green spinel. (real size).

Fig. 11. Spinel (S)-magnetite (M)-staurolite (T)-garnet-sillimanite (S)-biotite-plagioclase (L)-rock, a xenolith coll. by T. Takeuchi from the hornblende-hypersthene-andesite, Mt. Amataki, Tsuda-machi, Pref. Kagawa. Photomicrograph, polarizer only. ×ca. 70. (RM41111403).

Fig. 12. Staurolite (T) fringed by spinel (P), associated with fibrous sillimanite (S) in the spinel-staurolite-sillimanite-cordierite-biotite-plagioclase-rock, a xenolith in the garnet-andesite from Nijō volcano near Osaka. Photomicrograph, polarizer only. ×ca. 70. (RM41123034).

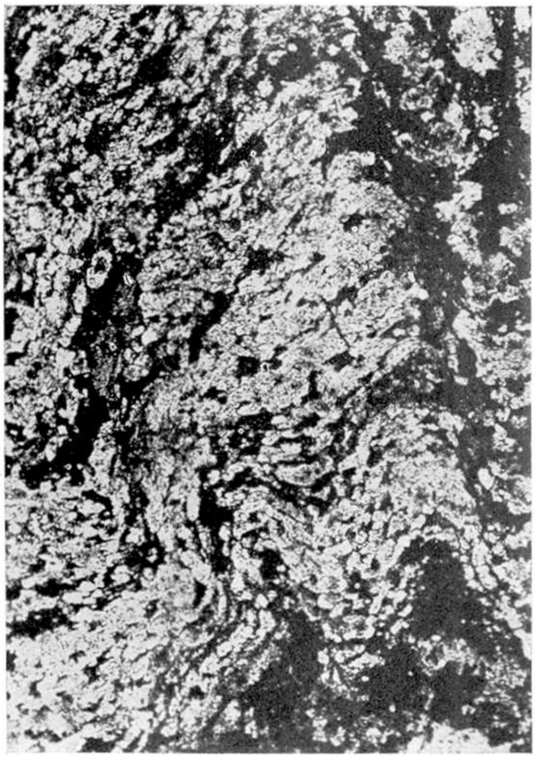
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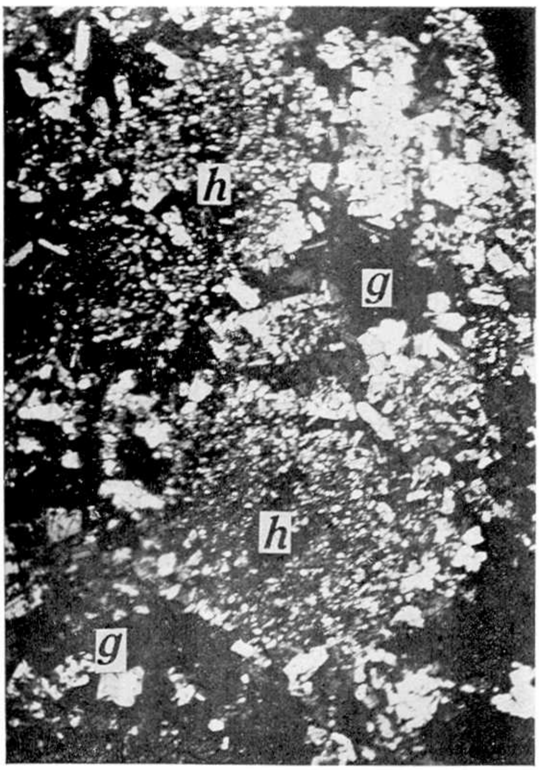
Fig. 2.



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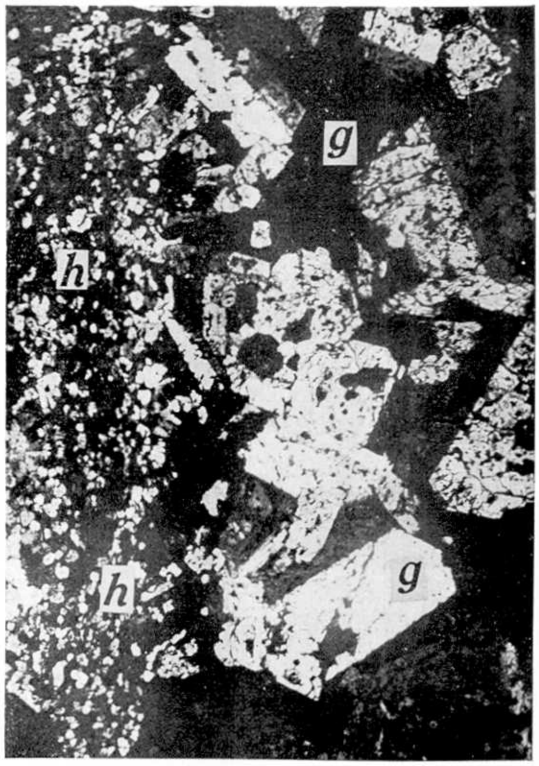

Fig. 4.

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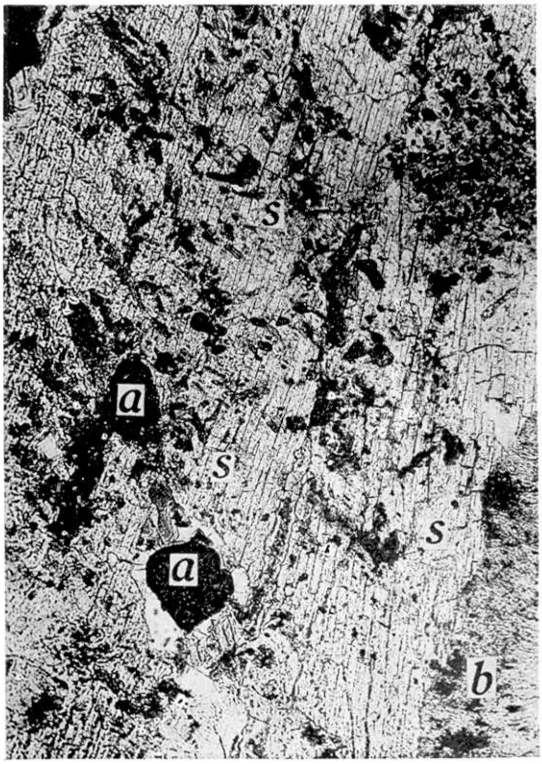


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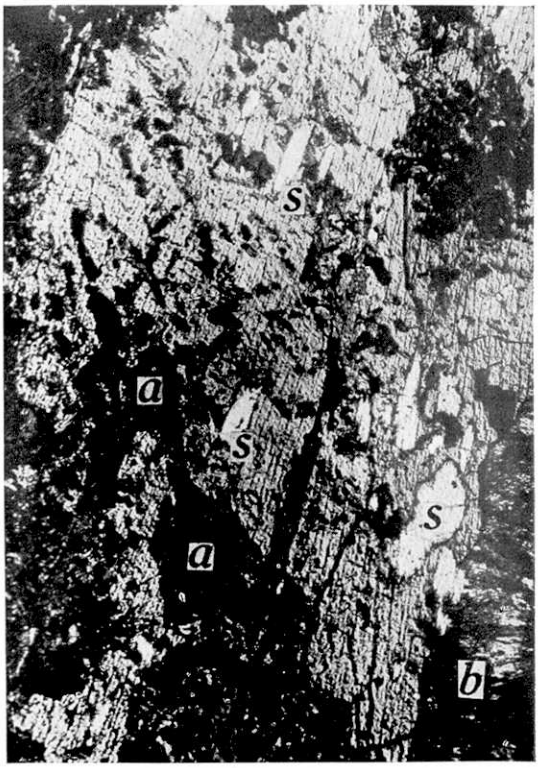


Fig. 6.

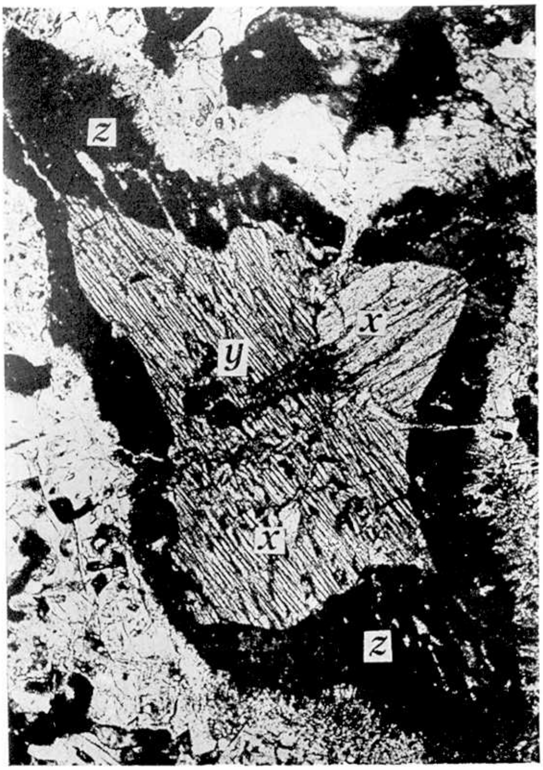


Fig. 7.


Fig. 8.

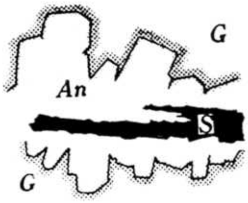


Fig. 9.

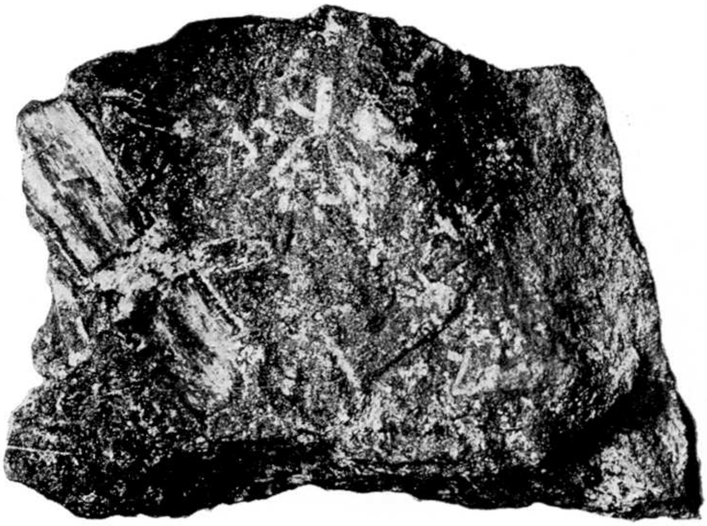

Fig. 10.


Fig. 11.

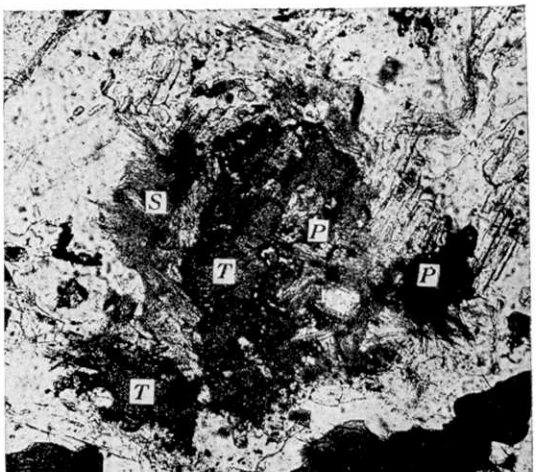


Fig. 12.