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GRADED LAYERING IN THE AL HADAH PLUTON NEAR AT TA'IF KINGDOM OF SAUDI ARABIA

by

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U. S. Geological Survey
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ABSTRACT

Graded igneous layering is exposed in the Al Hadah pluton near At Ta'if in the west-central part of the Arabian Shield in Saudi Arabia. The layers, which average 10 cm in thickness, are normally or reversely graded from bottom to top in terms of modal concentration with respect to the constituent minerals. No. preferential orientation of the minerals was observed. Biotite, hornblende, plagioclase, and heavy minerals are concentrated at the base of the layers, and coarse-grained potassium feldspar is concentrated at the top. Most layers have an average composition of quartz monzonite and show a differentiation trend, from base to top, from quartz diorite and granodiorite to quartz monzonite and granite, which was produced by mechanical processes.

The layers formed near the roof of the Al Hadah pluton from low-viscosity flow differentiation currents derived from depth, probably during emplacement of the pluton. Deposition of the layers was from within the pluton outward toward the country rock contact. The thickness of individual layers is thought to be a function of the duration of current supply.

INTRODUCTION

Layering was identified in a quartz monzonite pluton (herein referred to as the Al Hadah pluton) during geologic reconnaissance work in the vicinity of At Ta'if in the west-central part of Saudi Arabia (fig. 1). Layering in the granitic rocks is known elsewhere in the Arabian Shield (John Kemp, oral commun., 1974), but in contrast to layered mafic intrusions here and elsewhere in the world, layering in granitic rocks is relatively uncommon.

Layering in rocks of dioritic to granitic composition is rare and has been ascribed to gravitational settling (Gilbert, 1906; Emeleus, 1963; Harry and Emeleus, 1960), mechanical flow sorting in a zone with steep-velocity gradients such as at or near a solid-liquid interface (Wilshire, 1969), and gradational crystallization from a saturated, low-viscosity, low-density fluid at a solid-liquid interface (comb layering of Moore and Lockwood, 1973). Layering produced by normal magmatic crystallization in granitic rocks has been reexamined recently by Moore and Lockwood (1973) and defined as "schlieren layering."

Layering in the Al Hadah pluton is similar to that described by Wilshire (1969), but generally is unlike layering described by

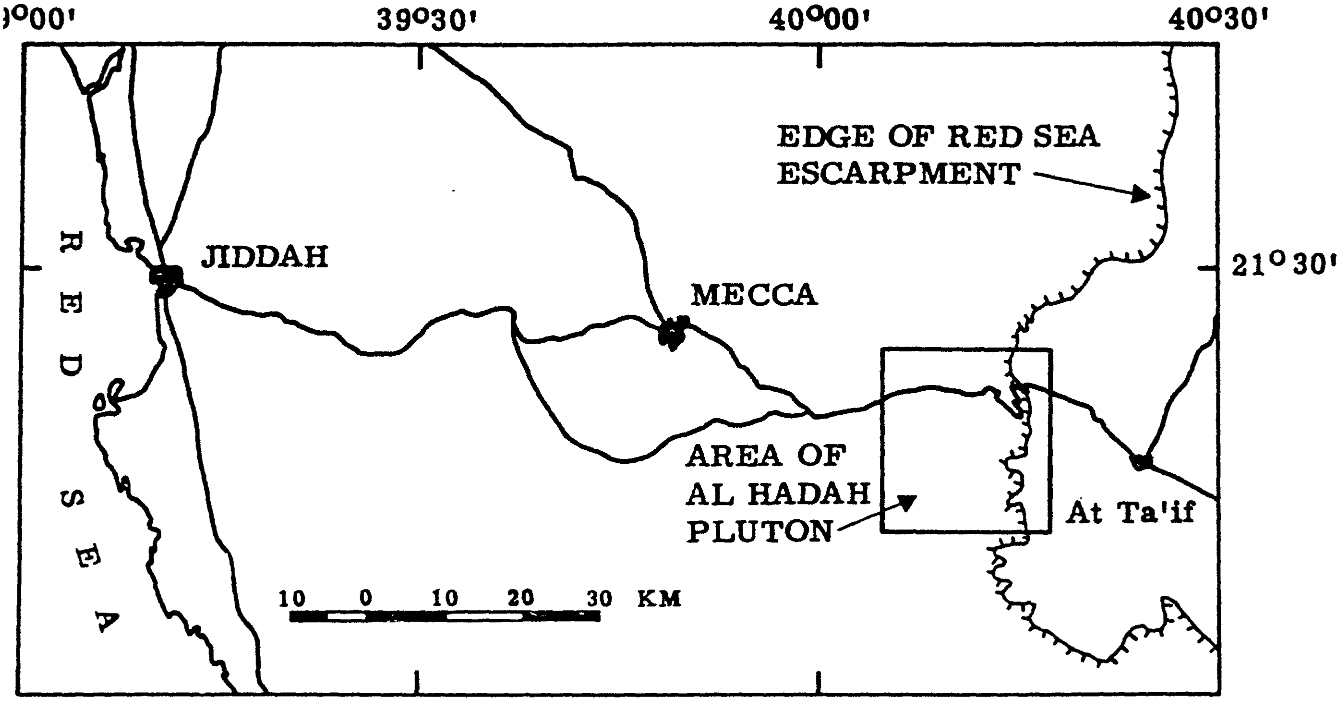


Figure 1. - Index maps showing the location of the Al Hadah pluton in the west-central part of the Arabian Shield along the Red Sea Escarpment between Mecca and At Ta'if.

other authors. We define the Al Hadah layering and compare and contrast its character and mode of origin with types of layering previously discussed.

Fieldwork for this paper was conducted during parts of October 1970 and April 1973, utilizing a topographic base map at scale 1:80,000 and aerial photographs at scale 1:60,000. The Al Hadah pluton is accessible by vehicle along a paved highway between Jiddah and At Ta'if. Layering is exposed in two areas, the most important being the upper contact between the pluton and diorite and gabbro, approximately 7 km along the highway below the edge of the Red Sea Escarpment (fig. 2), and the other, near the same contact, 1-1/2-2 km further west via the highway and below the upper exposure.

Fieldwork included measuring the layering, observing the general intrusive relationships of the pluton, and collecting samples for laboratory work. A modal petrographic traverse was made in the field across the full vertical extent of one exposure of layering. Spot modal counts of the intrusive rock above and below the layering also were made.

ACKNOWLEDGMENTS

This work results from investigations undertaken by the U. S. Geological Survey in accordance with a Work Agreement with Saudi Arabian Ministry of Petroleum and Mineral Resources. We are indebted to A. M. Helaby who prepared thin sections and assisted with other phases of laboratory work.

LOCATION AND GENERAL GEOLOGIC SETTING

The Al Hadah pluton crops out in the west-central part of the Arabian Shield (fig. 1) along the Red Sea Escarpment, about 18 km west-northwest of At Ta'if (fig. 1). Elevations from the base to the top of the escarpment in the study area range from about 400 to 2150 m (fig. 2). Greenstone, probably belonging to the Baish Group, (Schmidt and others, 1973) underlies most of the area. The Al Hadah pluton intrudes diorite and gabbro and is juxtaposed against greenstone along a northeast-trending major fault. The greenstone is the oldest rock in the area; quartz monzonite of the Al Hadah pluton is the youngest rock and is probably late Precambrian to early Paleozoic in age by comparison with other dated quartz monzonite plutons in the Arabian Shield (Fleck and others, in press; Schmidt and others, 1973).

Structures in the area trend northeast, truncating the older north-trending structures that are generally found in the south and south-central parts of the Arabian Craton (Schmidt and others, 1975; Greenwood and others, 1973, 1976). Metamorphism to the greenschist facies characterized the greenstone, diorite, and gabbro; whereas the Al Hadah quartz monzonite is not metamorphosed.

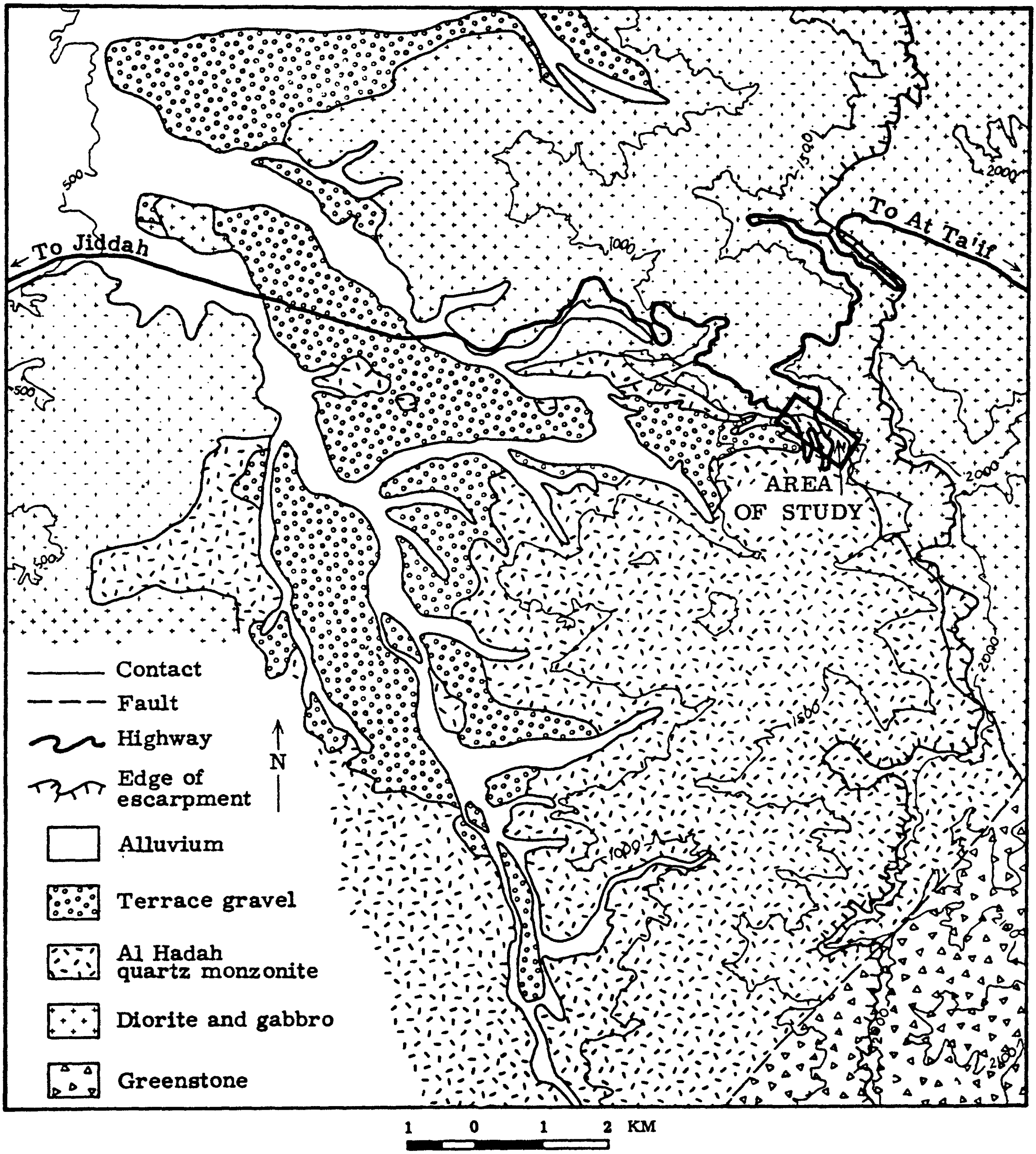


Figure 2.- Geologic map of part of the Al Hadah pluton. Contours in meters.

Figure 3.- Photograph of steeply dipping intrusive contact between Al Hadah quartz monzonite and diorite and gabbro. Taken about 50m above zone of igneous layering.

The escarpment forms the edge of a broad northeast-dipping plateau that was uplifted beginning in early to mid-Tertiary time (Brown, 1970; Brown and Coleman, 1972; Coleman, 1974; Coleman and Brown, 1971). Dissection of this physiographic feature has produced a conspicuous southwest and northeast drainage pattern demarcated by the escarpment edge. Wadis on both sides of the escarpment are filled by Quaternary alluvium, and on the west side dissected Quaternary to Tertiary gravel terraces occupy flanks of the major wadis (fig. 2).

DESCRIPTION OF THE AL HADAH PLUTON

The Al Hadah quartz monzonite forms a roughly circular pluton measuring 11.5 km east-west and 9.5 km north-south. Contacts with the country rock dip outward at about 15°W along the western border of the intrusion, and are steep elsewhere, dipping as much as 70° outward along the north side in the vicinity of the layering (fig. 3). Contacts generally are sharp and undulating and in numerous places are offset as much as 3 m by small faults (see lower left part of fig. 3). A prominent east-trending vertical joint system is present throughout the pluton. Weathering related to the joints has produced several immense exfoliation domes and numerous smaller ones.

Near the intrusive contact of the pluton, an area of igneous layering is exposed that consists of disrupted layers and a zone of generally nondeformed uniformly bedded layers 2-7 m thick. The area of layering probably constitutes less than 1 percent of the volume of the Al Hadah intrusion.

Pegmatitic and aplitic dikes related to the intrusion are of two ages: prelayering and postlayering. The prelayering dikes intruded massive nonstructured quartz monzonite beneath the layered zone and are truncated and terminated by the basal layers of the zone (figs. 4, 5). The older dikes are medium- to coarse-grained pegmatite and show three types of structure; dikes with massive centers and comb-structured margins (fig. 4); massive dikes containing elongate mafic bodies (fig. 5); and dikes in which mineral layering is parallel to the dike walls. The comb-structured dikes contain minerals (principally hornblende) that have grown perpendicular to the dike walls, producing a texture similar to comb layering described by Moore and Lockwood (1973). Mineral layering parallel to dike walls is the same type as discussed by Jahns and Tuttle (1963). An early part of the Al Hadah quartz monzonite was at least partly crystallized before development of the main layered zone and appears to have served as a floor for the deposition of the subsequent layers. The prelayering dikes are thought to be related to this phase of the pluton.

Postlayering dikes are composed of pegmatite and leucocratic aplite and range from 1 to 30 cm in width. They intrude the layered zone in many places and are coarsest near contacts with the country rock.

COMPOSITION AND MINERALOGY

Quartz monzonite is the principal rock type in the nonlayered parts of the Al Hadah pluton. Of five laboratory and five field modal analyses, seven plot as quartz monzonite, two as granodiorite and one as granite (fig. 6). The rock is medium to coarse grained, pale pink to light gray, dependent on mafic mineral content, and has hypidiomorphic-granular to hypidiomorphic-porphyritic texture. Above and below the layered zone, mafic minerals are uniformly disseminated. Below the zone, feldspar is medium grained and equant, sparse large phenocrysts of potassium feldspar are presently locally, and plagioclase crystals are as much as 10 mm long. Above the zone, potassium feldspar and plagioclase are coarse grained and porphyritic, and rapakivi texture is common. Plagioclase is less abundant above the layered zone than below the zone.

The main minerals of the Al Hadah pluton are quartz, microcline, and plagioclase. These comprise 80 percent or more of the rock (table 1). Subhedral to euhedral biotite and hornblende, together forming as much as 20 percent of some samples, are the varietal minerals. Small to trace amounts of accessory and secondary minerals (table 1) make up the remainder of the rock.

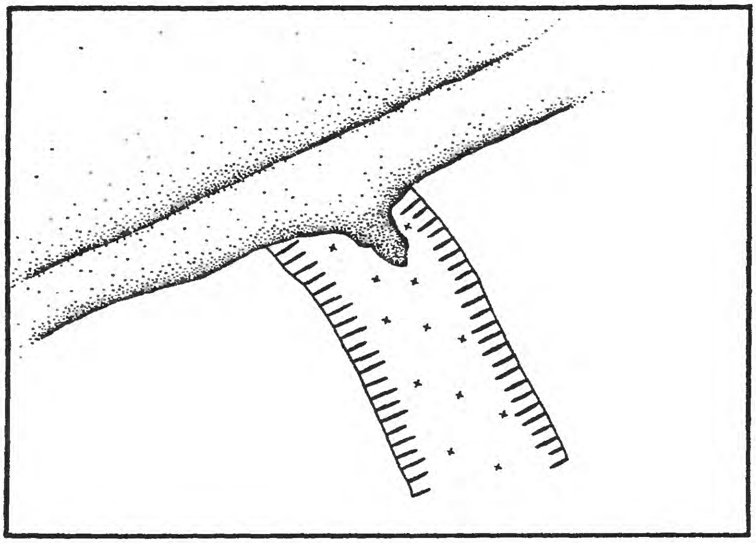


Figure 4. - Drawing of pegmatite dike truncated by graded layers, loc. 1. Hornblende prisms (heavy bars) have grown in a comb structure similar to that described by Moore and Lockwood (1973).

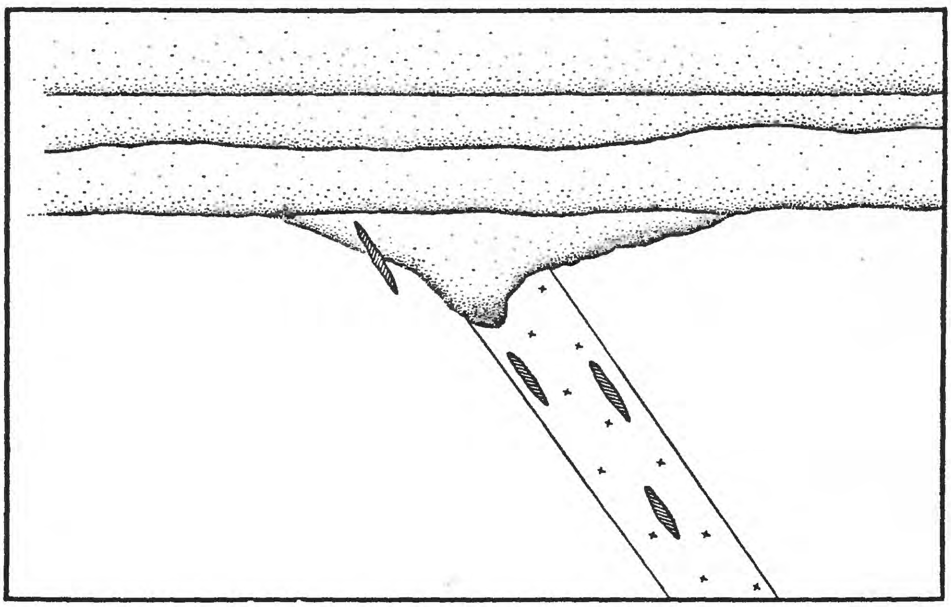


Figure 5. - Drawing of massive nonstructured pegmatite dike truncated by graded layers, loc. 1. A mafic bleb similar to those enclosed by the dike cuts across the lower boundary of one layer, indicating growth of the blebs in place.

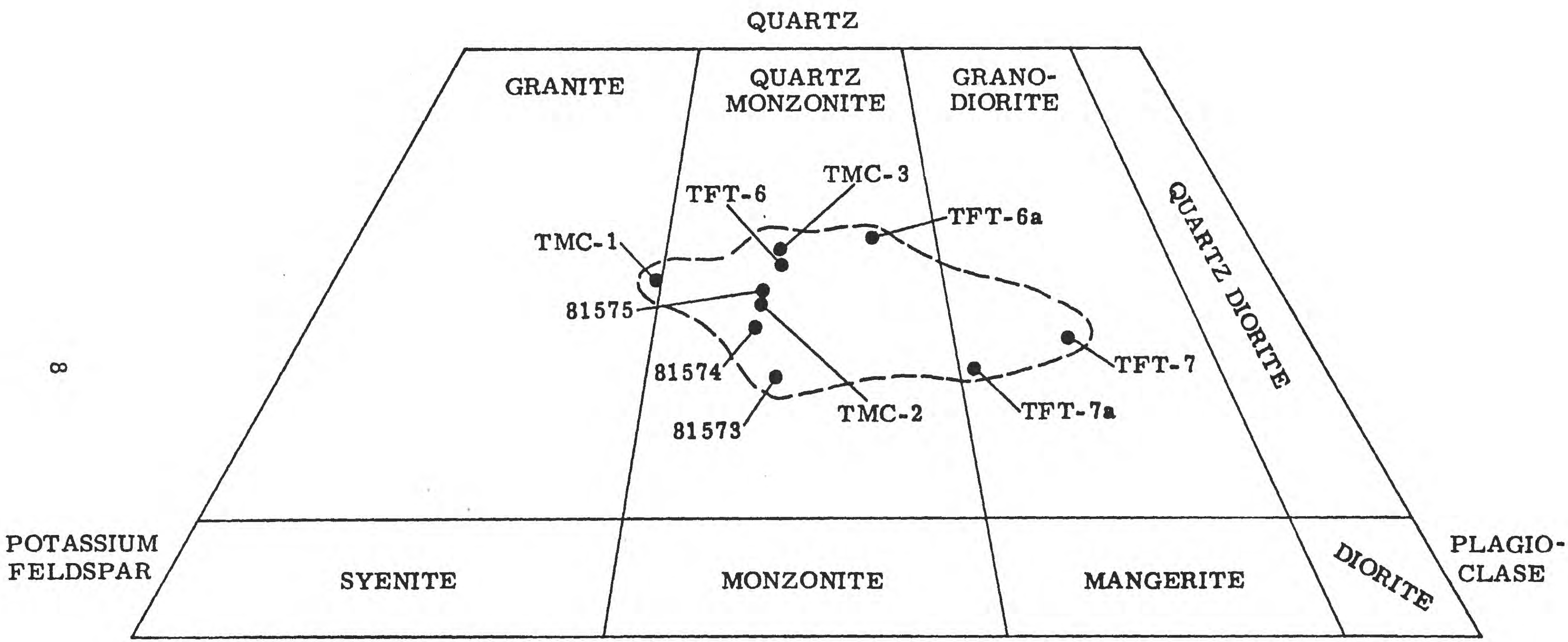


Figure 6. - Thin section and outcrop modal compositions of rock from nonlayered parts of the Al Hadah pluton. Samples TMC-1, 2, 3 represent field modal counts 10, 80, and 120 feet, respectively, above the main layered zone. Samples TFT-6a and TFT-7a are modal counts of stained slabs from samples TFT-6 and TFT-7. See table 1 for locations of the other samples.

Table 1. - Thin section modal analyses (in percent) of samples from nonlayered parts of the Al Hadah pluton.

	Samples				
	TFT-6	TFT-7	81573	81574	81575
Quartz	30.3	20.5	20.1	24.9	26.7
Potassium feldspar	34.1	14.3	36.2	37.5	34.5
Plagioclase	30.6	45.2	33.5	31.1	29.4
Myrmekite	--	--	1.1	0.6	Tr
Hornblende	--	5.4	0.6	Tr	1.9
Biotite	5.0	14.6	6.6	4.1	6.7
Chlorite	--	--	0.8	0.4	0.2
Sericite	--	--		Tr	Tr
Opaque minerals	--	Tr	Tr	Tr	0.4
Hematite	--	--	--	--	0.2
Sphene	Tr	Tr	0.8	0.6	Tr
Allanite	--	--	0.2	Tr	Tr
Zircon	Tr	Tr	Tr	Tr	Tr
Epidote	--	--	Tr	Tr	Tr
Calcite	--	--	Tr	0.6	Tr
Apatite	Tr	Tr	Tr	--	--
Total percent	100.0	100.0	100.1	99.8	100.0
No. point counts	600	600	636	469	565

Sample TFT-6 Quartz monzonite collected about 500 m west of the study area
Sample TFT-7 Granodiorite collected about 50 m south of layered loc. 1.
Sample 81573 Quartz monzonite collected 3 m above layered loc. 1.
Sample 81574 Quartz monzonite collected 7 m above layered loc. 1.
Sample 81575 Quartz monzonite collected 3 m below layered loc. 1.

LAYERING

Terminology

Except for comb layering in the pegmatite dikes, layering described in this paper is called graded layering. Graded layering is defined here as a succession of holocrystalline plutonic layers, each layer of which is normally or reversely graded from bottom to top in terms of modal concentration of the constituent minerals. Individual minerals were not observed to be preferrentially oriented in the graded layers. Table 2 compares graded layering in the Al Hadah pluton with types of layering described in the literature.

Graded layering is similar to Wager and Deer's (1939) cryptic layering (table 2), where the layering is defined by upward changes in chemical composition of the constituent minerals within individual layers with or without changes in modal composition. No chemical analyses of individual minerals from Al Hadah graded layers are available, but flat-stage microscopic examination does not indicate any systematic changes in optical properties of minerals that would suggest chemical differences from bottom to top of layers. Graded layering is also similar to layering in granite described by Harry and Emeleus (1960) in southwest Greenland. They refer to the layering as rhythmic layering, and it is, in part, in that there are alternating bands of light and dark minerals. The dark minerals in the Greenland rocks, however, are graded and are not arranged in the sharp individual bands characteristic of rhythmic layering.

Graded layering in the Al Hadah pluton is unlike rhythmic layering (Wager and Deer, 1939), Willow Lake and Skaergaard-type layering (Poldervaart and Taubeneck, 1959), comb and schlieren layering (Moore and Lockwood, 1973), and phase layering (Hess, 1960). Preferentially oriented minerals (mainly mafic) within individual layers, characteristic of Willow Lake-type, comb, and schlieren layering, are not observed in graded layers of the Al Hadah pluton. Some layering terms described by different authors are essentially the same. For example, rhythmic layering and schlieren layering basically define layering of the same type. Although not stated by Wager and Deer (1939) in their definition of rhythmic layering, the constituent minerals are generally elongated parallel to the plane of layering. Rhythmic layering is the preferred terminology; schlieren layering is poor usage because schlieren are layered structures by definition. In addition, a layering term proposed by one author may be a group term which describes two types of layering by another author. For example, Poldervaart and Taubeneck (1959) proposed thatrhythmic layering be subdivided into layering of the Skaergaard type and Willow Lake type. Thus, rhythmic layering essentially encompasses the two main types defined by Poldervaart and Taubeneck.

Table 2. - Types of layering in igneous rocks

Layering	Definition	Rock type	Area	Reference
Rhythmic	Repeated alternation of two or more kinds of rock in relatively thin, but laterally extensive layers.	Primarily gabbro	Skaergaard intrusion, east Greenland	Wager and Deer (1939)
Cryptic	Repeating layers of igneous rocks in which there are changes in chemical composition of the constituent minerals within individual layers with or without changes in modal composition.	Primarily gabbro	Skaergaard intrusion, east Greenland	Wager and Deer (1939)
Willow Lake	Layering in small gabbroic plutons in which crystals of the constituent minerals are arranged with their longer axes at high angles (60°-90°) to the plane of layering.	Gabbro	Willow Lake pluton, Oregon to east-central California	Poldervaart and Taubeneck (1959)
Skaergaard	Layering in large gabbroic plutons in which crystals of the constituent minerals show a preferred orientation of their longer axes in the plane of layering.	Mafic rocks	Skaergaard intrusion, east Greenland	Poldervaart and Taubeneck (1959)
Comb	Layering in granitoid rocks in which constituent crystals are oriented nearly perpendicular to the planes of layering.	Gabbro to quartz monzonite, but mostly diorite	Sierra Nevada batholith, California	Moore and Lockwood (1973)
Schlieren	Layering in plutonic rocks defined by alternating layers enriched or depleted in normal mafic minerals of the pluton. Elongate minerals are oriented parallel to the planes of layering.	Gabbro to quartz monzonite, but mostly diorite	Sierra Nevada batholith, California	Moore and Lockwood (1973)
Phase	Layering in an igneous mass defined by the appearance and/or disappearance of a specific mineral.	Gabbro, dunite, norite, peridotite, anorthosite	Stillwater complex, Montana	Hess (1960)
Graded	A succession of holocrystalline plutonic layers, each layer of which is normally or reversely graded from bottom to top in terms of modal concentration with respect to the constituent minerals and where the individual minerals are not preferrentially oriented.	Quartz diorite, quartz monzonite, granite (primarily quartz monzonite)	Al Hadah pluton, Saudi Arabia	This paper

General description

Layering in the Al Hadah pluton is exposed near the contact with the diorite and gabbro for about 200 m, except for the part covered by talus (see arrows in fig. 7). A poorly exposed area of layering is about 1/2 km west of the main area, but was not studied in detail. The numbered locations shown in figure 7 are used as a basis for the following discussion.

Layering consists of uniform, repetitiously bedded and crossbedded graded units. In the main layered zone (locs. 1-3), the layering is deformed and complexly distorted in some places. Deformed layering is also found below the main layered zone, as well as schlieren and blocks of quartz monzonite that contain graded layering and deformed graded layering. The schlieren and blocks are not contiguous with the main layered zone and appear to be engulfed graded layering formed and subsequently disrupted prior to formation of the main layered zone. They probably formed by the same processes of flow differentiation that is proposed for origin of the main layered zone.

The main layered zone ranges from 2.0 m (fig. 7, loc. 1; fig. 8) to 6.7 m thick (fig. 7, loc. 3; fig. 9). At loc. 1 detailed measurements and outcrop modal petrography of the layers were made. The layers range in thickness from 2.2 to 30.4 cm and average 9.8 cm. They strike N.88°W. and dip 36°NE.; at loc. 2 the layers strike N.53°W. and dip 32°NE.

Layers in the main layered unit show a variety of structures. Single layers may be traced for as much as 5 m before they are truncated or merge with other layers (figs. 9, 10, 11). Thinning of layers is common. Other structures include channels (figs. 4, 5, 10, 11), "ripple marks" (fig. 12), crossbedding (fig. 12), and overturned or folded structures (figs. 13, 14). In places one or more layers are offset by small-scale faults (fig. 15). The offset layers are bounded by nonfaulted layers, indicating faulting penecontemporaneous with formation of the layers when they were probably in a semiconsolidated state.

Deformed and complexly distorted layers (figs. 16, 17) are found in the main layered zone. The deformed layers are invariably convex downward, that is, in the direction of the oldest layers, and are generally sandwiched between undeformed layers (lower part of fig. 16). This suggests penecontemporaneous "soft-sediment"-type deformation similar to that described above for the interlayer faults. Complexly distorted layers like those shown in figure 17 probably do not result from "soft-sediment"-type slumping, but are the result of disruption caused by late intrusions of quartz monzonite magma. The late intrusions are petrographically similar to the rest of the Al Hadah quartz monzonite and probably came from the same source.

Schlieren and isolated masses of graded layering (10-14 by 60-100 cm) occur in nonlayered quartz monzonite as blocks, lenses, and irregular zones of rock containing well defined, mostly nondeformed layers (figs. 18, 19) and blocks with moderately to highly contorted layers (fig. 17). Schlieren that contain contorted layers have diffuse boundaries with the host rock. In general, the schlieren have characteristics similar to those of the main layered zone. They represent layering that was formed, broken up, and engulfed by intrusive activity in the Al Hadah pluton prior to development of the main layered unit. Evidence of the repetitive intrusive activity is easily seen in the field (fig. 17). For example, one schlieren block in coarse-grained prophyritic quartz monzonite is sharply terminated on one end by medium-grained nonporphyritic quartz monzonite that marks an intrusive contact (fig. 18, 19).

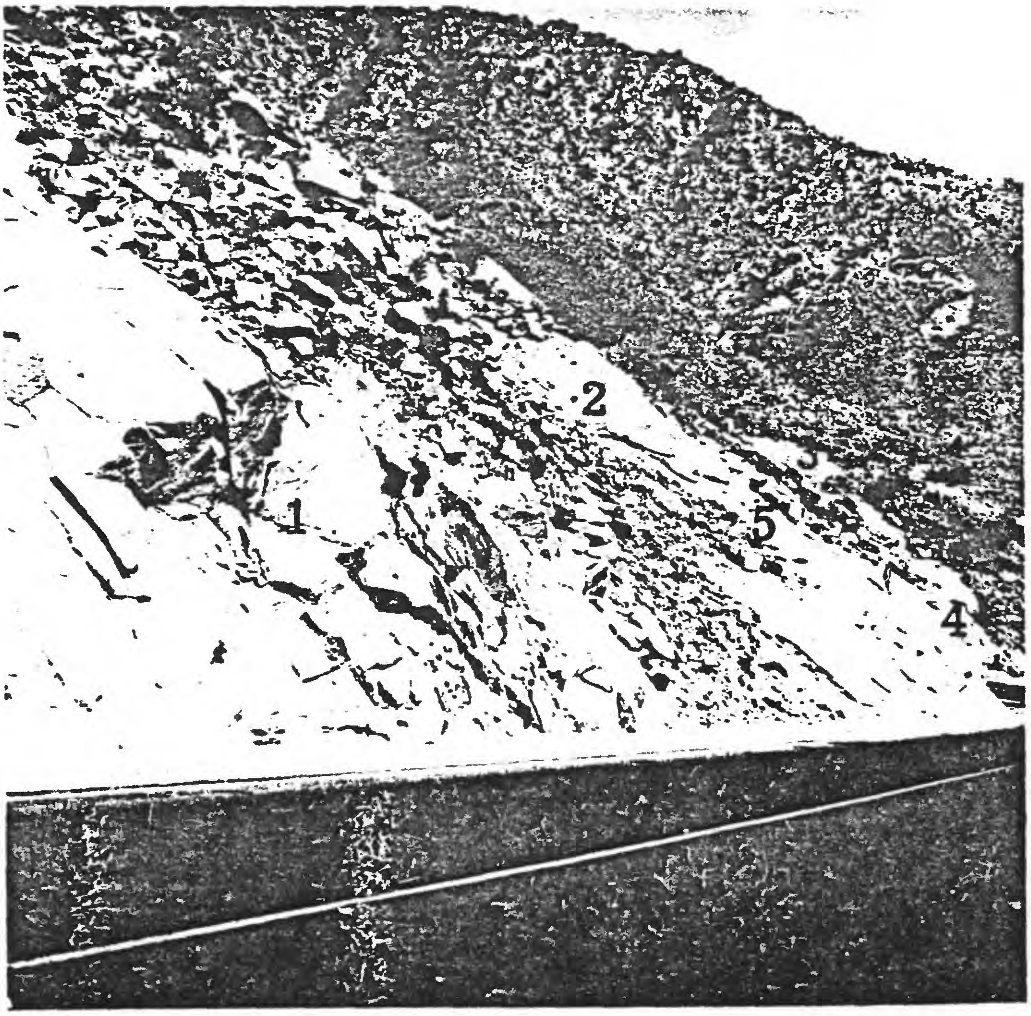


Figure 7.- Photograph of layered rock showing locations 1-5.

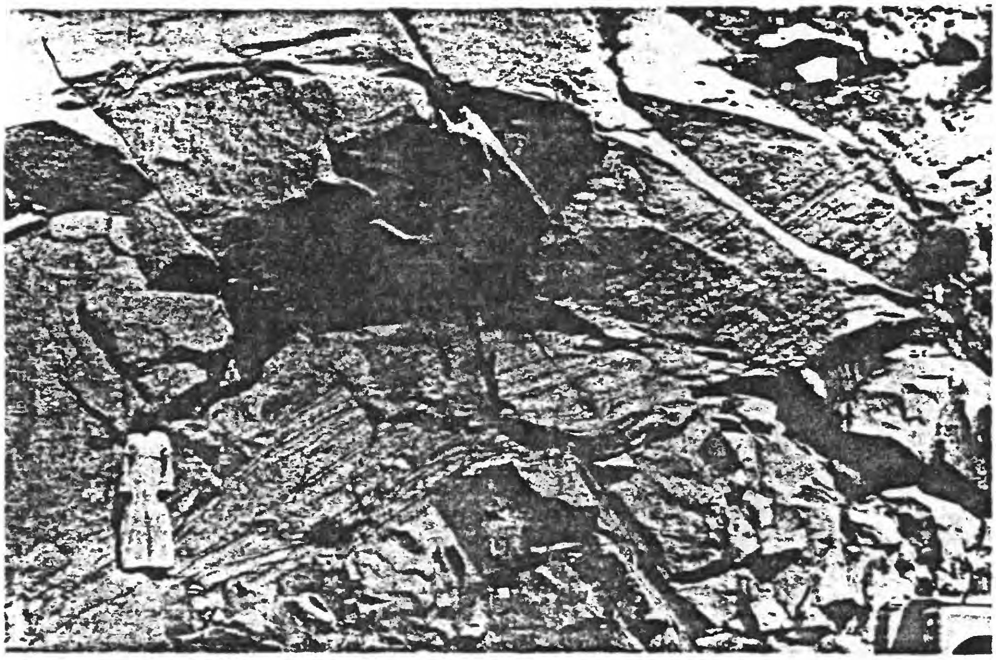


Figure 8.- Photograph of layered zone at loc. 1, showing moderate dip of layers.

Figure 9.- Photograph of thick zone of thin-bedded graded layers at loc. 3. The layers show abundant truncation and anastomosing features in this area.

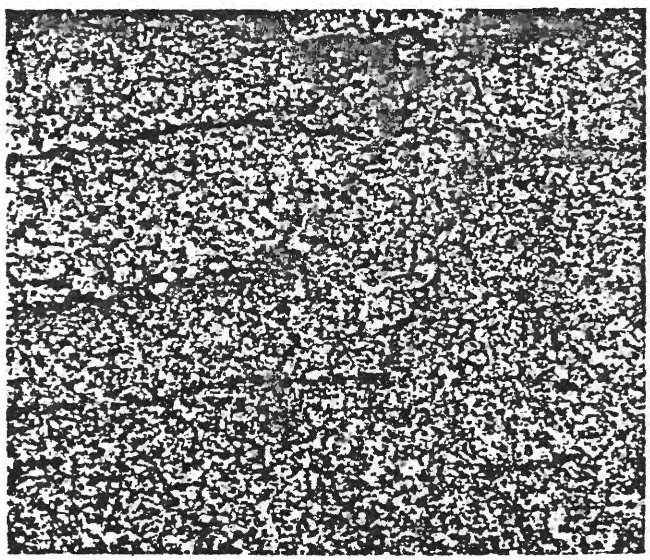


Figure 10.- Photograph of channeling or downslope (?) movement of graded layers, loc. 1.

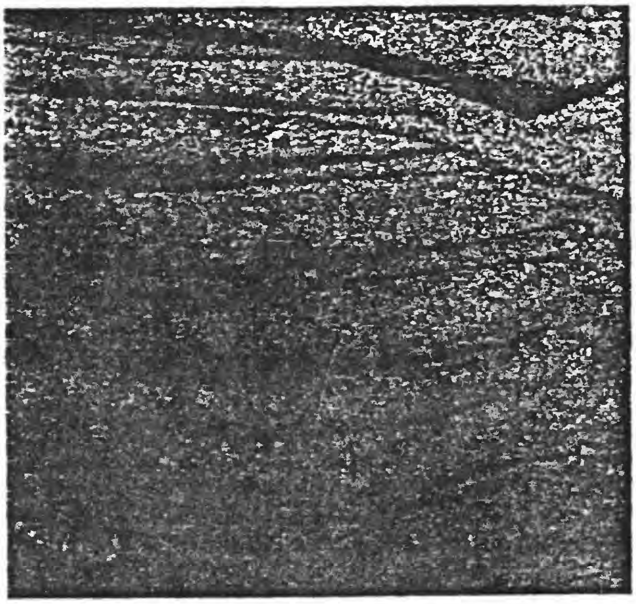


Figure 11.- Photograph of thinly bedded graded layering showing some channeling and truncation and concentration of mafic minerals in the channel troughs, loc. 2. The thicker layers are 2-3 cm thick.

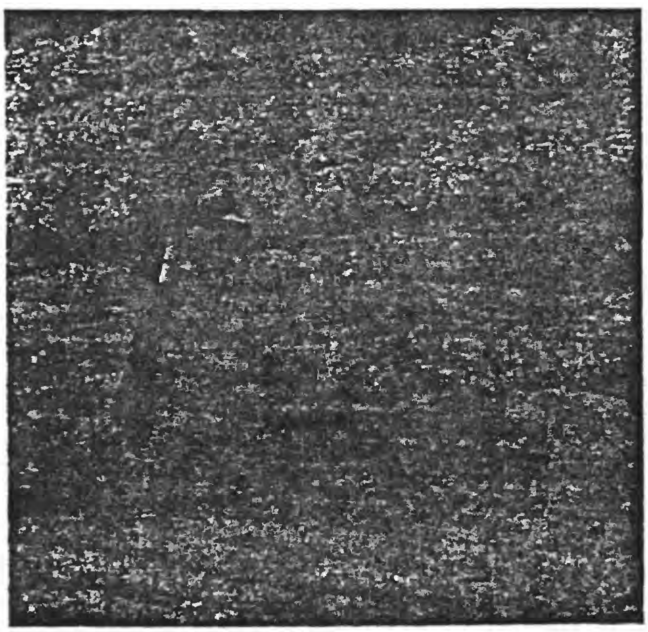


Figure 12.- Photograph of ripplelike features (middle of photo) showing dune forms and widely spaced foresets and igneous crossbedding (lower part of photo), loc. 2.

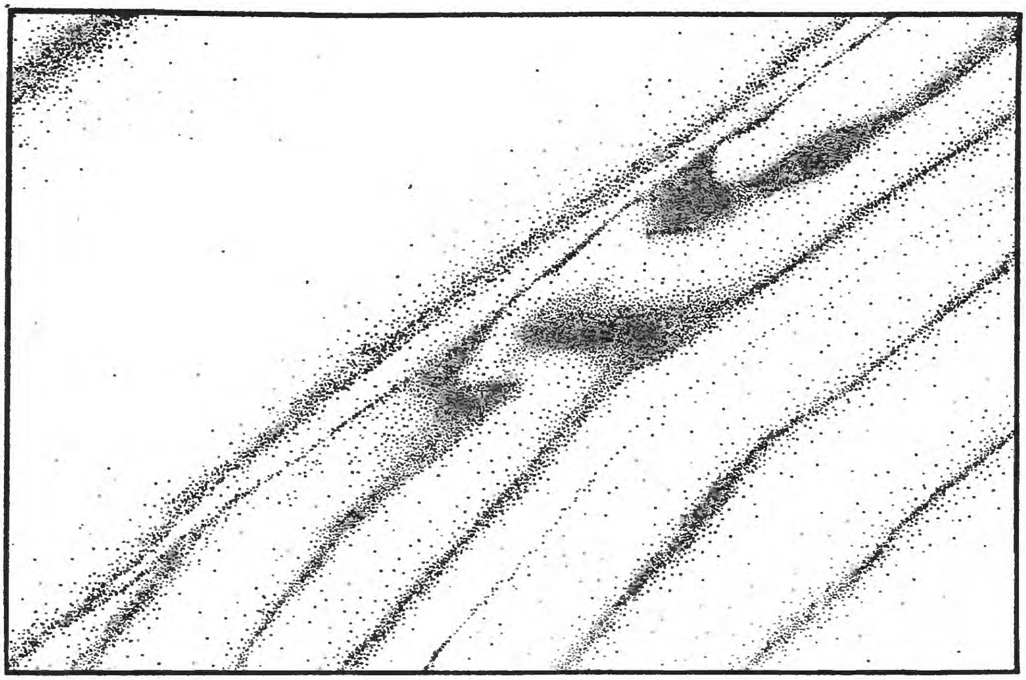


Figure 13. - Drawing of slump-folded and truncated graded layers.

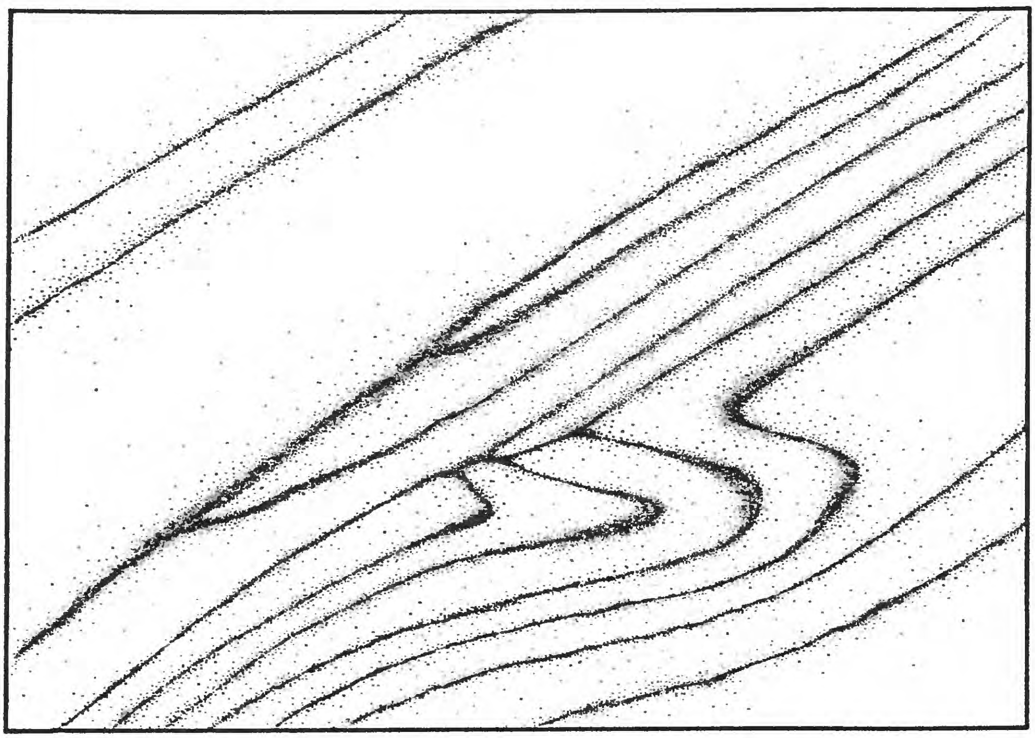


Figure 14. - Drawing of slump-folded layers showing truncation of some fold limbs by younger igneous layers and other truncation features, loc. 1.

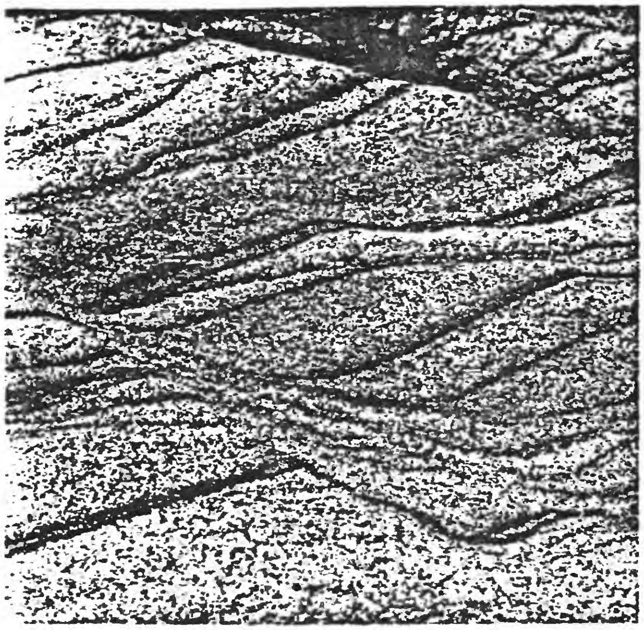


Figure 15. - Photograph of fault offset of graded layers in a nearly consolidated state. The fault dips about 30° away from the viewer and shows normal movement. Layers dip 30° to the left. Loc. 2.

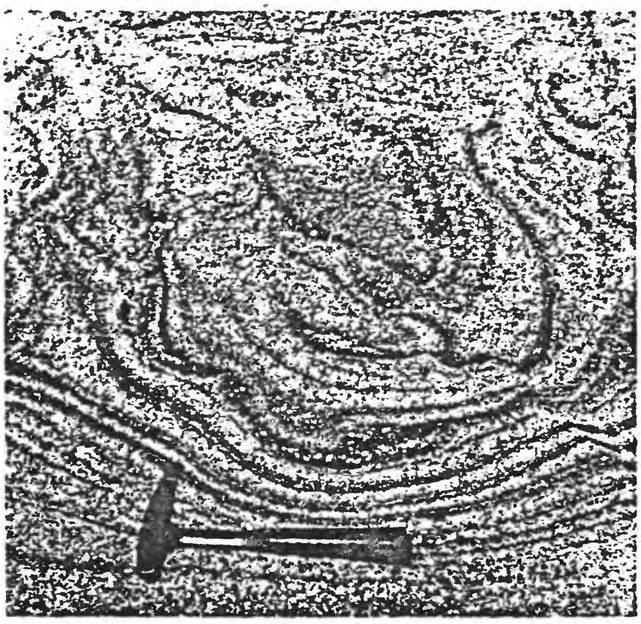


Figure 16. - Photograph of "soft-sediment" deformation of graded layers in a semiconsolidated state. The feature shown here has the character of a load structure. Loc. 2.

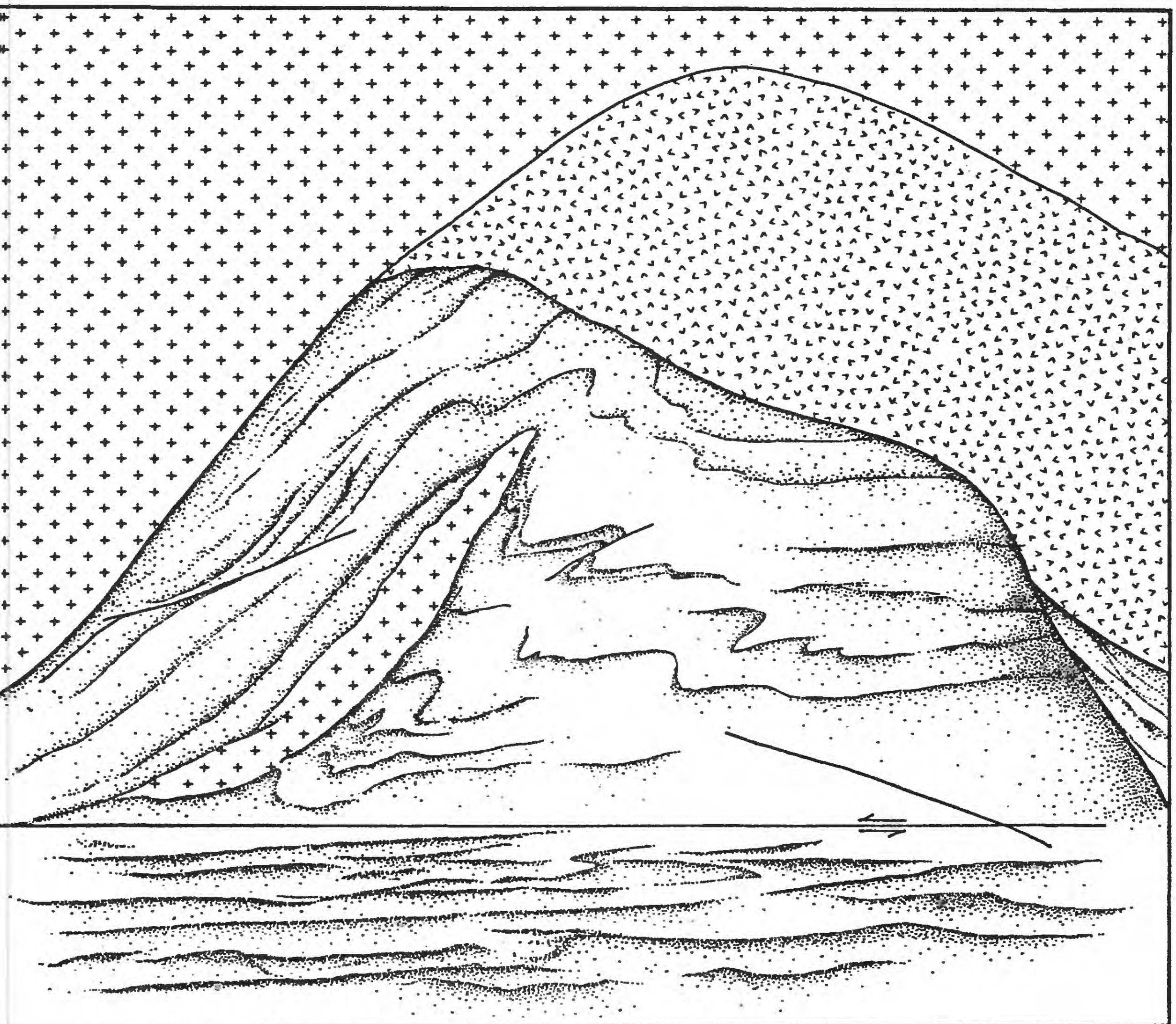
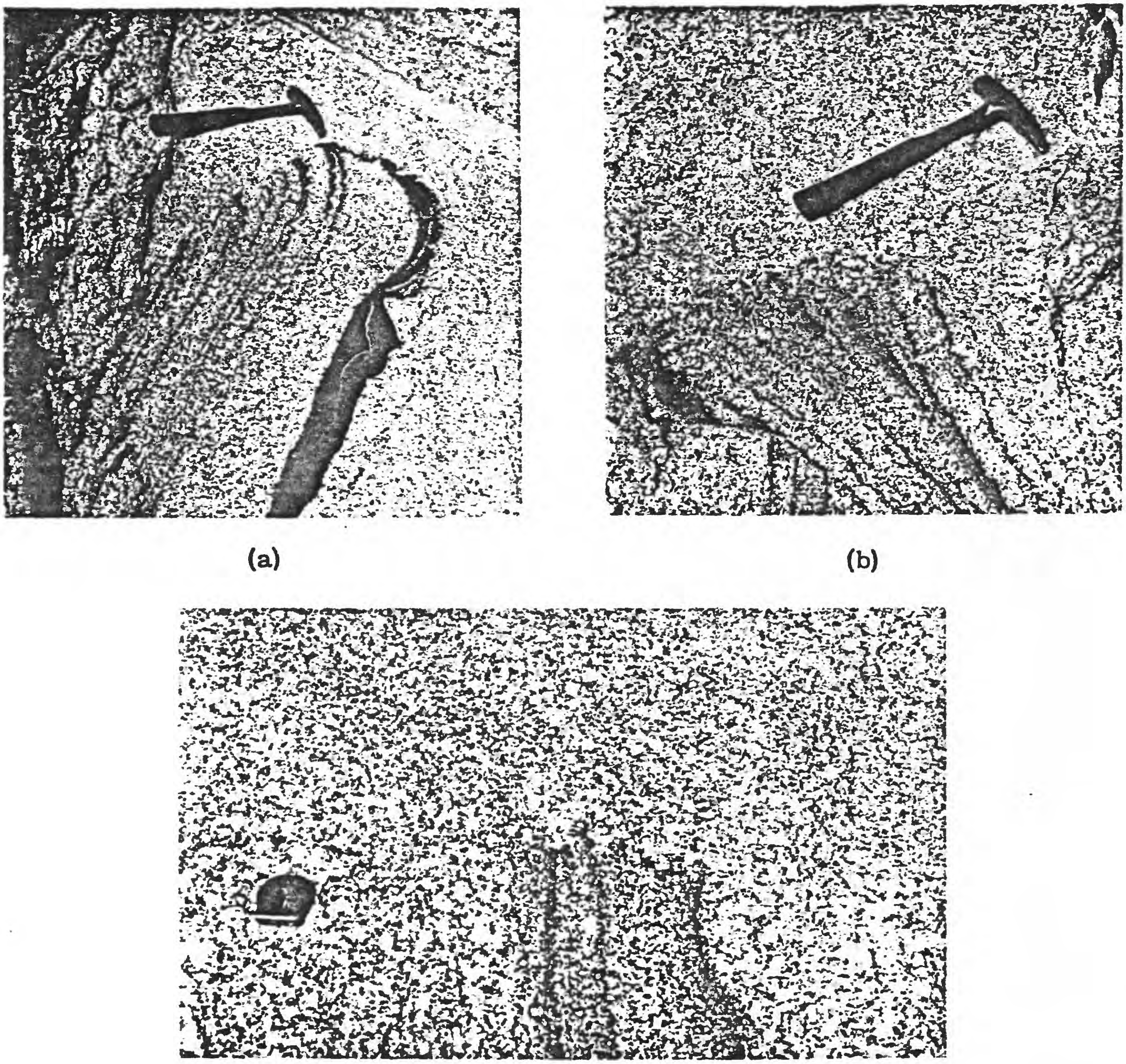


Figure 17.- Drawing of complexly deformed and faulted graded layers intruded by two different phases (shown by patterns) of Al Hadah quartz monzonite at loc. 5. The deformation and faults are directly related to the intrusive phases. Width of drawing is 3 m.



(a) (b) (c)

Figure 18. - Photographs showing details of contact between the zone of disrupted graded layering (loc. 5) and overlying coarse-grained quartz monzonite. Note the truncation of layers (a, b, c), the sharp intrusive contact parallel the hammer handle (b), and elongate xenolith at the contact (a). The intrusive material shown here is approximately parallel to the layered zone and the main intrusive contact at loc. 7.

Figure 19. - Photograph of layered slab in overlying nonlayered unit, loc. 5, showing small xenoliths near dark layers at the top of the slab. The slab shows arcuate deformation and probably slid or was stoped off the main layered zone during minor tectonism following deformation of the layered unit.

Petrography

Outcrop analysis

Modal analysis of the main layered zone at loc. 1 was conducted by point counting on the outcrop. A lined plastic grid was placed over the layers and counts were made parallel to layers, with 5 mm spacing between points and 1 cm spacing between count lines. Forty counts were made on each line. By this procedure a continuous modal analysis of 21 graded layers and control areas below and above the zone (fig. 6) was accomplished. Additional control counts were made at spot localtions several meters above and below the layered zone.

Figure 20 shows a moving average of the modal distribution by count line through the layered zone. This plot shows the layers to be defined by abrupt increase in plagioclase and mafic minerals at the base of the layers followed by a rapid drop of mafic minerals generally within 1-3 cm into a zone dominated by plagioclase and quartz (figs. 21, 22). This zone is succeeded upward by a zone of potassium feldspar with subordinate quartz and plagioclase and traces of mafic minerals.

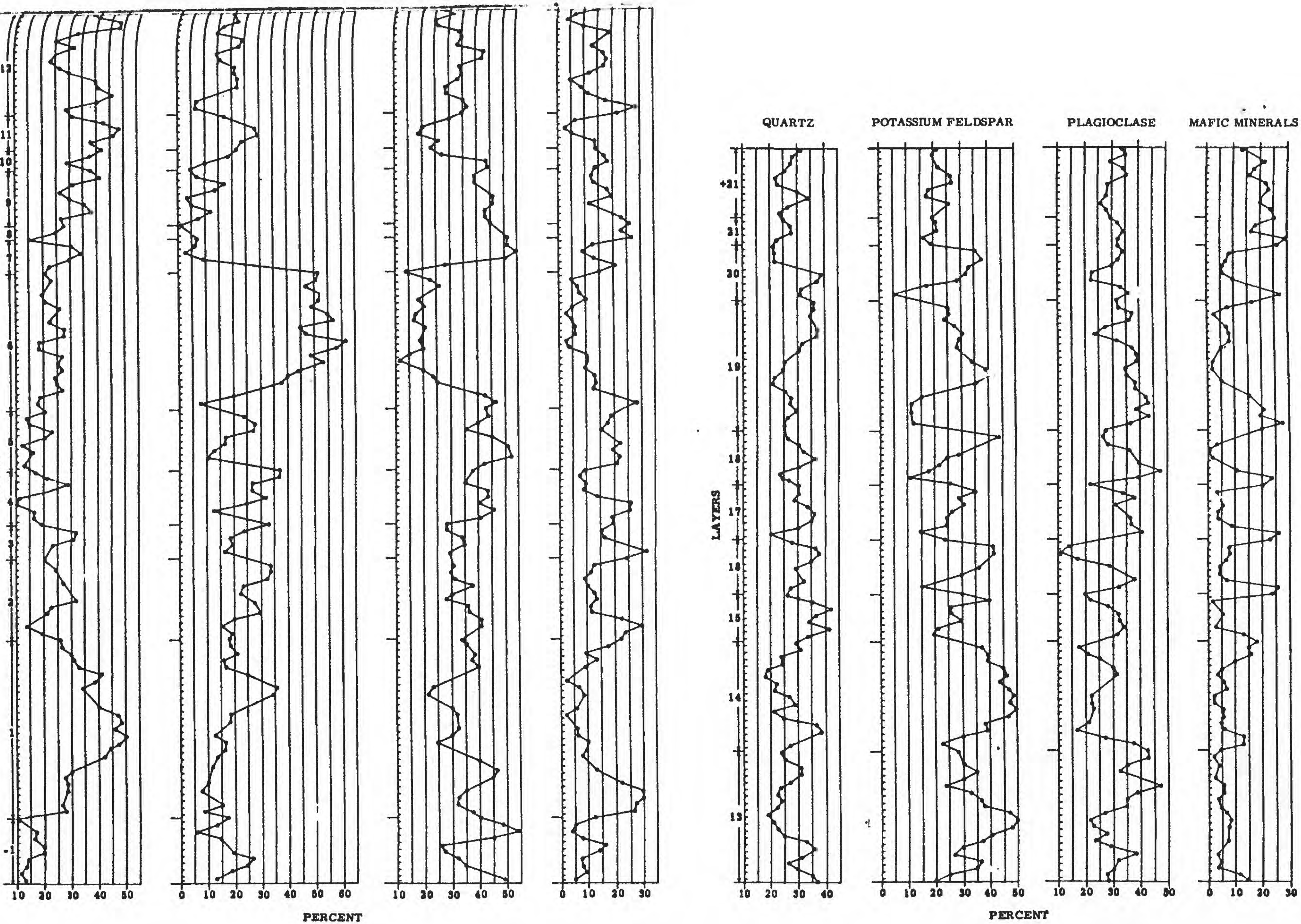


Figure 20. - Linear modal plot of quartz, potassium feldspar, plagioclase, and mafic minerals from outcrop petrographic analysis of layered zone at loc. 1. Modal counts -1 and +21 indicate nonlayered areas analyzed, respectively, below and above the layered zone.

Transitions between plagioclase and quartz and overlying potassium feldspar-quartz-plagioclase zones are gradational.

Ternary plots (fig. 23) of individual layers show a general pattern, starting with quartz diorite to granodiorite at the base and shifting to quartz monzonite to granite in the upper part of the layers. A summary plot (fig. 23) of all layers shows that the average composition of each layer ranges from granodiorite to quartz monzonite.

Laboratory analysis

A sample of layers 14 through 19 was sliced for detailed laboratory analysis. Only these layers could be sampled. Obtaining samples from the entire layered zone at loc. 1 would have required blasting, which was not practical. Serial thin sections were prepared from one of the slabs (fig. 24) and phenocrysts were traced (fig. 25) from another slab 1 cm thick parallel to the one from which the thin sections were made. Modal data from the thin sections are given in table 3; quartz and feldspar are grouped because modal data for the primary minerals from layers 14-19 are presented in figures 20 and 23. Mafic and heavy-mineral data data are summarized in table 4.

Plagioclase.-- Plagioclase, more abundant near the base of the layers, generally forms interlocking laths of anhedral grains with quartz and potassium feldspar as rare large (10-14 mm) phenocrysts. Zoned plagioclase generally is found throughout the graded layers. Normal zoning of plagioclase appears to be most typical, but some oscillatory zoning is indicated by alternating zones of saussurite. In normally zoned grains, the cores are in general moderately to strongly saussuritized, followed by clear rims of twinned and untwinned, nonsaussuritized plagioclase. Most twinning is of the albite law, but Carlsbad and pericline twinning are common. Rapakivi plagioclase rims are commonly myrmekitic. The rims are about equally thick between the bottoms and tops of the graded layers. Some rapakivi rims are doubly or triply zoned, having alternating saussuritized (calcic) zones followed by clear nonsaussuritized (sodic) zones. Myrmekite is found only with generally unaltered untwinned plagioclase. The anorthite composition is chiefly oligoclase, ranging from An_{24} to An_{30}. Anorthite determinations by the Michel-Levy method show no appreciable differences between the bottoms and tops of the graded layers.

Potassium feldspar.--Potassium feldspar is mainly a complex intergrowth of microcline and perthite, but both pure microcline and perthite phenocrysts are common. Phenocrysts, qhich are more commonly microcline, are generally 5-10 mm long, but range to 13 mm long. The potassium feldspar is subhedral to euhedral, is abundantly rimmed by clear twinned and untwinned rapakivi plagioclase, and is extremely fresh, showing only slight kaolinization.

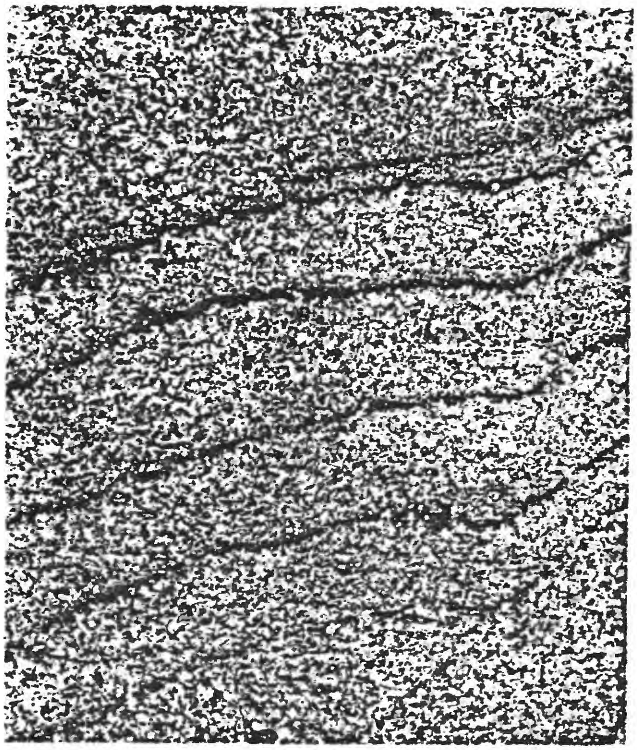


Figure 21.- Photograph of uniform graded layers at loc. 1. Note the progressive decrease in mafic minerals upwards from the base of each layer.

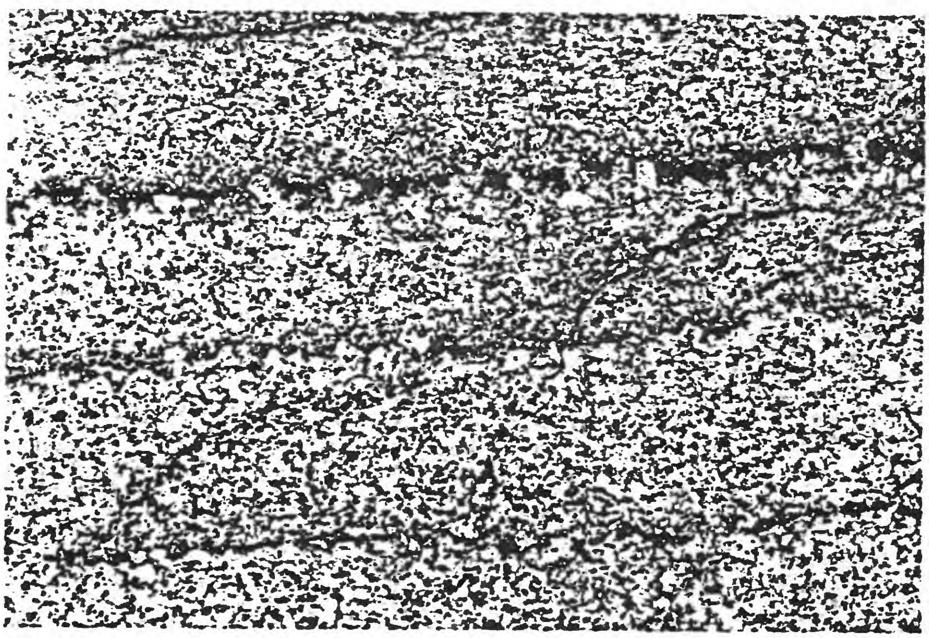


Figure 22.- Close-up photograph of graded layers at loc. 1 showing rapakivi texture (potassium feldspar mantled by plagioclase) at the top of some layers.

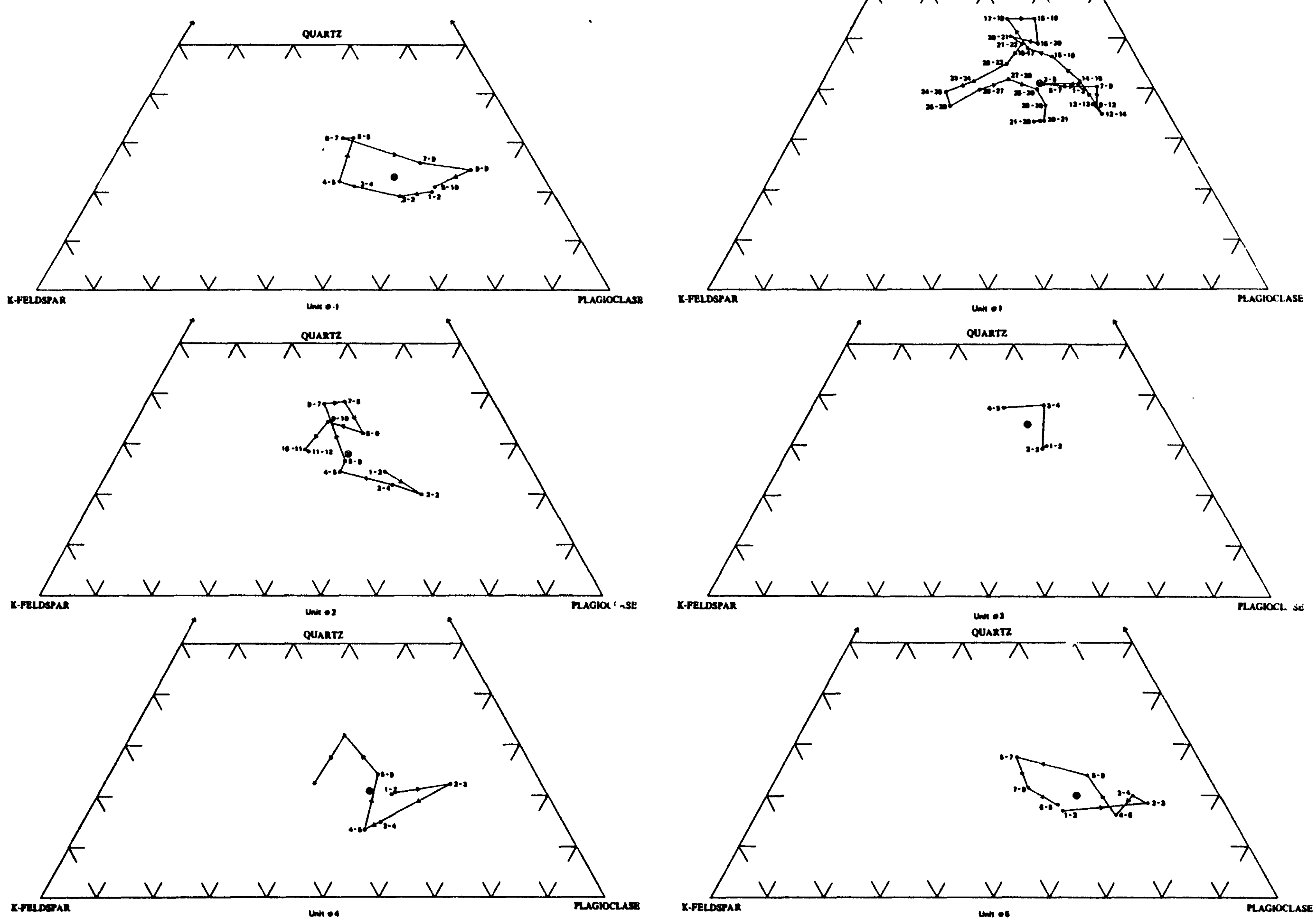


Figure 23. - Modal compositions of the 21 graded layers and nonlayered rock below (unit -1) and above (unit +21) analyzed in the field at loc. 1. The last diagram is a summary plot for all layers (-1 to +21). The numbers, excluding the summary ternary diagram, represent the line number on the grid. Modal counts -1 and +21 indicate nonlayered areas analyzed, respectively, below and above the layered zone. ⊗ represents the average composition of each layer or nonlayered area (-1 and +21).

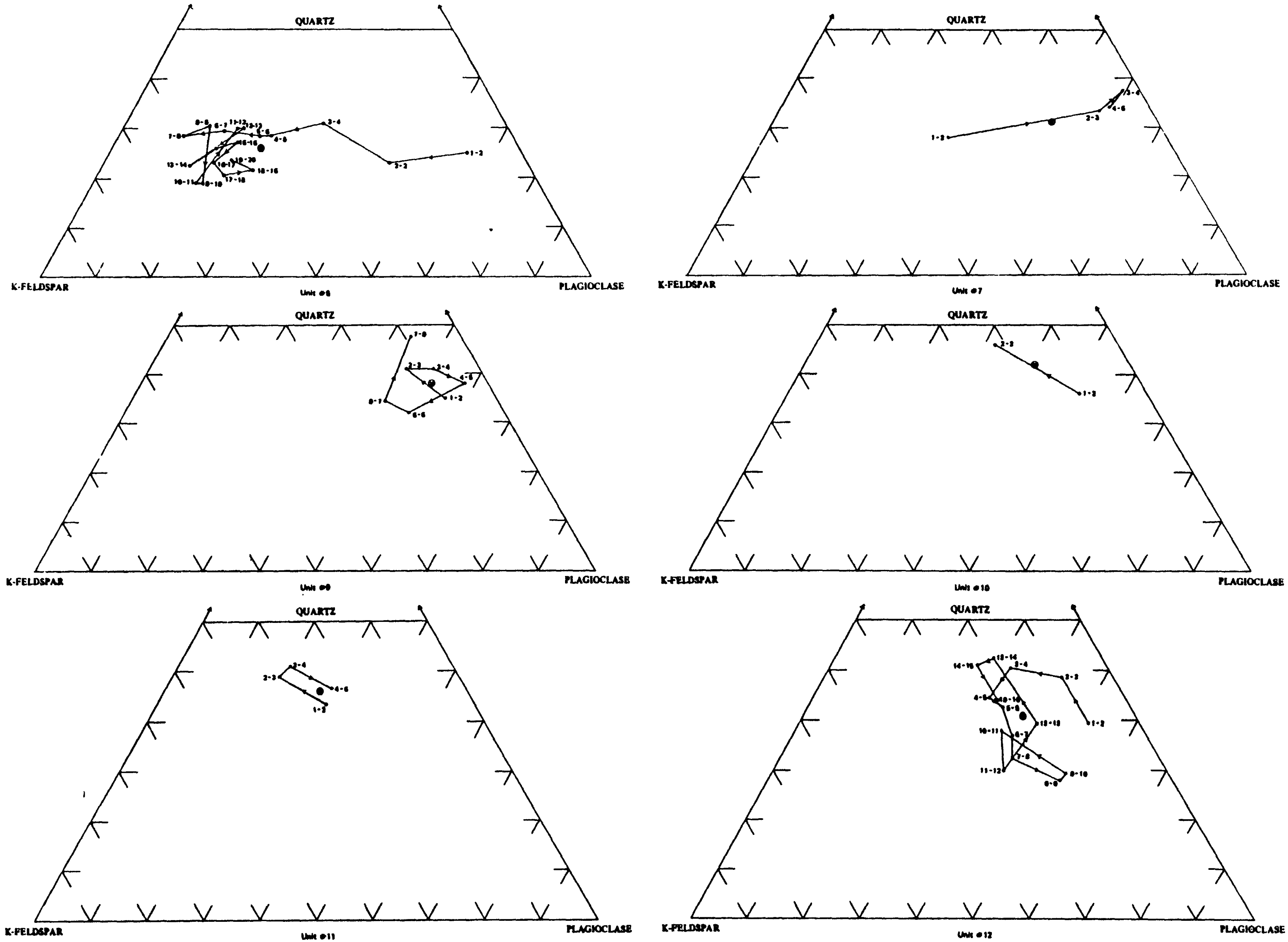


Figure 23. - Modal compositions of the 21 graded layers and nonlayered rock below (unit -1) and above (unit +21) analyzed in the field at loc. 1 - Continued.

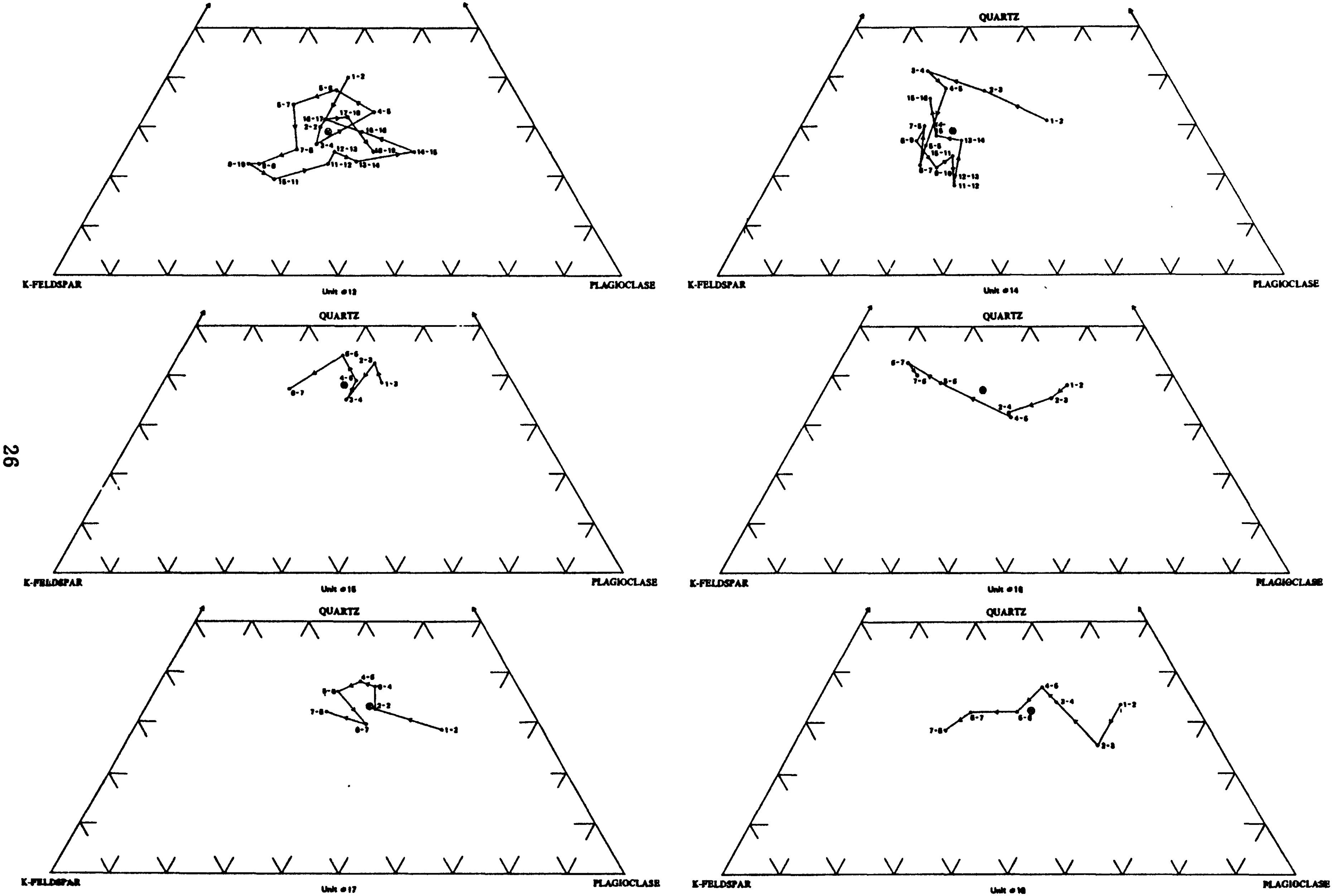


Figure 23. - Modal compositions of the 21 graded layers and nonlayered rock below (unit -1) and above (unit +21) analyzed in the field at loc. 1 - Continued.

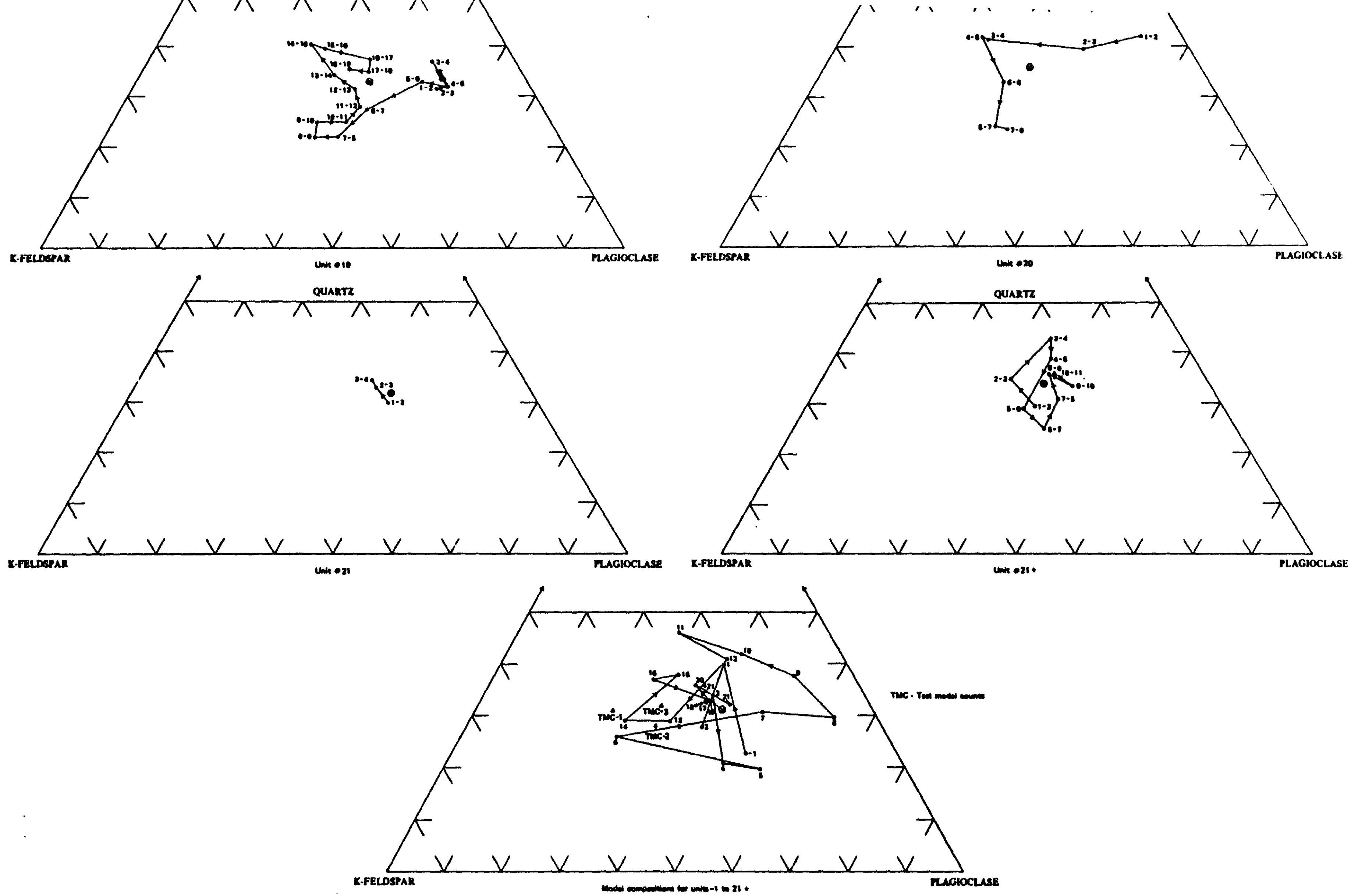


Figure 23. - Modal compositions of the 21 graded layers and nonlayered rock below (unit -1) and above (unit +21) analyzed in the field at loc. 1 - Continued.

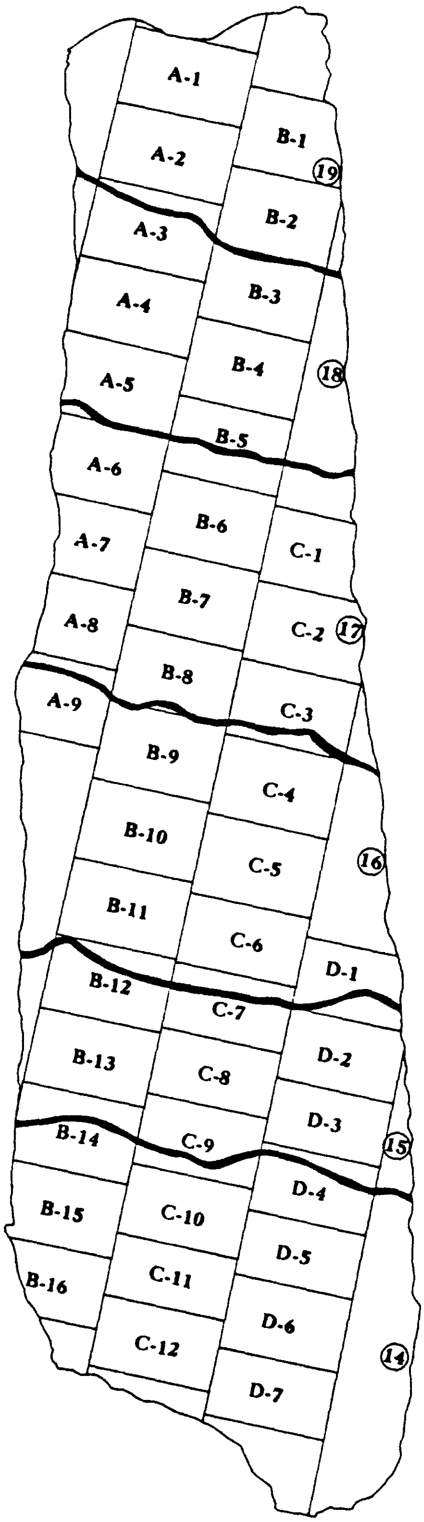


Figure 24. - Slabbed sample of graded layers 14-19 used for laboratory petrographic analysis, showing how serial thin sections were cut. Sample from outcrop at loc. 1.

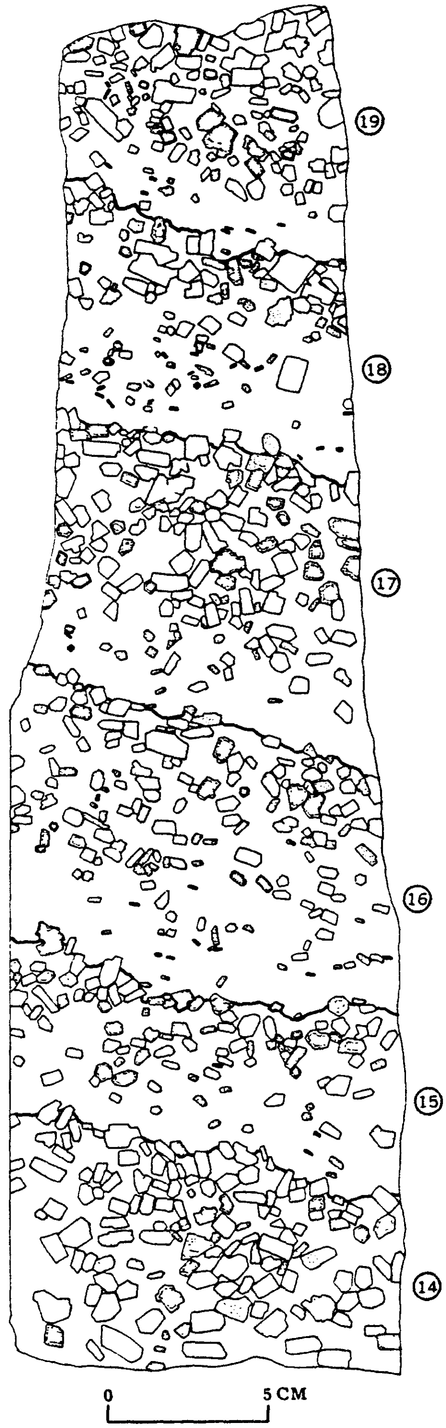


Figure 25. - Plagioclase (stippled) and potassium feldspar (clear) phenocryst trace from a slab cut parallel to that shown in figure 24. Note the common rapakivi phenocrysts.

Table 3. Laboratory modal analysis data of some thin sections prepared from the slab shown in figure 24.

Slide No	A-1	A-2	A-3 LP[1]	A-3 LP[2]	A-4	A-5	A-6	A-7	A-8	B-1	E
Mineral											
Feldspar & Qtz.	96.5	94.8	97.3	86.6	94.4	94.1	95.0	99.5	96.5	96.0	92
Biotite	2.9	3.3	0.6	9.2	2.2	4.0	3.9	0.2	2.5	2.4	5
Hornblende	0.2	0.8	0.3	0.9	2.4	0.3	0.3	--	0.4	0.9	0
Zircon	--	--	--	0.5	--	--	--	--	--	--	-
Sphene	--	0.2	--	0.9	0.4	0.3	0.2	0.2	0.4	0.3	0
Apatite	--	--	0.3	0.4	0.2	--	--	--	--	--	-
Allanite	--	--	--	--	--	0.3	--	--	--	0.2	0
Magnetite	--	--	0.9	1.4	0.2	0.3	0.5	0.5	--	--	-
Chlorite	0.4	1.1	0.6	--	0.4	0.8	--	--	--	--	0
Total	100.0	100.1	100:0	99.9	100.2	100.1	99.9	100.4	99.8	99.8	99
No. point counts	510	643	330	217	637	378	621	429	483	586	54

Slide No.	B-3	B-5 LP	B-5 UP	B-7	B-8 LP	B-8 UP	B-9	B-10	B-11	B-12 LP	B-UI
Mineral											
Feldspar & Qtz.	96.4	98.5	76.1	97.5	91.8	97.9	97.5	95.8	94.9	94.6	88.
Biotite	2.6	1.4	17.2	2.1	2.6	1.8	0.4	2.7	4.3	3.2	8.
Hornblende	0.3	0.5	3.9	--	4.6	0.3	1.3	0.7	0.1	0.8	1.
Zircon	--	--	0.4	0.2	--	--	--	--	--	0.3	--
Sphene	--	--	0.8	0.2	1.0	--	--	--	--	0.3	0.
Apatite	--	--	0.4	--	--	--	--	0.1	0.1	--	--
Allanite	--	--	0.8	--	--	--	--	--	--	--	--
Magnetite	0.5	--	Tr	--	--	--	--	--	--	--	0.
Chlorite	0.7	--	--	--	--	--	1.0	0.4	0.5	0.3	0.
Total	100.5	100.0	99.7	100.0	100.0	100.0	100.2	99.7	99.9	99.5	99.
No. point counts	566	218	487	537	194	325	476	671	740	373	295

Slide No.	B-13	B-14 UP	C-1	C-4	C-5	C-6	C-7 UP	D-2	D-3	D-4 UP
Mineral										
Feldspar & Qtz.	90.8	89.6	97.0	99.2	96.2	96.0	87.0	95.5	96.5	90.0
Biotite	8.0	9.1	2.2	0.1	2.4	3.6	12.0	2.5	2.1	7.8
Hornblende	0.9	0.4	0.5	0.1	0.8	0.2	--	1.3	0.7	2.2
Zircon	--	--	--	--	--	--	--	Tr	--	--
Sphene	0.4	0.4	--	0.1	0.2	0.1	0.8	0.3	0.2	--
Apatite	--	--	--	--	--	--	--	Tr	--	--
Allanite	0.2	0.4	--	--	--	--	--	--	--	--
Magnetite	--	--	0.2	0.1	0.2	--	--	--	--	--
Chlorite	--	--	0.2	0.2	0.3	0.1	0.3	Tr	0.5	--
Total	100.3	99.9	99.9	99.8	100.1	100.0	100.0	99.6	100.0	100.0
No. point counts	563	221	589	649	613	579	357	673	578	409

1. LP - Lower part of slide 2. UP - Upper part of slide

Table 4. Summary of mafic and heavy mineral modal analyses (in percent) based on data from table 3.

Layer number	Part of layer	Biotite	Hornblende	Zircon + Allanite	Sphene	Magnetite
		Minerals and sense of grading				
19	Upper Lower	2.7 7.3 N[1]	0.5 0.8 N	0.1 0.3 N	0.2 0.5 N	0.0 0.4 N
18	Upper Lower	1.6 10.6 N	0.2 2.1 N	0.0 0.8 N	0.2 0.6 N	0.5 0.2 R
17	Upper Lower	2.5 2.3 R[2]	0.4 1.8 N	0.0 0.0 -	0.1 0.6 N	0.1 0.0 R
16	Upper Lower	0.3 10.4 N	0.7 0.9 N	0.0 0.0 -	0.1 0.7 N	0.1 0.0 R
15	Upper Lower	2.9 8.5 N	1.0 1.3 N	0.1 0.0 R	0.3 0.3 -	0.0 0.2 N
Range of all layers	Upper Lower	0.1-3.2 4.0-17.2	0.1-1.3 0.1-3.9	0.0-0.3 0.0-1.2	0.0-0.3 0.0-1.0	0.0-0.9 0.0-1.4
Average of all layers	Upper Lower	2.0 7.8	0.6 1.4	0.1 0.2	0.2 0.5	0.1 0.2

1. N - Normal (decreasing concentration upward) 2. R - Reversed

Quartz.--Quartz ranges from anhedral and interstitial in the lower parts of the layers to euhedral and phenocrystal in the upper parts. Grains have a maximum length of 8 mm. The quartz exhibits nonundulose to moderately undulose extinction, and generally is very weakly undulose. Quartz is approximately as abundant in the lower parts of the layers as the upper parts (fig. 23).

Biotite.--Most biotite is subhedral, but euhedral grains are common. Grain size ranges from 0.1 to 1.7 mm. Pleochroism is strong, ranging from light brownish green to dark brownish green and from light greenish yellow to deep green. A few grains are altered to chlorite. Euhedral zircon crystals in biotite are surrounded by darkened radioactive halos.

Hornblende.--Hornblende grains are subhedral to mainly euhedral and strongly pleochroic, ranging from pale to medium to deep green. They range from 0.1 to 1.8 mm long. Small to abundant amounts of anhedral magnetite grains are commonly enclosed by hornblende.

Accessory and secondary minerals.--Accessory and secondary minerals and their percentages are shown in table 3. They generally constitute less than 2 percent of a whole graded layer. Sphene is the most abundant of the heavy accessory minerals followed by magnetite and allanite. Sphene crystals 0.1 to 2.0 mm long, are mainly euhedral. Magnetite is anhedral for the most part and forms small (less than 0.05 mm) grains within hornblende. Allanite is euhedral, strongly zoned, and ranges from 0.2-0.8 mm long. The layers also contain small amounts of apatite, zircon, and chlorite. Trace amounts of calcite, epidote, sericite, and interstitial fluorite were seen in a few slides but are not recorded in table 3.

Summary.--The graded layers analyzed in the laboratory (14-19) are assumed to be petrographically representative of the whole layered zone. Phenocrysts begin to increase in size and quantity 2 to 4 cm above the base of each layer (fig. 25). Biotite and hornblende show a general quantitative decrease upward from the base of each layer (figs. 20-22, table 4). Heavy minerals, with some exceptions and excluding magnetite, show a general reduction in concentration upward from the base of each layer. For example, sphene is 3-5 times more abundant in the lower parts than in the upper parts of most layers (table 4). There are some gross changes between layers 15 and 19 of the same general sense. For example, there is more biotite and hornblende in layer 15 than in layer 19. This relationship, however, is not apparent for the heavy minerals.

DISCUSSION AND ORIGIN OF LAYERS

Several different mechanisms have been proposed in the literature for the origin of layering in igneous rocks (table 5). Most authors subscribe to the deposition of igneous layers in granitoid rocks by dynamic fluid currents. In mafic intrusions formation of layering by convection currents (Grout, 1926), by gravity settling influenced by convection currents (Wager, 1953, 1963; Wager and Brown, 1967; Wager and Deer, 1939), and by differentiation and gravity settling of successively introduced batches of magma (Coleman and others, 1973) have been proposed, but these mechanisms do not seem applicable to the Al Hadah pluton.

To test the gravity settling mechanism and its applicability to Al Hadah layering, settling rates were calculated by using the average crystal sizes measured and the crystal settling curves of Shaw (1965, fig. 3) for a liquid with a viscosity of 10^6 poises. The minerals were treated as spheres and for the sizes indicated, the following rates were obtained: biotite and hornblende (2 mm diameter, 0.7 m/yr; plagioclase (2 mm and 16 mm diameters), 0.4 and 3 m/yr; and potassium feldspar (2 mm and 10 mm diameters), 0.2 and 5 m/yr. These calculations indicate that fine-grained mafic minerals cannot be concentrated from coarse feldspars by gravity settling alone.

Layering in the Al Hadah pluton is considered to have formed by deposition of crystals suspended in low-density low-viscosity currents of granitic magma. Flow differentiation appears to have produced the compositional trends seen in the individual layers. The mechanism envisaged herein is similar to the mechanism postulated for genesis of layering in the Twin Lakes granodiorite (Wiltshire, 1969), and in terms of deposition by fluid currents (no entrained crystals), the mechanism is similar also to that proposed by Moore and Lockwood (1973) for layering in the Sierra Nevada batholith. However, field relations and character of the layering in these three areas differ in several ways, and for these reasons have been compared and contrasted (table 6).

The chief similarity between the Al Hadah, Twin Lakes, and Sierra Nevada layering is deposition of the layers near contacts of the intrusive bodies. The principal difference is that the Twin Lakes and Sierra Nevada layers accumulated on the country rock walls and accreted away from the country rock toward the magma chamber, whereas, Al Hadah layers were deposited on a partly or wholly crystalline granitoid substrate and were successively deposited toward the country rock (fig. 26). Fluid igneous currents generated at depth probably rose along the border of the pluton during a late phase of emplacement in the manner described by Wiltshire (1969) and Moore and

Table 5. - Mechanisms proposed for the origin of layering in igneous rocks

Mechanism	Layering type	Rock type	References
Gravity accumulation from fluid, highly volatile magma, affected by unspecified magmatic currents	Rhythmic	Granitoid	Gilbert (1906), Sherlock and Hamilton (1958), Harry and Emeleus (1960), Harry and Pulvertaft (1963). Emeleus (1963), Ferguson and Pulvertaft (1963).
Shearing of inhomogeneities in magma	Rhythmic(?)	Granitoid	Balk (1937)
Deposition by convection currents	Rhythmic	Mafic rocks	Grout (1926)
Gravity settling influenced by convention currents	Rhythmic, cryptic	Primarily gabbro	Wager (1953, 1963), Wager and Brown (1967), Wager and Deer (1939)
Flow sorting	Rhythmic	Granitoid	Bateman and others (1963), Wilshire (1969).
Inward deposition along contacts between wallrock and solidified magma by upward flow of low density, low viscosity aqueous fluid	Comb, schlieren	Gabbro to quartz monzonite, but mostly diorite.	Moore and Lockwood (1973)
Outward deposition by flow differentiation currents	Reversely size graded; normally graded with respect to mafic and heavy minerals	Primarily quartz monzonite, but includes quartz diorite, granodiorite, and granite.	This paper

Table 6. - Comparison of layering in the Twin Lakes granodiorite, Colorado, Sierra Nevada batholith, California, and the Al Hadah pluton

Formation	Layering type	Layer description	Location of layering	Attitude of layers	Mafic minerals	Mineral orientation	Mineral concentration	Layer compositional changes	Individual layer composition	Direction of layer deposition	Depositing mechanism
Sierra Nevada Batholith	Comb Schlieren	Comb: Granitoid layers in which the constituent minerals (primarily plagioclase and hornblende) are oriented about perpendicular to the plane of layering. Schlieren: Granitoid layers alternately enriched or depleted in mafic minerals elongated parallel to the plane of layering.	At or near contact with country rock	Vertical to steeply dipping (commonly overhanging)	Hornblende	Perpendicular and parallel to plane of layering.	None	Mafic mineral-rich and mafic mineral-poor layers commonly alternate	Uniform	Toward intrusion	By aqueous fluid currents; no suspended minerals
Twin Lakes Colorado	No term given	Granitoid layers consisting of minerals segregated in bands and lenses of contrasting color and grain size.	At or near contact with country rock	Mostly vertical	Biotite and minor hornblende	Irregular	Graded from base to top	Layers maybe enriched in mafic minerals, orthoclase, or plagioclase.	Commonly graded with respect to mafic minerals and feldspars	Toward intrusion	By flow differentiated currents; mafic minerals and feldspars in suspension.
Al Hadah pluton Saudi Arabia	Graded	Granitoid layers, each layer of which is normally or reversely graded from bottom to top in terms of modal concentration with respect to the constituent minerals.	At or near contact with country rock	Moderately dipping	Biotite and sparse hornblende	Irregular	Graded from base to top	Layers are uniform in composition	Invariably graded from mafic and plagioclase-rich bases to mafic poor and K-spar rich tops	Toward country rock.	By flow differentiation currents; mafic minerals and feldspar in suspension.

Lockwood (1973). In the case of Twin Lakes and the Sierra Nevada batholith, the intrusive bodies were probably emplaced into colder country rock relative to the intrusive cores and therefore layers were deposited inward and away from the country rock contact (fig. 26). In the Al Hadah pluton, field evidence indicates that the layers were deposited on partly to wholly crystalline rock. Partial subsidence of the core may have opened a channel way at the margin of the nearly crystalline Al Hadah pluton. The country rock adjacent to the channel way probably was hot. Gravitative forces appear to have favored layer deposition on the foundered core and toward the country rock contact in the outward-sloping channel way (figs. 26, 27).

Al Hadah layering is interpreted to have formed as follows. Flow differentiation currents produced a concentration of mafic and heavy minerals and fine-grained plagioclase at the bases of the layers and a concentration of coarse-grained plagioclase and potassium feldspar at the tops of the layers. This size segregation suggests that some crystals were being carried in suspension and were sorted by a mechanical process (table 6). One result of the sorting process is the general compositional shift from quartz diorite and granodiorite in the lower parts of the layers to quartz monzonite and granite in the upper parts (fig. 20). From experimental evidence, coarse-grained particles under laminar flow conditions migrate toward the zone of minimum shear stress (Bagnold, 1954, p. 62; Simkin, 1967, p. 64-69). In the Al Hadah layers, this zone was the outward (nearest the country rock contact) part of the layers (fig. 27). Hence, the outward parts of the layers contain the coarsest minerals. Potassium feldspar was the earliest of the primary minerals to crystallize in the Al Hadah magma chamber and therefore became the largest grained (fig. 25). As it was supplied to the layered zone entrained in the low-viscosity currents, it was concentrated outward, producing mechanically differentiated layers. In addition to laminar flow conditions that operated to concentrate fine-grained minerals (mafic and heavy) at the base of layers, large zircons, sphene, and allanite were also concentrated downward (table 4), probably by gravity settling because the densities of these minerals differed so greatly from the density of the currents that gravity overcame the mechanical processes responsible for size sorting of the feldspars.

In the main layered zone, the layers are remarkable uniform in composition and character of grading throughout, the only difference being the thickness of the layers. This suggests that changes in physical or chemical properties of the current fluids were not rapid during deposition. Relatively abrupt stops in the supply of the currents took place periodically which marked the end of one layer and the start of another. Once one layer was deposited, however, the material supplied to the next was the same as the preceding one. The thickness of a given layer probably was a function of the duration of current supply.

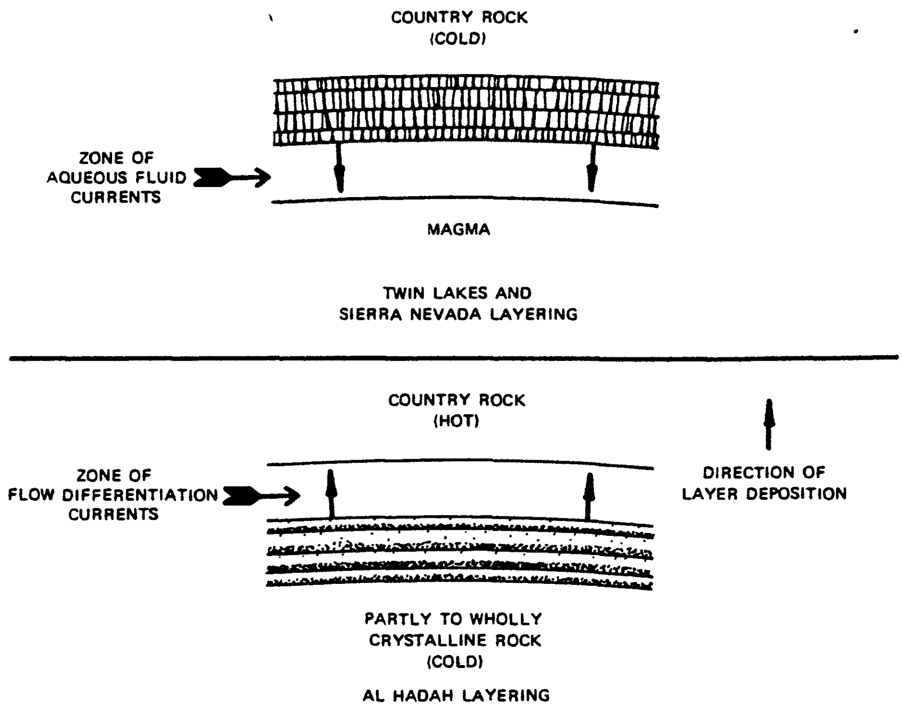


Figure 26. - Field relation of layered rock at Twin Lakes, Colorado, in the Sierra Nevada batholith, California, and in the Al Hadah pluton, Saudi Arabia. For simplicity, layering in the upper part of this figure represents only comb layering.

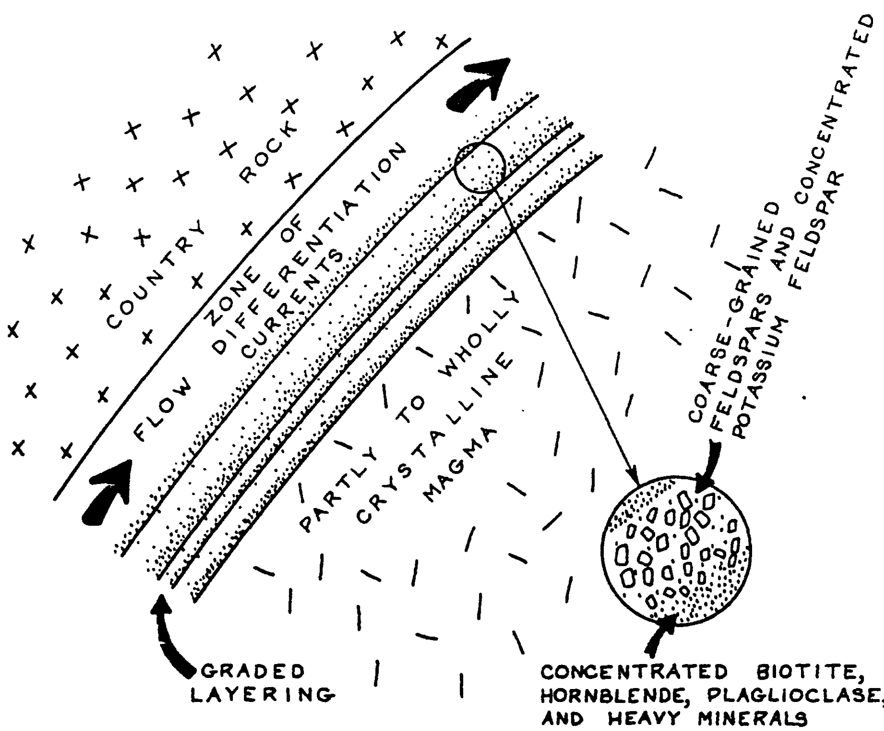


Figure 27. - Hypothetical illustration showing the geologic conditions proposed for origin of the Al Hadah graded layering by deposition of graded layers in a low viscosity fluid zone on partly to wholly crystallized granodiorite-quartz monzonite.

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