THE TSINAN INTRUSIVE.

BY GEORGE B. BARBOUR.

CONTENTS

I. INTRODUCTION.

"One of the striking features in the Tsinan plain is a group of isolated hillocks standing up boldly from it. Though mainly overgrown with vegetation, they are distinguishable by their shape and dark colour from the light-grey tabular limestone islands which from the last outposts pushed forward by the mountains lying to the south."[1]

Tsinanfu, the capital of Shantung, lies at the foot of the northern slope of the T'aishan massif, where the edge of the Huang Ho flood-plain abuts the downwarped margin of the Shantung horst. The most striking feature, which never fails to attract the eye of any one approaching the city, is the group of hummocks, rising abruptly from the plain, aptly described by v. Richthofen.

These hillocks have been the object of comment by Willis and Blackwelder,[2] Lorenz, and others, but the distances separating them have usually made a connected study of their nature and relationships out of the

question in rapid reconnaissance work.

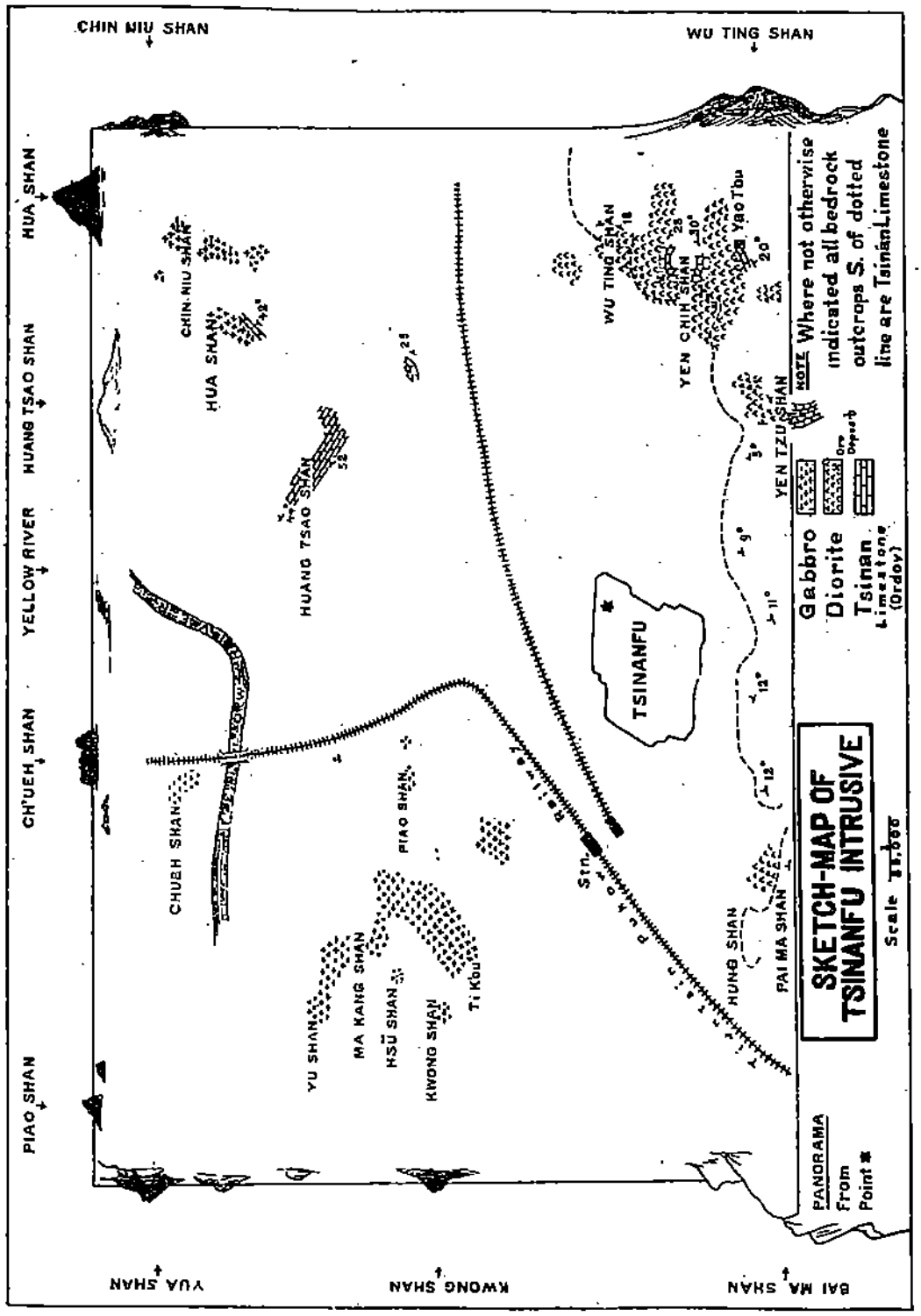
Several of these hills fall within the limits of a more detailed map by Mr. T'an[4] of the Geological Survey of China, in connection with a magnetic survey of the iron deposits of the area; but the immediate practical object in view put the investigation of certain phases outside the scope of his report.

A statement is now offered of the questions raised by recent observations bearing on the nature and origin of these hillocks, and their relation to the surrounding rocks. They form an interesting example of magmatic differentiation in a gabbro body with deuteric action and contact metamorphism; a special mineralogical feature is the biotite reaction-rims. A correct interpretation of the facts throws light on the structure of northern Shantung, proving to support, for instance, the contention of Willis and Blackwelder that no marginal fault of any magnitude is necessarily involved at this point, and that simple downwarping is the determining factor in the structure of the north margin of the Shantung island. The discussion involves also certain magnetite deposits (of little economic value) and has a possible bearing on the origin of the famous Tsinan springs.

The author is glad of this chance to express his gratitude to Dr. V. K. Ting, and Dr. W. H. Wong, Directors of the Geological Survey of China, who generously offered information, material and facilities for reference and research. He is also under a debt of obligation to Mr. Loo, Librarian, and to other members of the Survey, especially Mr. H. C. T'an, the results of whose previous reconnaissance, and familiarity with the area were freely placed at the writer's disposal. Professor Frederick K. Morris, Geologist of the American Museum of Natural History's III Asiatic Expedition to Mongolia, first pointed out the area as offering a problem worthy of study, and most generously placed data and material at the writer's disposal; these and his helpful criticism and suggestions have been of a value it would be hard to overestimate.

II. Area Involved.

The position of the hillocks in question is shown on the map. They fall within an elliptical area 10 miles long by 4 miles wide. But the outcrops are not limited to these, for at some points in the low ground, the rock can be traced almost continuously for considerable distances.


CHIN NIU SHAN
WU TING SHAN
HUA SHAN
HUANG TSAO SHAN
YELLOW RIVER
CH'UEH SHAN
PIAO SHAN
YU SHAN
KWONG SHAN
BAI MA SHAN
CHIN NIU SHAN
HUA SHAN
HUANG TSAO SHAN
WU TING SHAN
YEN CHIN SHAN
YAO TOU
YEN TZU SHAN
CHUEH SHAN
PIAO SHAN
MA KANG SHAN
HSÜ SHAN
KWONG SHAN
Ti Kou
YU SHAN
HUNG SHAN
PAI MA SHAN
TSINANFU
Stn
NOTE Where not otherwise indicated all bedrock outcrops S. of dotted line are Tsinan Limestone
Gabbro
Diorite
Tsinan Limestone (Ordov)
SKETCH-MAP OF TSINANFU INTRUSIVE
Scale
PANORAMA From Point *

Along the base of the foot-hills occurs a series of intrusives of more acid character. Up till now they have been regarded as a distinct type, but it seems possible to show that a genetic connection exists between them and the outcrops in the plain, the whole being parts of a differentiated unit.

The exact form of the igneous body can best be discussed after considering the marginal relations, but evidence favors a compound or multiple laccolith.

III. Sedimentary Formations.

The sedimentary formations exposed in the area include the Tsinan dolomitic limestone (here exposed in its type locality), loess, and river alluvium, interbedded with more consolidated boulder and gravel deposits, the latter washed down from the lateral slopes of the limestone ridges. A marmorized series of limestone beds found close to igneous contacts in the area has been regarded by some observers as an independent formation. They are more probably metamorphosed Tsinan limestone recrystallized under special conditions. The sediments are therefore limited to Ordovician and post-Pliocene in age.

IV. The Hyperite Body.

Main varieties:

The two main varieties of *igneous rock* are best discussed independently before considering their mutual relationships. The type most generally attracting notice owes its resistence to weathering—and hence its prominence—to its basic character. It is described as a hypersthenfels, hyperite,[6] or olivine-hypersthene-gabbro. Rocks resembling the one described by Blackwelder[7] occur at K'uang Shan, Yua Shan, Piao Shan, Ch'ueh Shan, Hua Shan, and at intermediate points (see map) A specimen (Ts 203) from the low ridge north of Ti K'ou, near the village of K'ung A, is a medium grained granitoid, speckled, brown-black rock, weathering grey-brown. It may be taken as typical, though some more basic samples have been met with. Under the microscope (Plate I. Fig. 1) it is seen to contain augite, plagioclase-feldspar, hypersthene, olivine, biotite, magnetite, and accessories, in approximately that order of abundance. The *olivine*, which seems to have crystallized first, is fresh, except for slight incipient decomposition along cracks to serpentine and magnetite dust. It is idiomorphic towards all other

minerals, but shows rounded outlines, a characteristic which, though normal of olivine, is here shared in general by the later minerals as well. The relations existing between the latter indicates a less definite sequence, and varies slightly in different localities. Without doubt the periods of crystallization overlapped considerably, probably with resorption and interaction. The olivine itself, where in contact with the feldspar, was observed by Blackwelder to show bushy growths of what were judged to be tremolite fibres. This feature is not extensively developed in the slide described, but several needles of a similar mineral occur in that relationship (Ts 206). The *augite* is pale green-brown, and tends to develop better outlines than the feldspar, but this is not invariable. It is non-pleochroic, shows distinct dispersion, and gives maximum extinction angles up to 38°. It frequently occurs twinned, sometimes showing polysynthetic lamellæ parallel to (100) and is markedly poecilitic, containing inclusions of biotite, magnetite, apatite, plagioclase, and olivine, while some crystals show a Schiller structure. A characteristic feature is the great development of needle inclusions (presumed to be ilmenite), which seem to lie in planes parallel to (110). This feature is not found in the hypersthene, and, where present, is diagnostic. The *feldspar* is fresh, showing pericline as well as albite, and Carlsbad twinning, and has maximum extinction angles varying from 16° — 38° (average 26°) in zones perpendicular to (010), hence ranging between andesine and labradorite. The *hypersthene* tests negative and shows characteristic pleochroism (Z—pale green, X—brownish-pink). Dr. Wong drew my attention to the fact that some specimens in possession of the Survey showed oblique extinction, and Professor F. K. Morris has suggested that the augite molecule may be present in solid solution. Careful examination of all rock sections prepared show a number of crystals with this characteristic, giving extinction angles as high as 12,° but otherwise indistinguishable from the majority showing parallel extinction. Since in other respects including the optical sign (—) the mineral tests as hypersthene, the likelihood of this explanation is undeniable. The mineral is fresh and is often allotriomorphic towards the feldspar. Besides the early *magnetite*, occuring in euhedral form and as granules scattered through the augite, some belongs to the same period as the hypersthene with which it is often intergrown, sometimes in vermicular fashion as if in eutectic

relationship. Where the magnetite is in contact with the feldspar, reaction-rims of *biotite* frequently develop. These have an important bearing on the history of the rock which will be considered later. *Apatite* and *sphene* are present as accessories.

Subsequent strains have accentuated the cleavages in both pyroxenes, development of fracture being characteristic of the hypersthene as well as of the olivine. At several points the later, more lath-shaped feldspars are noticeably distorted, suggesting slight local movement at the time of solidification. Limonite staining is the typical weathering product, otherwise the rock is remarkably fresh.

The rock may be classified as an *olivine-hypersthene-gabbro* or *hyperite*.

Variations in several directions develop locally. At K'uang Shan the magnetite, although also locally euhedral, is more common as an interstitial product. The greater development of needle skeletons in the augite is also noticeable.

The Piao Shan rock is of finer grain, and shows the feldspar allotriomorphic to both pyroxenes; both the latter carry inclusions and have developed better outlines than in the coarser types. The early ferromagnesian minerals show the same rounding observed at K'uang Shan, suggestive of later resorption. The micropoecilitic habit of the augite is characteristic, and there is a strong tendency to zonal arrangement of the granular inclusions (Plate II, Fig. 1), whereas larger needle inclusions are less common. The feldspars (acid labradorite) in this rock are more tabular and subequigranular, and sometimes show a core filled with the same inclusions as the pyroxene. Magnetite is abundant, both as rounded grains and euhedral crystals; the biotite reaction-rim is constantly met with. A little biotite also seems to occur in slightly earlier primary relationship. Slender needles of apatite are more abundant.

At Hua Shan there is a marked diabasic tendency; the biotite rims are very strongly developed, and the same mineral appears to occur also as late primary interstitial plates of a size commensurate with the other minerals, but in the latter relationship it is optically so like reaction-rims surrounding and almost destroying magnetite cores that the possibility of a similar origin can not be denied.

At Chin Niu Shan nearby, the rock is slightly streaked, and examination shows that differentiation has produced a more basic phase in which olivine is relatively abundant, and magnetite (with a slightly purple tint in reflected light) more common, the lighter streaks being composed almost entirely of plagioclase.

Elsewhere a coarsely gneissoid structure, not visible in the hand specimen, becomes evident on weathering, and indicates differentiation preceeding the development of primary flow banding, as, for instance, at Hua Shan (Plate I, Fig 6).

The rock closely resembles one described by Rogers[3] from the Cortlandt Series in the Highlands of the Hudson. In the norite types he finds the plagioclase is andesine (occasionally labradorite in darker types) with orthoclase sometimes amounting to one-third of the total feldspar. Hypersthene, augite, and biotite are essentials, with apatite, ilmenite, pyrite etc. as accessories. Oriented ilmenite inclusions are frequent. As biotite and augite fall off, the rock passes into hornblende norite. There is little evidence of dynamic metamorphism except round inclusions, but a banded gneissoid structure, believed to be primary, is taken as proof of magmatic differentiation.

Beside the basic rock already described, there is an acid type which shows considerable variation, especially where syntectic effects come into play. In an average sample (Ts 303) taken at Hsü Shan, only four yards from the basic one described above, the feldspar is zonary, with a more calcic core, and has an average composition about oligoclase (a small quantity of orthoclase is also present). Quartz occurs in vermicular intergrowth. Augite is the ferromagnesian mineral. Biotite and olivine are both absent, and magnetite almost so. The relationship of the vermicular quartz to the feldspathic minerals is of sufficient importance to be reserved for detailed description below. It has direct bearing on the interpretation of the history of the intrusive and indicates active end phases following on magmatic differentiation.

The acid phase occurs as weaker streaks through the basic rock, and as larger masses. It grades insensibly into the pegmatite phase, and the two are often associated. The basic phase is due to magmatic segregation at various points within the body.

The typical erosion results in the two types are so different that they may be distinguished from a distance. The basic rock weathers into rugged, joint-dissected masses, or is found as rounded boulders scattered over the ground in a manner resembling blocs perchés. In marked contrast to this, the acid phase, with its associates, weathers into rounded mounds, with sloves of disintegrated material.

The Pegmatites :

The pegmatite phase is very definitely localized, and does not occur cutting the basic portions of the mass. In fact the vein types in general are restricted to the areas which also show marked contact effects. The best exposures are at Ch'üeh Shan and in the high ground south of Yua Shan. From the field evidence it cannot be decided how far these effects are developed only at the margin of the mass, and might therefore be used as indicators in mapping the approximate outline, or to what extent blocks of the country rock have actually sunk and become incorporated as xenoliths, and even entirely absorbed and syntectically reorganized, but the mineralogy strongly favors the latter occurrence, as will be shown below.

The pegmatites, in the main, represent the extreme phases of the acid type with which they are associated, and throw light on the later history of consolidation. The plagioclase-feldspar, which occurs in crystals up to 5 cm. in length, shows a zonary tendency, the core often being grey and slightly more transparent than the flesh-coloured outer zones; it varies from a medium labradorite to the acid end of the scale. Play of colours is often seen. A sample taken at Yua Shan (Ts 502) shows orthoclase, and large tabular microcline and microperthite.

Quartz occurs in small quantity, both as an interstitial component, and in micrographic intergrowth with the feldspar. Titanite forms large isolated red-brown double-wedges up to 1 cm. in length. Apatite appears under the microscope as large crystals, some with slender cavities elongated parallel C-axis. The usual ferromagnesian minerals are elongated pyroxenes, measuring up to 2 cm., slight pleochroism suggesting the presence of the acmite molecule; but biotite and hornblende have been observed. Magnetite is interstitial. A few crystals of pyrite and calcopyrite occur. At some points miarolitic cavities occur, into which crystals developing euhedral form

extend; the latter include quartz, pyroxene, epidote. Often the vein forms grade out into the rock which they cut, so that sharp demarcation is absent.

A specially interesting feature in one specimen collected from the same locality by Professor F. K. Morris, are the end-product minerals occupying angular interstitial positions between the earlier feldspar, pyroxene, etc., In particular, a colourless mineral forming radiating aggregates of fibrous crystals seems to throw light on the processes at work towards the end of the period of consolidation. This mineral has parallel extinction, negative elongation, refractive index between 1.58 and 1.70 and a birefringence .001. It therefore tests in a manner resembling either andalusite or dipyre (or other scapolite) according as to whether it is uniaxial or biaxial. (The radiating structure prevents the formation of a good interference figure, but the mineral appears biaxial, in which case it behaves like non-pleochroic andalusite.) Its relation to the rock in which it occurs is of interest. (Plate II, Fig. 4). It fills sharply definite polygonal cavities, but also often extends back into the feldspar of the walls by replacement. Within the area filled by this unknown mineral itself occur two roughly oblong cavities into which projects a fringe of parallel rectangular needles of the same mineral, sometimes in optical continuity with the mineral across the selvage of limonite staining which marks the wall of the cavity. The extremities of these needles are held fast in a second layer of much finer needles, set parallel in a felted fringe; these, however, show a positive elongation, but are so badly stained as to preclude other tests. Whether or not the angular cavities were previously occupied by a now entirely replaced primary interstitials mineral, somewhat less stable than the feldspar, cannot be definitely decided, but the habit of the mineral strongly suggests that it itself represents a final crystallization product capable of replacing the earlier feldspar.

Contact effects :

The chemical activity of liquid and gaseous solutions from which the pegmatites crystallized, make them also responsible for contact effects; the products of simple crystallization, reorganization, and syntexis are so thoroughly intermixed that even in a hand specimen passage can be traced from vein to reorganized country rock and back three or four times in as many inches. The only exposures of relatively undisturbed limestone close

to a gabbro contact are in the northwest of the area at Hua Shan, and Huang Tsao Shan; here syntexis is noticeably absent, the gabbro remaining typically basic to within 60 feet of the contact, and then only cut by a few veins of more acid material. But beyond local slight development of diopside in the limestone, thorough recrystallization and the colour changes are practically the only contact effects observed.

Contact effects of a more vigorous kind, showing advanced stages of reorganization are found in a number of localities, where the limestone found has clearly been detached from its original position The best development is at the north end of Ch'üeh Shan, across the Yellow River; the unmistakable history displayed with text-book clearness throws light on more obscure relationships noted elsewhere and well repays the difficulty of reaching the spot. Here the limestone is found in all recognizable stages of digestion. Where coherent beds have not been permeated or subjected to chemical reorganization by the intrusive, the rock is a strongly recrystallized marble, the character varying from bed to bed with original differences in quality and structure of the rock. The invading rock here is more acid and porphyritic in type than the usual gabbro, and grades rapidly into a hornblende quartz-latite; it clearly belonged to a more marginal portion of the intrusive body, subsequently juxtaposed by faulting against the basic mass now forming the main hill. That the limestone was actually a detached xenolith carried in from the margin and is not contact wall rock in place is suggested by the surrounded position of the mass, and the much greater vigor of metamorphism compared with marginal contact effects elsewhere.

The first and most general stage in silication is the formation of diopside which is found as an envelope wherever the igneous and sedimentary rocks are in contact; usually the zone is sharply defined, so that where solution weathering has subsequently removed the limestone, an almost smooth-walled cavity is left, perhaps with an undissolved limestone core partially occupying it, surrounded by a dense wall of finely crystaline deep emerald-green diopside. This relationship is well shown in Plate I, Fig. 3 where the pyroxene envelope varies from $\frac{1}{4}$ to 8 or more inches in thickness. Beyond this there is often an outer less regular envelope of massive grossularite extending back to an equally sharply defined contact with the igneous rock.

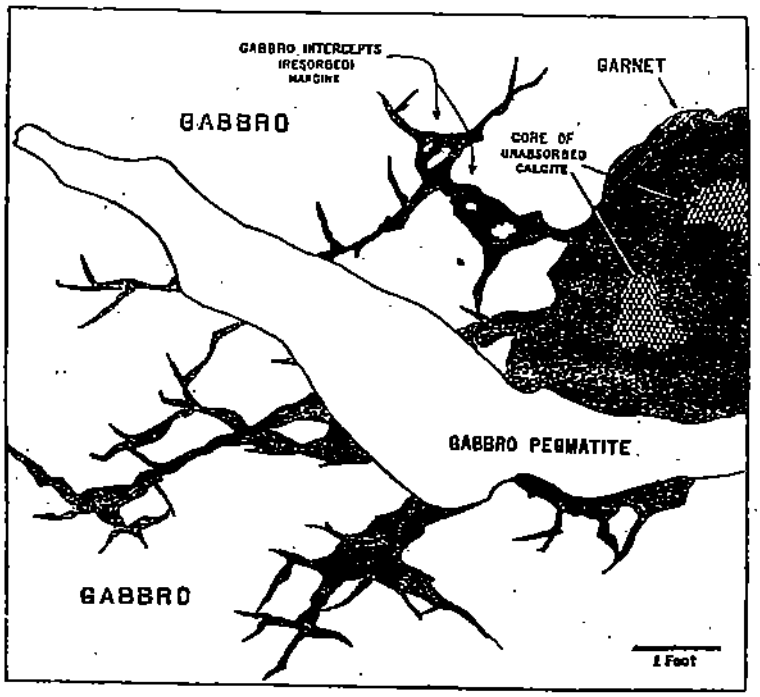


Fig. 1. Diopside veins (black) cutting Gabbro near limestone contact.

Forty yards distant the outcrops are of a dense diopside-feldspar rock with garnet cores several inches across whose composition and habit suggest a xenolithic origin. At other points stringers run from the larger pyroxene masses out into the surrounding rock, cutting it sharply in a network of connected veins which do not admit of any such xenolithic explanation (Plate I, Fig. 4). In other cases the history is more obscure, for the behaviour of limestone under pressure has been known to give a xenolith the appearance of an igneous vein. A similar occurrence of green diopside and associated minerals in a bluish calcite at Cascade Lakes, Essex County, N.Y. is explained by Kemp[10] as a mass of Greenville Limestone caught up in anorthosite. In discussing Emmons interpretation of the vein-like habit of this marble as an injected mass of plutonic rock, Kemp points out that "the views are not so unreasonable as they might appear. Limestones are so often molded like dough, that they might easily convey to one not aware of their plasticity the impression that they were intrusive." Such deformation occurring when contact reorganization was already far advanced would readily account for the vein-like habit of many of the diopside-feldspar streaks through the igneous

rock at Tsinan. The whole series may be cut in turn by true pegmatite dikes, and since the various processes clearly overlapped in time, the results are correspondingly complex. A case such as that shown in Fig. 1. can only explained on the basis that the gabbro, when almost consolidated, reacted with the limestone, having its own composition modified, and giving rise to the diopside; the latter was still fluid when the gabbro a few feet distant was almost rigid. Slight disturbance produced planes of fracture along which the diopside intruded itself to a distance where the gabbro itself was of a sufficiently different composition to be unstable in presence of the diopside solution and react with it, undergoing partial resorption in consequence. After both had solidified they were cut pegmatitically by the more acid end-products of the magma.

Though the early stages of the attack on the limestone are not so clearly shown elsewhere, those of the more advanced reorganization are well represented. At Yua Shan, Hsü Shan, and Ma Kang Shan partially absorbed xenoliths are abundant. They appear as dark green patches, often with sharply defined outlines, floating in the more acid rock, and may be followed through all stages of digestion until no longer recognizable. Under the microscope the xenoliths prove to be mainly diopside-feldspar aggregates, occasionally with the accessories common to the gabbro (apatite, sphene, etc.). The grass-green diopside is slightly pleochroic, probably due to the presence of the acmite molecule; it is glass-clear, and all stages of growth can be seen in a single field, from the last recognizable traces of carbonate attacked by the siliceous magma, and the first syntectic reorganization into aggregate of coarse granular pyroxene mosaic (Plate II, Fig. 2a), which supplies euhedral crystals that drift off as phenocrysts into the adjoining igneous rock, and can be distinguished by their intensity of colour and lack of inclusions. The further stage of anamorphism is represented by the formation of honey-coloured grossularite (showing optical anomalies) at the expense of diopside; large crystals of the latter are invaded and gnawed by the garnet until sometimes only an open lace-work of the pyroxene is left, (Plate II, Fig. 2b). Hence ultimately massive garnet may be found in patches of over a centimeter across. Other samples show a green spinel, possibly representing a reorganization of a more magnesian part of the dolomite. At Ma Kang

Shan there is a garnet diopside rock with what appears to be an iron-free chinochlore, probably after mica. A specimen collected at Piao Shan by Prof. F. K. Morris and kindly loaned by him in this connection shows the same mineral. It is pale green, non-pleochroic, and almost uniaxial, as the separation of the hyperbolae can only just be detected. It has positive elongation, a refractive index of about 1.57, birefringence approximately .012.

Alteration changes the diopside rocks to serpentine. A pale, yellow-green antigorite, with well-developed lattice-structure may entirely replace everything except small granular cores of garnet; the feldspar sometimes shows sericitization in these same localities, probably part of the same hydrothermal alteration.

All the contact minerals occur in "veins" of every degree of fineness, and the banding of the minerals may be almost microscopic—the feldspathic zone grading rapidly into a garnet-diopside-feldspar rock and beyond that to a garnet-pyroxene rock with apatite, epidote, etc.

A feature seen occurring with special frequency is the presence of fine veinlets of diopside cutting the igneous rock in all directions. Sometimes the vein is banded, basic plagioclase forming the heart of the vein with diopside on each side suggesting a reaction between the silicious residue and the limestone at the contact, giving rise to the pyraxene and increasing the lime content of the feldspar.

Calcite Veins :

Except at Chüeh Shan: none of the original carbonate country-rock, recognizable as such, is preserved, but a type of special significance (first reported by Professor Morris from the knoll north-west of Piao Shan) is a pegmatite rock in which large pyroxenes are embedded in a sky-blue carbonate. The latter mineral, though interstitial, may form large pegmatite crystals, measuring up to 3 cm., and enclosing well-shaped pyroxenes, which may be traced through finer euhedral stages back into the massive aggregate already described. At places the calcite is removed by solution leaving irregular cavities, into which project the points of these perfectly shaped pyroxenes.

The relationship of this blue carbonate to the other minerals and especially its extremely localized occurrence, taken together with the entire

absence of calcite-magnetite veins from this part of the igneous body, suggest inevitably that we are dealing, not with a normal late pegmatite, but with a portion of included country rock not entirely absorbed syntectically. Such incomplete digestion is corroborated by the obviously xenolithic shape of many of the diopside aggregates, the zoned and banded distribution of the different stages of attack and mineral reorganization, and the general shape and distribution of the rock masses. which bear no direct relation to the outline of the gabbro body. Though the mineralogy of the absorbed block is changed beyond recognition, the original distribution of parts showing variation in composition may be roughly preserved in the arrangement of the syntectic minerals. Berkey and Rice,[11] in noting such an "antecedent structure" in the gneisses of the Highlands of the Hudson remark that "it is neither a product of differentiation nor of movement, but a structure that has been crudely preserved after the rock which it represents has been otherwise wholly destroyed; and it is a result of the failure to redistribute completely its chemical constituents, rather than a particularly efficient assembling of them."

There is always the possibility that these masses are part of the roof of the magmatic chamber; but it will be pointed out below that the upper and peripheral portions of the body show distinctive characteristics not found in the gabbro of the Piao Shan neighbourhood. Daly[12] has suggested also that syntexis by marginal assimilation is largely effective only during the early part of the magma's history when it is absolutely and relatively very hot, whereas abyssal assimilation of sunken stoped blocks may be coextensive with the life of the magma and that the superficial area exposed to attack in the latter case is greatly increased.

It seems probable therefore that these specially marked reorganization effects have been produced in limestone blocks detached by the magma and liable to a chemical attack from all sides more insidious and thorough than would have occurred marginally. In this immediate vicinity the composition of the gabbro would necessarily be altered and since diffusive absorption was incomplete at the time of final solidification, the change in composition of the remaining liquid was progressive. How extensively actual modification of the composition of the magma by syntexis has occurred is hard to decide. The extreme likelihood of such a process in the case of larger igneous masses

makes it probable that it has occurred on a small scale in many instances without being appreciated. Brögger[13] has offered this suggestion for the primary carbonate found in the abnormal rock types of the Fenn District of Norway, where the variations in composition of rocks of intrusive habit may be explained by the solution of an older limestone beneath the pre-cambrian granite. Teall had previously offered a similar explanation for the feldspathoid constituent of the Sutherlandshire borolanite.[14]

Kemp, discussing the action of a more acid magma on limestone at San Jose, Mexico,[15] suggests a history more like that probably indicated for the Tsinan rock ". . . The question may be raised as to whether the eruptive has melted into its substance sufficient limestone to yield the zones which have then crystallized out from fusion. This view is opposed both by the sharp contacts afforded by the eruptive against the garnet zones; by the variability of the zones of mineralogy, and by the fact that the necessary ingredient (iron) of andradite would not thereby be afforded."

A still closer parallel is that of the amphibolites described by Adams from the Bancroft-Haliburton area.[16] Some of his descriptions of mineralogy and structure produced by acid contact alteration of the less vigorous type might be applied word for word to the case of the more basic Tsinan rock. In particular "the calcite where present in the rock is usually in the form of very coarsely crystalline aggregates cementing the other constituents, and into which the other minerals grow in the form of perfect crystals and with excellent terminations. This calcite represents portions of the original limestone which have survived in an unaltered condition, except that they have grown more coarsely crystalline. When the calcite is subsequently removed in solution by percolating waters, spaces results which are found lined with beautiful crystals of pyroxene and other constituents of the rock." At Tsinan the vein-like behaviour of the calcite strongly suggests that actual fusion or solution has occurred, although, as has been already pointed out, the capacity of limestone to be moulded has been noted experimentally as well as in the field. The sky-blue calcite here, on account of its limited distribution and the conditions of its occurrence, seems probably to be best regarded as a remnant of original carbonate rock which was fused or dissolved, so as to behave locally like a pegmatite mineral, but not taken up syntectically

into those last juices of the norite which were intruded as true vein mineral solutions.

Biotite Reaction Rims:

Throughout the area biotite appears as a "reaction-rim" at the contact of magnetite with plagioclase feldspar. The mineral shows strong absorption; in basal section it is reddish brown, being almost opaque except in very thin sections; in vertical sections pleochroism is very marked (x—pale buff, z—dark grey-brown). In the coarser rocks the late magnetite which formed contemporaneously with the hypersthene, as shown by the intergrowth with the latter mineral, is somewhat more readily affected by the reaction than the earlier more euhedral crystals; but this is not invariable. Plate I, Fig. 2 shows a typical example of the magnetite intergrown with hypersthene developing biotite fringes of this description. At the points where such fringes occur apparently entirely surrounded by pyroxene, it is probably the result of a feldspar contact made out of the plane of the slide.

The presence of such reaction rims in a Swedish hyperite was described first by Törnebohm in 1876[1] and such occurrences have since been recorded by a number of observers; but no reference appears to be made explicitly to the action of hypersthene in promoting the reaction.

In a slide of the fine-grained rock from Piao Shan a count was made to determine under what conditions the biotite did or did not tend to develop. The following number of mineral associations in contact were noted in this one rock-section; it may be noted that the ratios agree closely with those also found in coarser specimens.

(a) Magnetite, feldspar, hypersthene *with* biotite	118
(b) Magnetite, feldspar, *with* biotite, no hypersthene	17
(c) Magnetite, hypersthene *with* biotite, no feldspar	5
(d) Hypersthene, feldspar *with* biotite, no magnetite	13
(e) Feldspar *with* biotite, no hypersthene or magnetite	0
(f) Magnetite, feldspar, hypersthene *no* biotite	197
(g) Magnetite, feldspar, *no* biotite or hypersthene	193

It will be noted that of the places where biotite occurs (a, b, c, d) by far the largest number (a) actually show the presence of hypersthene, the biotite in fact usually developing on the side of the magnetite nearest the

hypersthene. In the cases (b) where hypersthene was not seen, there is strong probability that a contact may have been made outside the plane of the slide. Similarly it is likely that some at least of the cases (c), (d) where also biotite is present may originally have had the fourth mineral just out of the plane of the section. So that a considerable portion of the counts (b), (c) and (d) should properly be transferred to (a). Equally significant is the comparison of the feldspar-magnetite contacts (g), (b) where no hypersthene was noted; in 193 cases biotite was absent, and in only 17 cases was it present (while even some of these may have involved hypersthene just out of the plane of the rock-slice). As to the frequency with which the reaction happens to have occurred in this case, given the optimum conditions, comparing (a) and (f) it will be seen that in only considerably over one-third of the cases of the triple contact did biotite form in the plane of the section. Presumably the supply of material or the time available limited the development.

No detectable preference was shown for the later anhedral grains of magnetite except in so far as these are usually more closely associated with the hypersthene than the earlier euhedral crystals of magnetite. In the coarser rock types the euhedral magnetite is distinctly less liable to the reaction than the later irregular grains,—possibly on this account. Hence it is always possible that the later magnetite found typically associated with the hypersthene in the slide just described, being of later date, is of composition slightly different and more liable to give rise to biotite.

Exactly what part the hypersthene plays it is difficult to determine, as the mineral appears itself usually to be little affected. At some points it presents a distinctly irregular outline in contact with the biotite, though this may merely represent a previous irregular contact with magnetite now entirely converted to biotite. On the other hand the hypersthene would be a natural source for the magnesium occurring in varying quantity in biotite, and some such equation as the following might symbolize a possible reaction, involving only the addition of water and the potasso-siliceous constituents that would otherwise give rise to orthoclase or perthite, both of which occur in the pegmatites;

$$Fe_2O_3.FeO + 3\,(2\,Mg,\,Fe)\,SiO_3 + H_2O + K_2O.Al_2O_3.6\,SiO_4$$
$$= 2\,(K,H)_2(Mg,Fe)_3(Fe,Al)_2\,3\,SiO_4 + 3\,SiO_2$$

Such an equation must of necessity suffer the disadvantages of all those designed to picture as a definite reaction a gradual chemical exchange involving products so variable in composition as biotite. Moreover it will be noted that no plagioclase feldspar has been introduced into the formula, since the imaginery orthoclase plus water is found to supply more than enough of the required constituents not previously present. In reality, since none of the introduced materials reach the site of the reaction in exactly the proportions needed to form the hypothetical minerals suggested, but probably come in the dissociated state, the alumino-siliceous radicals are taken in the first instance from less acid material of the feldspar already present in the adjoining plagioclases, and the balance of the products must be left to move on and adjust their own equations as best they can outside the sphere of the reaction!

With the limited library facilities at his disposal, the writer has no means of ensuring an exhaustive search, but in no publication available is specific reference made to the mineral association here noted. In a microphotograph published by Sederholm[18] the magnetite developing biotite fringes is itself seen to be in contact with hypersthene, though the biotite rim only shows at the opposite margin of the magnetite.

The correct interpretation of these mica-fringes bears directly on the processes governing the last stages of the formation of the rock. Some mineral juxtapositions are rightly interpreted as primary, while others can with equal certainty be regarded as the result of regional metamorphism. Thus Bayley[19] has shown that the diallage coronas in the gabbros of Minnesota are of primary origin, and involve no reaction, the pyroxene fastening itself as a fibrous envelope indiscriminately around any mineral that had already crystallized out at the moment of its development. On the other hand the garnet "reaction-rims" in the Adirondack anorthosites recently described by Kemp and Roesler[20] are probably to be explained by regional metamorphism and are therefore secondary. In the case under discussion the diagnostic criteria for either of the above causes are lacking. Where fringing magnetite, the biotite cannot be regarded as belonging to a normal primary crystallization sequence, since it depends on definite mineral juxtapositions; it is therefore truly in the nature of a reaction product. There is however no granulation or evidence of any less extreme subsequent dynamic metamorphism.

Wadsworth[21] describing a similar occurrence, refers to it as the result of a secondary interaction between the magnetite and feldspar, and not as a primary growth. Kemp[22] expressed the opinion that the feature was original.

It seems clear that the reaction which gave rise to the rims was of relatively late date. It involves magnetite which crystallized with hypersthene, or actually formed subsequent to both it and the feldspar. The formation of biotite moreover implies the presence at that period of both hydroxyl and the potash ions, which belong naturally at the acid end of the scale. Also the reaction has taken place coextensive with the igneous body itself. Clearly there remained over a differentiated liquid acid residue after the main consolidation, and these juices were sufficiently active to render the previous mineral association unstable in their presence, with the consequent reaction tending to acidify the rock. Evidence of this progressive change of composition in the residual magma is to be found in the pegmatites which carry quartz, in the vermicular quartz intergrowths with plagioclase in the acid phase and possibly in the resorption effect noted in the coarser basic types.

Blackwelder[23] records reaction-rims of what are probably tremolite, between the olivine and the feldspars in the Tsinan gabbro. The selective position of these rims would seem to make them open to the same explanation. Bayley[24] has noted reaction-rims resembling these, of definitely primary origin, since they are seen to be in optical continuity with adjoining crystals and therefore only represent the incipient stages of crystallization of the fringing mineral. Williams, discussing the Baltimore gabbro[25] describes other tremolite reaction rims which he regards as definitely secondary. From their description those noted by Blackwelder in the Tsinan rock seem unquestionably to be similar in type to the latter.

Holland[26] speaking of altered periodotites in Mysore remarks that "the minerals of early consolidation may be attacked and altered soon after their formation by the vapors originally included in the magma——or they may become attacked at a distinct and subsequent period. In the former case the processes of primary crystallization and secondary alteration are continuous, and really phases of the same process——and the term "secondary" when applied to rock alteration is but relative."

Sederholm[27] has discussed the origin of these rims, together with somewhat similar mineral associations, and has applied the word "deuteric" to reactions of this kind[28] thus distinguishing between metasomatic changes which belong to a later period of metamorphism (i e. strictly secondary), and those which took place in direct continuation of the consolidation of the magma itself. The biotite rims of the Tsinan gabbro are unquestionably to be placed among these "deuteric" reaction products.

Several features observed in one section (Ts. 301) of the acid type supply a beautiful corroboration of this conclusion. In this instance the plagioclase which forms the bulk of the rock has the average composition of oligoclase-andesine. It frequently shows a marginal intergrowth of vermicular quartz in a relationship of such significance as to call for fuller description. Careful application of the Becke refractive index test failed to identify any potash felspar in the section and no perthite is present. The quartz resembles the tentacles of a "sea-anemone" (Actinaria), the slightly recurved club-shaped processes usually extending back basally to the border of the feldspar it invades, though occasionally an oblique plane of section isolates them; the margin itself is sometimes embroidered with a fine thread of quartz, which may be in optical continuity with the vermicular growth. At other points the development is less advanced and only microscopic streaks and patches of quartz can be found, these appearing to favour the cleavage weaknesses of the feldspar

A characteristic feature is the irregular indented outline of the feldspars especially at points where the vermicular quartz shows strongest development, the plagioclases locking into each other with projections and reentrants which have no crystallographic basis; for example prismatic sections of two adjacent crystals which are oriented with *c* axis practically parallel, meet in a sharply zigzag contact (Plate II, Fig. 5.)

The intergrowth of vermicular quartz and plagioclase closely simulates that familiar in some acid rocks to which Sederholm[29] applied the term "myrmekite" This latter has been discussed under a variety of names and explained variously as a primary eutectic (Becke[30] et alii), a secondary corrosion effect (Michel Lévy[31]) and a reorganization product of a deuteric type, where the myrmekite replaces a potash feldspar; the last is Sederholm's

own explanation.

But in the rock under discussion no potash feldspar occurs and there is no evidence that it was ever present. Another explanation must be sought. The possibility of a primary eutectic is ruled out by the scalloped contacts between adjacent feldspars. For the same reason although the incipient development of quartz on the feldspar cleavage suggests corrosive attack with metasomatism, this cannot represent the complete history. The only satisfactory explanation for the feldspar outlines is to regard them as the results of localized resorbent action of siliceous magmatic residue upon previously formed plagioclase and of subsequent recrystallization in deuteric proportion. The plagioclase recrystallized in optical continuity with the undissolved core of the crystals, the quartz interfingering it, and any siliceous balance introduced latterly occupying a marginal position.

Mineralogically the result is identical with the reaction micro-pegmatite of the granites, but its history is slightly less complex. It somewhat resembles the intergrowths described by Osann from a gabbro in the Ottawa valley,[33] except that the feldspar there was probably orthoclase. The process indicated involves a solution by later active residues of the early primary minerals and is clearly analogous to the deuteric action which gave rise to the biotite reaction rims.

V. The Diorite Bodies.

Main Types :

In three localities along the base of the hills occur rocks somewhat more acid than those described from the plain. Whether or not the various types are to be connected, it is desirable to describe this acid type before taking up the interpretation. The acid series shows considerable textural variation and is usually badly weathered.

A sample from the village of Yao T'ou, 5 km. east of Tsinan is a medium grained quartz-diorite, with zonary *plagioclase feldspar* (oligoclase to andesine), showing a tendency to diabasic structure. (Plate II, fig. 3). The interstitial feldspar is altered to kaolin; the basic cores of lath-shaped crystals are somewhat less altered (sometimes converted to chlorite, zoisite, etc.,) the outer zones being the least effected of all. Hornblende is poecilitic and where

unaltered is strongly pleochroic (dark green to yellow-green) but is usually bleached to green and subsequently altered to actinolite or reorganized, with the rejection of iron as magnetite, to a mass of epidote, with chlorite and biotite. In several localities the rock is relatively fresh, but the hornblende has entirely yielded to an alteration resembling propylitization, and the feldspars show sericite. *Magnetite* also occurs as large irregular grains often in close association with the decomposing amphibole, but allotriomorphic towards it. Both *titanite*—distinctly pleochroic (pink to greenish yellow)—and *apatite* occur as accessories; the latter is often crowded with inclusions. The *quartz* stands in essentially interstitial relationship, but has also invaded the boarders of earlier minerals by replacement; at one point a single crystal of quartz was observed making irregular concave embayments in adjoining hornblende, magnetite, and plagioclase, though at their further margins these latter crystals develop characteristic outlines towards each other. The quartz itself yields to carbonate replacement.

The relationship suggests an acidic end phase which modified the earlier mineralogy, under hydrothermal conditions.

Variations of texture are found corresponding with varied conditions of cooling. The sill-like outcrop on the west face of Yen Tze Shan shows a beautiful porphyritic hornblende andesite; it has large elongated hornblende phenocrysts, in a felted ground-mass composed mainly of minute plagioclase dotted with magnetite crystals; the feldspars are too small, confused, and clouded by alteration for identification as individuals but the Becke test shows the refractive index of andesine. In other types, close to the margin of the intrusive, the grain is often extremely fine; and the light pink-grey colour of a typical sample from Yen Tze Shan suggests a thoroughly acid rock, but the microscope shows a composition close to quartz-diorite.

Besides these various types found in the foothills, there is one outcrop of special significance out on the plain. This is the rock grading into that responsible for the contact effects at Ch'ueh Shan already described. Forming the most northerly outcrop on the plain it is most distant from the foothills, and is separated from them by the entire central gabbro mass. It has a bearing on the position of the northern boundary of the intrusive, and indirectly on the relationship existing between the diorite and gabbro bodies.

The rock responsible for contact effects referred to is a coarse grained acid gabbro but grades rapidly through porphyritic stages to a pinkish rock almost free from ferromagnesian minerals, and locally so fine-grained as to be nearly felsitic. Under the microscope it is seen to be a fine hornblende quartz monzonite. The rock carries bright-green hornblende and abundant titanite; small amounts of magnetite and apatite complete the accessories. Intermediate outcrops on the shoulder of the hill show a range of samples indistinguishable from similar types in the foothills except for their greater freshness. The increasing fineness of texture and the changing composition unquestionably indicate an approach to the northern boundary of the intrusive.

Dike and Vein Phases

The margin of the diorite bodies are frequently much dissected by dikes and veins. As in the gabbro body the vein types and the contact reorganization products are intimately mixed. The diorite weathers poorly and extensive alteration often obscures the relationships, increasing the difficulty of interpretation. No counterpart of the extremely coarse pegmatite was observed, the texture of the rock in general being somewhat finer than the gabbro. Fine-grained acid dikes, mineralogically like the diorite frequently occur. These are of relatively late date, and come after the main formation period. They are usually pink-grey, so fine-grained as often to appear lithic, are somewhat more acid, and stand weathering much better than the rock they cut. But this resistence may be due to their finer grain, and also to the especially adulterated composition of the diorite close to the contact where the dikes occur, for under the microscope the alteration appears equally thorough in both rocks.

A dike (Ts. 119) cutting the diorite at the col between Pai Ma Shan and Hung Shan is mainly a fine equigranular mosaic of tabular feldspar (zonary oligoclase-andesine) with some orthoclase and interstitial quartz; hornblende and magnetite in very subordinate amounts are also allotriomorphic to the earlier feldspar; a few sphene crystals and many needles of apatite complete the accessories. The description of the rock given above would apply word for word to a sample (See MSS).

Other more acid specimens show orthoclase partially developing its own shape, and the larger zonary feldspars fringed with a microgranular

mosaic which invades their margins. Calcite is introduced. The rock is badly altered, but was evidently a very fine-grained quartz-diorite or monzonite.

From the marginal position of their occurrence, and the close similarity of their composition it is reasonable to relate them to the main body of the rock. Willis and Blackwelder report a still more acid type from a locality evidently close to Pai Ma Shan. "The only dike igneous rock found in the limestone hills near Tsinanfu occurs near the border of the plain, 2.5 miles southwest of the city. At first sight it has the appearance of a fine-grained pink granite, but upon microscopic examination it proves to be a quartzose syenite-porphyry; it has a finely crystalline ground-mass, composed of sodic feldspars and quartz, with small phenocrysts of hornblende and feldspar like those of the ground-mass. The composition of this rock is such as to indicate that it is not genetically related to the hypersthene gabbro."[33]

However the observation quoted above was made in ignorance of the existence at other points in the neighbourhood of the series of rocks of intermediate type described above; and although the nature of the evidence precludes absolute certainty, judging from the marginal position of the acid dikes, the close similarity of their composition, and the observed range of the acid series it would seem probable that many, if not all, of the dikes are closely related to the diorite body and hence, as will be shown below, to the gabbro itself.

Contact Effects and Magnetite Deposits:

At several points to the southeast magnetite deposits occur both in direct contact relationship, and also as small vein and collateral deposits a few feet from the diorite. None of them attain any size, and the largest observed was not above 4 feet in length. A magnetic survey made by Mr. H. C. T'an of the Geological Survey[34] recorded several slightly larger dimensions, but none of economic importance. The magnetite is associated with calcite veins which cut the margin of the diorite body in all directions. In these magnetite crystals occur often a centimeter in diameter, showing the usual octchedron (111) and dodecahedron (110) faces, with two hexoctohedral forms (apparently 531 and 543) and a trapezohedron (311) which sometimes

occurs with alternate pairs of faces meeting on one axis suppressed.

The vein association is regular, magnetite forming the margin of the veins, and calcite following usually with a brown siderite or limonite band at the contact of the two minerals. These marginal veins appear to cut parts of the diorite showing syntectic effects, and possibly some of the calcite is to be regarded as resurgent, that is to say limestone actually completely absorbed by the magma and retained as the last liquid juice left to form vein material. On the other hand, with calcite and magnetite there is frequently associated large amounts of epidote, and the latter mineral is prominent as a reorganization product of the hornblendes in the diorite of this same zone. Thus up to the last the diorite was progressively modified by products of the same magma from which it originated, and part of this change may be attributable to the incorporation within itself of parts of the country rock which it invaded.

Usually the iron bearing solutions have not entered the surrouding rock to any distance. But at some points, especially where the rocks have been disturbed, there is evidence of solutions having penetrated along lines of weakness.

A pretty example is shown in Plate II, Fig. 6. which shows "skeletons" of limonite projecting in a kind of "bastion" structure from the walls of the cavity they lie. The rock is a finely crystalline limestone; the limonite staining is sharply defined at its outer margin occasionally running back into the wall rock in an essentially invasive relationship. The zigzag limonite framework is equally abrupt at its inner edge; the carbonate now filling the colourless centre of the druse has crystallized in continuity with the cores in which the limonite lies. The crystals giving rise to the "bastion" were clearly epigenetic to the country rock and presumably deposited as a solid solution of the siderite molecule in some other carbonate. The habit, which becomes increasingly coarse in pattern towards the centre of the vein, suggests a dolomitic composition so that the original mineral may have belonged to the ankerite series and have been decomposed by subsequent reaction. Or possibly the history was more complex; the wall being first for a time crusted with a carbonate of a different composition from the country rock, and more liable to reaction involving interchange of bases in presence of iron bearing solutions, thus giving rise to ankerite which itself later decomposed with the rejection of

limonite along the carbonate cleavage planes. In other localities, especially where the rocks are disturbed, fault weaknesses have given easy channels of access to percolating water, as in the gorge above Yao T'ou, where the entire limestone is stained to buff.

In general the limestone is not marmorized to any great distance from the contact; at most points the recrystallization ten feet from the igneous rock is on so fine a scale as to be undetectable in the hand specimen. Occassionally the rock is a coarsely caystalline marble. On Wu Ting Shan, the contact rock has become a mass of radiating feathery groups of prismatic carbonate.

At Pai Ma Shan and Hung Shan the situation is complicated by the effects of dynamic metamorphism in addition to contact alteration. Close to the contact (only exposed at one point) the limestone has been bleached and restained in patches of yellow and red. In the largest quarry on the hill face of Hung Shan the recrystallized granulated limestone is pale sky blue, while a schistose phase nearby is found cut by a vein of coarsely crystalline blue calcite. Both the vein and the country rock at this point carry abundant small rod shaped crystals of a contact mineral. These develop most readily, though by no means invariably, parallel with the foliation, and usually weather out leaving elongated cavities with oblique terminations. Against the slate or rusty colouring of the weathered carbonate rock in which they occur, the crystals appear as a grey silky mass, fibrous parallel with their elongation which averages about five times the width. Decay starts from the outer surface of the crystal, leaving needle-like cores of darker, denser looking material. Under the microscope the outlines of the cavities appears to be monoclinic (possibly triclinic) with prismatic elongation.

The friable condition of the rock and the disintegrated state of the mineral itself makes recognition uncertain but it resembles antigorite. If so the definite shape of the outline of the mass, and the decayed appearance strongly suggests pseudomorphs of antigorite after pyroxene.

VI. Relationship Between Igneous Bodies.

A connection between the various gabbro outcrops is clearly indicated by the lithological similarity and the field evidence (see map). Except for the limestone outcrops at Hua Shan and Huang Tsao Shan, which will be

discussed later, no reentrents of country rock invade the area of the hyperite outcrops. There is no reason to doubt the connection of these.

The intrusive outcrops along the base of the hills for six miles from Wu Ting Shan to Hung Shan show textural variations but are often mineralogically alike, are cut marginally by similar acid dikes, show the same vein and contact effects, occasionally giving magnetite deposits, and where not actually visibly connected with each other, are invasive at a fairly constant horizon in the Tsinan limestone as nearly as can be determined. A similar origin if not a genetic connection between them is clearly indicated.

Before discussing the form of the two types of intrusive rock it is necessary to consider whether or not any relationship can be established between them, despite the dissimilarity which has led to their being classed as genetically distinct.

The field data might admit of interpretation in either way. The gaps between the outcrops are so situated that if the series grades from gabbro to quartz-diorite, it is interrupted at almost identical critical points parallel with the margin, and the few intervening outcrops are so badly weathered as to be indeterminate. F. v. Richthofen would appear to have been ready to assign the two types to the same period had he not been convinced of a structural interpretation which later observation seems to challenge. "Fraglich ist es allerdings ob die letzteren Gänge in diesen Zeitabschnitt gehören. Sie finden sich in so unmittelbarer Nähe der Kuppen von Hyperit und Gabbro bei Tsinanfu dass es nahe liegt, sie mit ihnen zusammenzustellen. Für diese aber machen die Tektonischen Verhältnisse ein geringeres Alter wahrscheinlich."[35]

Against the idea of a genetic connection is the superficial mineralogical dissimilarity. This in itself led v. Richthofen to class them as entirely independent and to infer an intervening dislocation. Even though Willis and Blackwelder question this inference on structural and physiographic grounds, such rocks as they did see they concluded were not genetically related.

It may also be argued that if a single intrusive is in question, the magnetite deposits are limited to diorite contacts, and are too insignificant for so large a body. It may be pointed out in reply that the actual contacts

exposed only represent a portion of the total original contact surface and being perhaps lateral marginal wedges at that, only received a fraction of the ore which was deposited more centrally over the higher parts of the intrusive, and that anyhow the characteristic irregularity of such deposits may so dispose them that the present surface of erosion exposes none of any value. The absence of magnetite from gabbro-limestone contacts is inconclusive: no upper contact is anywhere exposed.

In favour of a genetic connection the following points may be noted:

1. In both diorite and gabbro there is evidence of an active acid end-product capable to some extent of modifying previously crystallized rock by deuteric action throughout their whole extent, showing that each comes from a magmatic body of some size capable of differentiation over a large area.

2. Moreover both types show syntectic reorganizations which are so similar at times as to be indistinguisable. On the other hand with a rock of such comparatively simple and uniform composition as the Tsinan dolomite two entirely unconnected intrusives could, if equally active chemically, react to form very similar products.

3. Pegmatites containing quartz are found in the gabbro and vermicular quartz was referred to in the more acid type described; the average magma must therefore have been more siliceous than is suggested by the prominent more basic outcrops, and thus closer in composition to the quartz-diorite. This would involve differentiation no more extreme than is known to occur elsewhere. Loughlin's description[36] of the laccolith at Preston, Conn., shows differentiates ranging from gabbro, through quartz-hornblende gabbro to oligoclase granite. Diller reports dacitic types associated with gabbro from Port Orford, Oregon[37]. In larger bodies a still greater range of composition may be found; the familiar case of the Sudbury nickel-eruptive with its variation from micropegmatite granite to sulphide ores might be instanced.

In particular the rocks of the Cortlandt series seem to offer a close parallel. Berkey[38] summarizing the work of Rogers distinguishes among other types mica and hornblende-diorites (sometimes with quartz), biotite-augite and hornblende norite noting that often the most basic members grade into one another, the analyses indicating an unmistakable serial relationship. Within an area of 25 miles the various norite differentiates lie at the centre,

flanked by pyroxenites with a diorite area intervening at one point.

The biotite reaction-rims and vermicular quartz seem to point clearly to a water-charged siliceous residue, still gaseous or liquid when the bulk of the basic rock had solidified. In a recent discussion of "Magmatic Differentiation of Igneous Rocks" Vogt[39] comments on the abnormal presence of biotite in some norites and alludes to the fact that many of the associated hornblendes are found to carry water.

In discussing the hornblendic features of the Purcell sills gabbro,[40] British Columbia, Daly cites Allen and Clement's experiment[41] as evidence that hornblende requires the presence of water in the solid amphibole solution in order to crystallize, and suggests that since the basic magma has absorbed some of the quartzitic country-rock, it must have absorbed water and other volatile substances originally enclosed in the sediments. Certainly the hydroxyl ion is essential to the mica-bearing rocks which develop typically toward the acid end of the scale—incidentally also the normal home of miarolites usually attributed to the presence of enclosed volatiles and steam.

In the case of the Tsinan magma there is no means of determining how far this water may have been derived from incorporated country-rock, especially at the margin or where syntectic absorption has occurred. Absorption of limestone by the Tsinan gabbro is unquestionable. But the fact that there is no localization of the biotite reaction-rim effect suggests that the presence of hornblende marginally is due rather to the juvenile water normally present in acid residual juices, and argues against any marked contribution of water by absorbed sediments. Since, even in the gabbro itself, differentiation is clearly indicated by the acid end-products and reactions, the pegmatites and the gneissoid banding, it would seem probable that quartz-diorite is the marginal differentiate, the gabbro representing the basic central core.

(4). If the likelihood of differentiation of this kind be granted, certain other observed features would be naturally explained. The acid types would tend to develop at the upper margin of the igneous body, the gabbroid segregations concentrating in the core and the base of the mass. This would explain the absence of pegmatites cutting the basic gabbro—except where in close association with products suggesting partially digested xenoliths—and the equally characteristic highly veined nature of the quartz-diorite.

VII. Faulting and its Relation to the Structure of Shantung.

There is evidence of fault movement both at Pai Ma Shan and south of Yao Tzu Shan, striking roughly parallel with the edge of the plain. As stated above, v. Richthofen saw no connection between the diorite occuring in the limestone and the gabbro hills. He hence postulated a fault of the first magnitude along the foot of the hills; "Wir haben also hier abermals eine Gebirgsverwerfung, und zwar die bedeutendste von allen bisher dargestellten."[42] Lorenz, though referring frequently to v. Richthofen's work, draws no distinction between the gabbro and diorite types. On the contrary, he seems to recognise the gabbro as responsible for all the contact zone alteration; "The north margin of T'ai Shan range presents a fault-line along which lava masses have come up. Remnants of these are still found as small knolls on the Tsinan Plain. In consequence the limestone in the contact zone is altered and exhibits a highly interesting mineral structure. As occurs frequently in East Asia, iron ore develops with the magma. Dislocation and intrusion with the development of iron deposits are commonly associated throughout Shantung."[43]

Evidence of disturbance is to be found close to the margin of the diorite bodies in several localities. At one point in the bed of the Nanho, east of Pai Ma Shan, the Tsinan limestone is brecciated locally, but there is no evidence of extreme disturbance. Along the face of Hung Shan ¼ mile further west, the limestone is considerably disturbed. The reversal of dip (south and southwest instead of the usual gentle northerly dip) is probably partly connected with the underlying intrusive. The mechanical results of movement are clearly shown and, though owing to the confused relationship it is hard to be certain, a local overthrust from the south seems indicated.

Here the Tsinan limestone is seen in all degrees of recrystallization grading from a fine sky-blue to a coarse black marble with crystals of a centimetre diameter. At many points the recrystallization has not kept pace with the granulation due to shearing, and the limestone is converted to a carbonate schist or a granulated rock which powders between the fingers. The entire range of these variations may be found within a few feet, the shearing, as usual, often being taken up in planes or zones, between less affected beds.

The bleaching, discolouration and marmorization of the beds suggest

that the contact lies buried only a few feet beneath. This is supported by the contact mineral pseudomorphs already mentioned. These have developed subsequently to the disturbance, for, although they show a preference for the planes of naturally easier growth produced by shearing, they frequently are elongated in directions normal to these planes and grow across them, while showing even under the microscope no evidence of being themselves sheared. This would indicate that if these contact minerals were due to the diorite intrusion as they certainly would appear to be, the bulk of the Hung Shan faulting was prior to the last stage of the magmatic history, and cannot be used to support v. Richthofen's contention. On the other hand it is entirely compatible with Lorenz's statement that dislocation and intrusion are commonly associated throughout Shantung.

Along the hill-face above Tsinan city the deceptively straight line of the mountain front is not supported by truncated spurs or any other evidence to suggest that it is a fault scarp or fault-line scarp of the type seen at Tai An Fu. Instead the stream-bed outcrops of chert-bearing limestone ½ mile and more from the base of Ch'ien Fo Shan show no sign of altering the regular gentle dip (c. 12°) towards the plain. At Yen Tze Shan, Yao T'ou and other points near the southeast exposed margin of the intrusion, disturbance is again evident, and in this instance took place in part at least after intrusion, as the igneous rock itself is involved, being crumpled and slickensided; since the general trend of the late calcite-magnetite veins is roughly parallel with the slickenslided faces, the slight disturbances may all belong to one protracted period. But in no case observed is there evidence that rocks previously widely separated have been juxtaposed; in most cases only the originally adjacent rock masses are involved, as at Ch'üeh Shan. As far as outcrops can be traced from the foot-hills towards the plain, there seems no reason to postulate a dislocation of the first magnitude; moreover reconnaissance in continuation of this line along the margin of the plain to the east reveals no sign of any such fault.

The stratigraphic reply is no less convincing. Projecting the gentle dip of the Tsinan limestone towards the plain across the gap between the outcrops would bring the top of that formation and the overlying Poshan Series (Carboniferous) to the level of the gabbro hillocks. Elsewhere in Shan-

tung (as at Tieh Shan) intrusives are found invading the Ordovician strata, while at higher horizons they are characteristic. It will be shown that the intrusive is in part at least concordant with a lower level than that of the Poshan series since the higher Ordovician beds lie above the marginal wedges of diorite; the depth of the igneous body itself happens to become a disturbing factor in the calculation. But the argument for a continuous rather than a faulted section is all the more valid.

The argument from physiography could not be put more lucidly than has been done by Bailey Willis, in balancing the case for peripheral warping against that for faulting. "The maturely eroded surface of the mountain region extends down to the alluvial plains in groups of hills. If these are abruptly cut off along a well-defined face, the existence of a fault may be reasonably assumed; if the hills terminate with an approximate alinement, even though they be separated by deeply eroded valleys, faulting may be considered probable. If, on the other hand, the hills lessen in height towards the plain, extend irregularly into it, and become more and more isolated, we infer that the sculptured surface is continuous beneath the alluvium. So far as we have seen the marginal relations of the Shangtung mountains in the vicinity of Tsinanfu and of Po-shan, the latter relation is the existing one".[44]

However the ultimate reason in v. Richthofen's mind for inferring any great dislocation was the petrographic dissimilarity of the two igneous rocks. With the demonstration of a petrographic continuity the hypothesis falls to the ground.

VIII. Age and Form of Intrusive.

The contact effects indicate clearly that the body is intrusive into the Tsinan limestone. No means of establishing a close upper limit to the age is available in the area. Comparison with similar intrusives cutting the Poshan (Carboniferous) Series elsewhere in Shantung led v. Richthofen and Lorenz to date the period of igneous activity as Permian. Throughout NE. China such intrusions appear to be characteristic of the Upper Ordovician (corresponding to the higher horizons of the Tsinan limestone) and of the overlying Carboniferous. Norin has described[45] alkali-syenites intruded between the Ordovician and Carboniferous sediments of western Shansi. Professor Nyström has commented in conversation upon the remarkable regularity with which

intrusions are found to occur at a horizon 30 to 50 meters below the top of the Shansi Ordovician. During a water-supply reconnaissance just north of the Chihli-Honan border the writer noted a similar concordant intrusive between strata of the upper Ordovician exposed in the bed of the Sha Ho.[46] At Ta K'un Lun north of Po Shan, gabbro is to be seen intruded into the sediments overlying the Jurassic coal series. This is in agreement with Willis and Blackwelder's conclusion that the rocks are probably not younger than early mesozoic.

The intrusive nature of the mass being beyond question, it might be (a) a large simple or multiple laccolith, (b) a portion of an irregular sill, (c) a boss or stock, (d) a single large neck or (e) a series of small chimneys or (f) laccoliths.

Willis and Blackwelder[47] remark, "the roundish areas of outcrop suggest that the hills may be old volcanic necks, but, if so, the ejectamenta of the volcanoes have long since been carried away in the degradation of the region, for no tuffs or lavas are visible there at present." The unity of the outcrops in the plain, however, is against a series of (f) small laccoliths or (e) necks. This is corroborated by the absence of the marginal vein types from the centre of the area. Against (d), a single large neck, is the form of the diorite bodies and the absence of any lava flows at a higher horizon in the Shantung beds compatible with a neck of such immense proportions.

As between other forms of intrusive, evidence may be sought in several directions; (1) the marginal relationships of the diorite, (2) the behaviour of the limestone outcrops out in the plain, (3) the differentiation features of the gabbro magma, (4) the analogy from similar occurrences elsewhere in Shantung and (5) general structural and tectonic considerations.

(1) Wherever the relation of the diorite to the overlying beds is exposed, the intrusive appears almost consistently to be following the bedding. Except where slight fault-modification occurs as at Yao Tzu Shan, the dip of the limestone closely follows the upper surface of the igneous rock, being frequently domed up over the intrusive; in fact this is the explanation of the shape of Yao Tzu Shan and doubtless also of other domes and local rolls in the limestone, even where these do not erode to form features like that just cited.

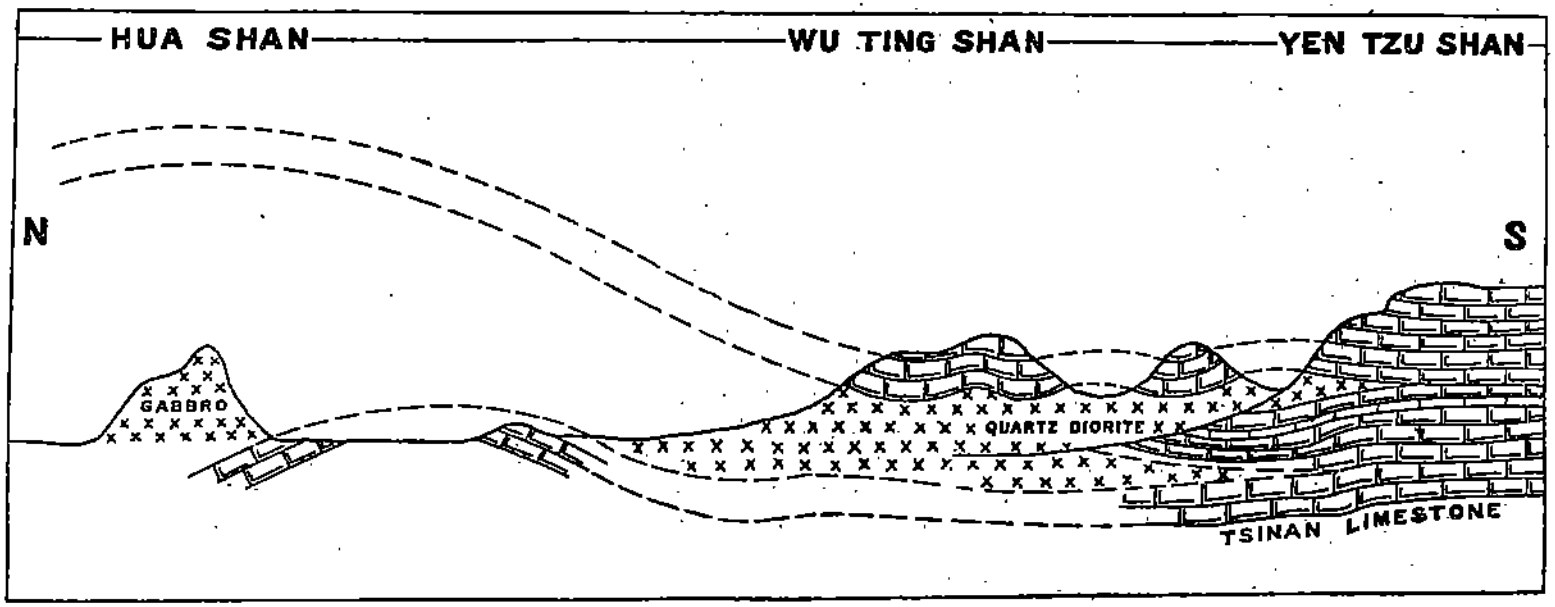


Fig. 2. Structure Section through east portion of intrusive

The lower contact is only exposed in one locality—on the west slope of Yen Tze Shan; the decomposition of the diorite yields a more fertile soil than the usual limestone talus, and the site has therefore been selected for a plantation made in connection with the afforestation scheme of the School of Agriculture of Shantung (Nung Yeh Hsüeh Hsiao). Where first met the diorite body is over 80 feet thick. As the outcrops are followed around the hillside to the southwest, the upper and lower contacts converge, the thickness decreasing from 35 to less than 20 feet between two gully exposures 200 yards apart, and apparently dying out 100 yards further south. These outcrops show the rapid textural variations of porphyritic types described above.

At this point the intrusive thus takes the form of a concordant wedge and might be the margin either of a true sill or of a simple or multiple laccolith with its main mass lying to the North, or even the marginal apophysis of a stock.

There is no means of determining exactly the northern limit of the intrusive. It must lie farther towards the great plain than the last outcrop of gabbro on Ch'üeh Shan. But, as has been noted, rocks that originally lay near the margin are now just protruding from the plain, and though they have been faulted against the gabbro adjoining, there is nothing to indicate a throw of extreme dimensions.

The evidence then points to an oval outline with the longer axis running east-west parallel with the front of the hills.

(2) In the plain the outcrops of limestone at Hua Shan, Huang Tsao Shan and near Chi Li Pù present significant features. v. Richthofen calls the rocks Crystalline Limestone without attempting to correlate them with any particular formation exposed farther south. Lorenz[48] mentions that he observed the marmorization of Tsinan limestone (grüsige sandkalk) by the eruptive, but offers no explanation. The only place where the actual contact is indicated lies under 30 feet of cover at the base of Hua Shan. Here marmorized limestone dips under the gabbro at a moderately inclined angle; there is no sign of fault movement, nor any development of contact minerals; moreover the gabbro is the typical basic variety, shows no increase in acidity as close to the margin as it is exposed, and is only cut by a few isolated very narrow veins. On the other hand the extent of recrystallization is such as to

make the limestone look unlike the typical Tainan dolomite even a few inches from the diorite contact in the foothills. At Huang Tsao Shan this marmorization affects the bulk of the hill. The observed facts point strongly to this as representing the original floor underlying the norite magmatic chamber. This would account not only for the field relationship, but for the extensive marmorization combined with the absence of contact alteration or other marginal acid effects, which would tend rather to occur at the upper and peripheral portions of the body. If this interpretation is correct—and when the other factors discussed below are taken into consideration it is hard to reconcile the facts on any other assumption—this tilted underlying floor of the chamber strongly suggests a body of roughly laccolithic habit, the gabbro being the basic differentiated core, if not actually the main bulk of the rock, and the diorite series the marginal wedge-shaped lobes extending laterally between the beds of the limestone. The dip of the limestone at Hua Shan might be a local flexure in the floor or the centripetal dip found more often in laccoliths of large size.

(3) The evidence afforded by the gabbro itself is in favour of a body of considerable size. The area occupied by the outcrops of uniform type, the coarse grain of the rock at all points where the basic phase outcrops, and the area over which differentiation must have occurred with moderate but equal vigour to produce such uniform deuteric effects, indicate a large body; moreover the absence of pegmatite veins over the main central area, except where there is unmistakable proof of adulteration by stoped blocks, and the prolonged active life necessary to account for vigorous differentiation of a body of this size, point to the same conclusion. The controlling factor in differentiation of bodies of comparable size is usually gravitation, and the results observed in this case are those to be expected from gravitative separation in a fairly large intrusive. A parallel might be drawn with the Glamorgan intrusive described from Ontario by Adams and Barlow,[49] or the Preston Laccolith already mentioned, which Loughlin regards as differentiated in this manner.

(4) Unfortunately the writer has had little chance to examine the other of the larger basic intrusives of Shantung which might throw light on the present problem. They are frequently referred to as laccolithic in type. At T'ieh Shan a diorite body some 8 km. in diameter is intruded into Ordovi-

cian Limestone. During a hasty visit to the magnetite deposits which are among the few paying iron mines in the province, no basal contact was discoverable, and the faulting complicates the relationship. The only rocks sampled were those close to the contact, and these are not unlike the diorite of Tsi Nan Fu. But at no point visited is the T'ieh Shan intrusive exposed to depths analogous to that of Tsi Nan Fu. The eastern outcrop is only a fraction of the total extent of the intrusive, and the deeply dissected core is probably not exposed so as to afford evidence of differentiation. But even within the limits exposed, gradation may be noted from a biotite-diorite to a coarser and more basic hornblende-diorite further from the contact.

At Ta Kun Lun near Po Shan, Jurassic sediments are invaded by gabbro. Here the intrusive is a multiple or compound laccolith, the eastern face of the hill showing wedges of igneous rock between the Mesozoic slates, sandstone, and conglomerates, cut at one point by a dike 15 feet across; this apparently served as the feeder for the later higher levels of intrusion. The rock shows a range of textural variation corresponding to differing thickness of the wedges; the main mass is typically gabbroic with local development of biotite and hornblende.

The combined evidence points to a moderately large intrusive of laccolithic behavior and non-regular outline. It remains to be seen how far such a conclusion is in accord with the structural facts.

(5) The whole question of the mode of formation of laccoliths calls for careful revision. In the matter of nomenclature there are at present grouped under one name small intrusives like those found in the Judith Mountains and large bodies such as the Bushveldt laccolith whose minor by-products may have more far reading effects than the total effect of the smaller intrusives. Ideas regarding the causal connection between the forces involved seem to be on an equally unsound basis. Keyes[50] has recently challenged the accepted hydrostatic origin formulated by Gilbert[51] from the type area, denying the competency of intruding magma to dome up overlying rock unaided.

But the formation of sills by a process akin to that involved in the blister hypothesis has never been called in question.

In the case of the Tsinan intrusion there is no reason to doubt that

the gabbro body represents the main core while the lateral wedges of diorite are subsidiary lobes intruded under a sufficient hydrostatic pressure to cause a local doming of the overlying limestone.

Recent work by Dr. J. G. Andersson and Mr. H. C. T'an of Peking, places the normal faulting of Shantung, and probably also the folding, in Oligocene or Miocene. The date of intrusion is certainly pre-Cretaceous. There is no evidence to show that the position or shape of the intrusive was determined by crustal weaknesses produced by earlier movement, nor does it correspond to any recognizable underlying structural direction in the T'aishan complex.

The elongated outline of the present area is partly explained by the ituation on the downwarped slope; but from the position of the diorite lobes it is probable that the main body actually has an east-west extension.

IX. Summary.

The Tsinan gabbro is the main phase of an intrusive of moderately large size, showing gravitative differentiation grading through quartz-diorite to more acid vein types. The development of vermicular quartz and biotite reaction-rims, supported by other evidences of deuteric action, points to a water-charged siliceous residue as the final separate.

The most severe contact reorganization occurs in limestone xenoliths where all stages from incipient silication to complete syntexis may be observed; small magnetite deposits are found at the marginal contacts. The shape of the body is irregularly laccolithic, with beaded marginal lobes, possibly of the multiple type. There is no evidence of severe dislocation either as the locus of intrusion or as a later structural factor.

Note on the Springs of Tsi Nan Fu.

An entirely subsidiary question is raised by the springs which have made the city famous from the earliest times. According to popular report they number 72, and are all within the limits of the wall of the Chinese City, but water has been drilled for successfully in the adjoining foreign settlement. The springs are artificially built up so that it is doubtful whether bed rock in place is exposed anywhere. The water comes to the surface at a level considerably above that of the plain, so that it can be led in open channels through

the streets, forming the natural water system which is a feature of the city. The springs themselves are scattered over a wide area and vary greatly in size; the most famous group is that known as Bao Du Ch'uen. I am indebted to Mr. Oliver J. Todd[59] for data regarding the flow from the three main springs, and the smaller tributaries which together form the stream at the electric light plant. In June, 1920, a Price current-meter at this point registered a discharge of 70 second-feet. Mr. Todd puts the average flow through the year at not less than 60 second-feet.

An analysis of the water from Bao Du Ch'uen was kindly made by Professor William H. Adolph of the Department of Chemistry, Shantung Christian University. Dr. Adolph reports:

Total solids	251 parts per million
Silica	4
Calcium carbonate	108
Iron and alumina	35
Magnesium carbonate	3
Calcium sulphate	21
Magnesium sulphate	2
Sodium chloride	17
Temporary hardness	110
Permanent hardness	64

The water analyses do not differ from the typical waters of limestone areas and the bottom of the well at Shantung Christian University is in Tsinan limestone. v. Richthofen connects them merely with the pervious quality of the loess on which the city rests[58]. But in view of the peculiar localized development of the springs, I am inclined to attribute the occurence to the presence of an uncharted sheet of intrusive rock below the ground forcing the water table to the surface. An exact counter-part on a small scale is to be seen just south of the plantation on Yen Tze Shan referred to already; here two wells 300 feet up the mountain side owe an almost uninterrupted water supply to the water-proof qualities of the underlying diorite sill. The writer has also described[45] a similar control of ground-water in the area northwest of Shun Teh Fu, where there is an extensive underlying sheet of rock whose presence was attested only by two small outcrops and which by producing a

local water-table kept the subsoil drainage close to the surface, until it reached the margin of the intrusive, where it at once sank out of reach. A similar explanation seems probable in the case of the springs at Tsi Nan Fu.

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Explanation of Plates.

PLATE I.

Fig. 1. Hyperite, Kwong Shan. Magnetite moulded round augite (dark grey, with inclusions along parallel cleavages) and developing fringe of reaction biotite towards labradorite (white, showing cleavage). Hypersthene with rounded outlines, showing stained fracture and cleavage lines. (Ts. 207 X 40).

Fig. 2. The same, enlarged to show biotite reaction-rim between magnetite and feldspar where in contact with hypersthene, the latter distinguishable from feldspar by higher refractive index and dactylic intergrowth with magnetite. (X 180).

Fig. 3. Handspecimen showing stages of contact metamorphism, Chüeh Shan. Limestone below, gabbro upper right hand margin, with intervening bands of (*d*) diopside (massive (dark) and granular with feldspar (light)) and of (*g*) garnet ($\frac{2}{3}$ natural size).

Fig. 4. Xenoliths and veins of diopside in gabbro, Chüeh Shan. ($\frac{1}{3}$

natural size).

Fig. 5. Limestone xenolith, partly dissolved by weathering, in cavity lined with diopside envelope, surrounded by irregular garnet zone; the whole swimming in gabbro. (See Fig. 3 above)

Fig. 6. Weathered block, four feet high, showing gneissoid banding due to differentiation, Hua Shan.

PLATE II.

Fig. 1. Fine-grained hyperite, Piao Shan. Showing zonary inclusions in augite phenocryst (dark grey), magnetite (black), labradorite (white), and orthorhombic and monoclinic pyroxenes (grey). (Ts. 312 X 40).

Fig. 2. (a) Diopside feldspar mosaic coalescing into large crystals. Contact zone, Ma Kang Shan. (Ts. 303 X 40).
(b) The same reduced to fretwork by alteration to garnet (black, isotropic). (Ts. 309 X 40, crossed nicols).

Fig. 3. Quartz-diorite (altered), Yen Chih Shan. Zonary plagioclase altering to grey in different degrees according to composition, magnetite (black) and hornblende altering to epidote (dark grey with black markings). (Ts. 601 X 42).

Fig. 4. Pegmatite mineral (?andalusite) as last cavity filler, replacing earlier feldspars. Specimen loaned by Prof. F. K. Morris (X 35, crossed nicols).

Fig. 5. Vermicular quartz at contact between two plagioclase crystals. Under microscope, though not shown by the photo, the twinning can be detected in the dark plagioclase (labradorite-andesine) nearly parallel with the zigzag contact from which the quartz appears to grow. (Ts. 301 X 35, crossed nicols).

Fig. 6. Bastion-shaped limonite skeletons in carbonate vein cutting Tsinan limeston, Yao T'ou. (Ts. 607 X 22).

Analysis

(When the following analysis was received, the paper was already printed. Therefore it can only be inserted here.—Editor.)

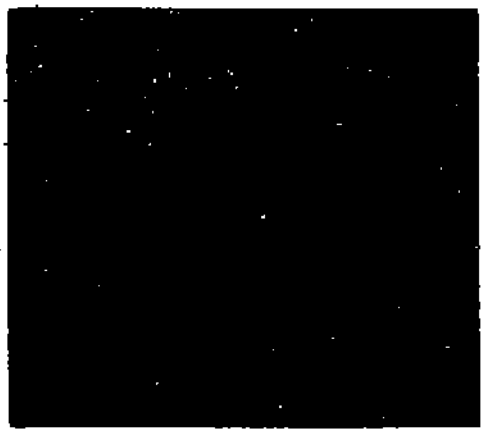
Dr. Harry V. Fuller of Peiyang University has very kindly analysed a fairly basic sample of the gabbro (Ts. 502) in which the reaction-rims have

developed extensively at the expense of the magnetite. A recast in terms of observed minerals is given for comparison. Since no orthoclase was noted all the K_2O is allotted to biotite, thus giving free quartz. Although the latter was not observed in the section examined and the biotite value is considerably high, the error is less than if calculated entirely as feldspar and the resulting composition of the plagioclase Ab_3An_5 tallies with observation. An arbitrary assignment of the lime balance to augite is found to give a ratio between the pyroxenes closely corresponding to that noted.

SiO_2	51.78	Albite	20.96
Al_2O_3	17.79	Anorthite	35.58
Fe_2O_3	2.10	Biotite	7.20
FeO	6.91	Magnetite	3.02
CaO	10.00	Augite	17.40
MgO	7.36	Hyperstene	12.85
Na_2O	2.48	Quartz	2.94
K_2O	0.76		
loss	0.32		99.95
	99.50		

Analysis by Dr. H. V. Fuller

Recast by G. B. Barbour



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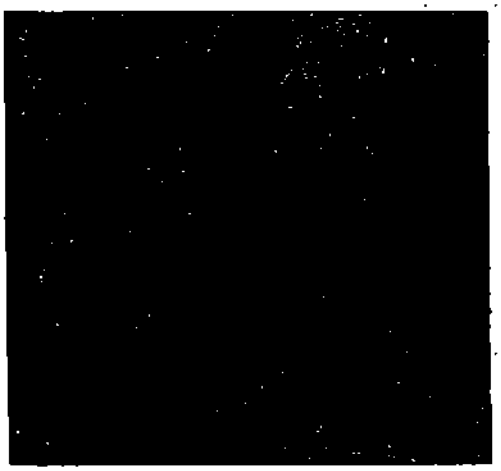

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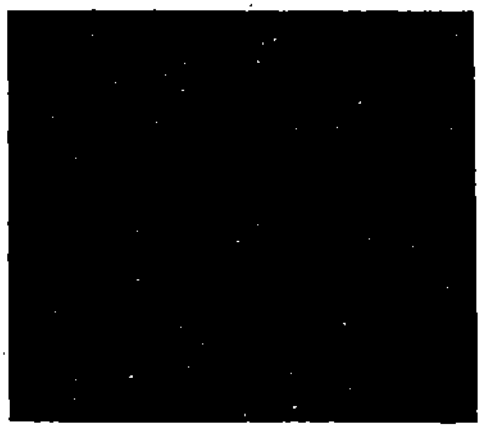

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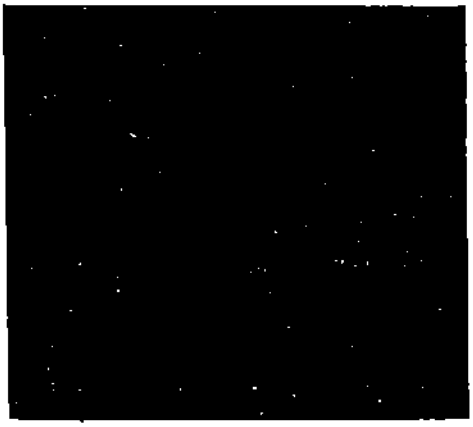

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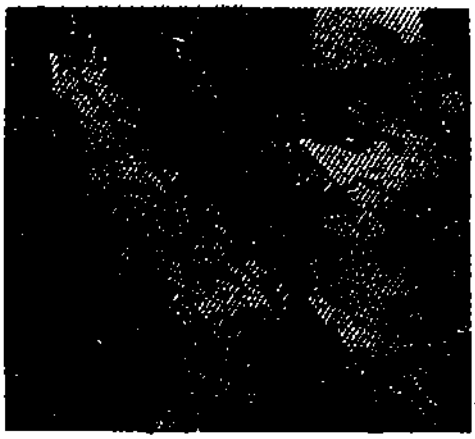

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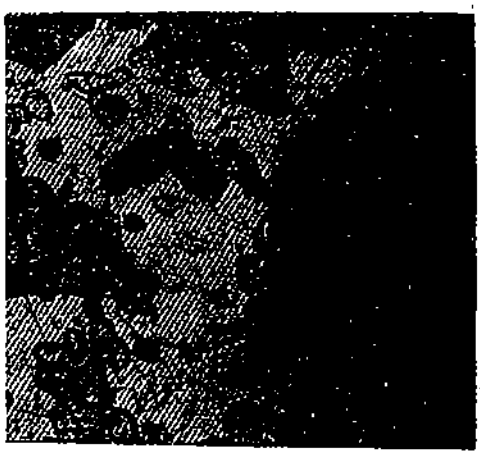

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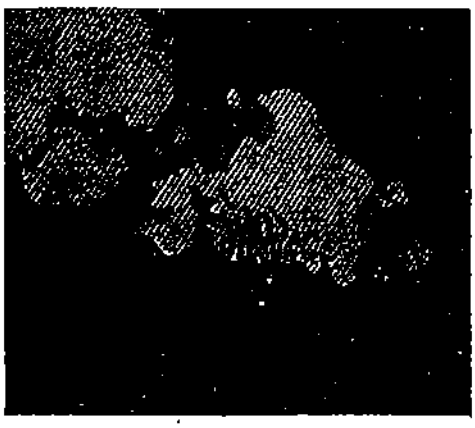

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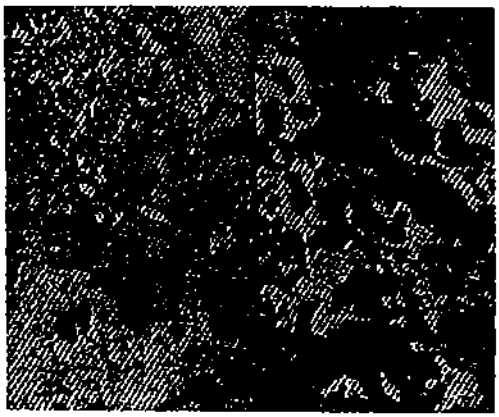

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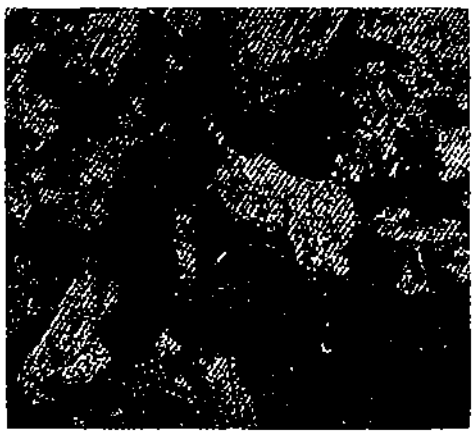

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