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Joints in Precambrian Rocks Central City-Idaho Springs Area, Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 374-B

Prepared on behalf of the U.S. Atomic Energy Commission and published with the permission of the Commission

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Joints in Precambrian Rocks Central City-Idaho Springs Area, Colorado

By J. E. HARRISON *and* R. H. MOENCH

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

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JOINTS IN PRECAMBRIAN ROCKS, CENTRAL CITY-IDAHO SPRINGS AREA, COLORADO

By J. E. Harrison and R. H. Moench

ABSTRACT

Attitudes of about 9,000 joints in Precambrian intrusive and metasedimentary rocks in the 50-square-mile area studied reveal that some joints sets are systematically distributed. Each of the principal Precambrian intrusive masses contains primary joints. Joints related to folds have formed during two periods of Precambrian deformation and probably during Laramide (Late Cretaceous and early Tertiary) arching of the Front Range.

A time sequence of geologic events and jointing can be worked out as follows: First, granodiorite was intruded during the older Precambrian deformation; primary joints formed in the granodiorite, and joints related to sinuous and doubly plunging folds formed in the metasedimentary rocks. Second, biotite-muscovite granite was intruded late in an older period of Precambrian deformation; primary joints formed in the granite. Third, Precambrian metamorphic and igneous rocks were locally deformed during a younger period of Precambrian folding; joints related to this folding formed in all Precambrian rocks, and a unique set of slickensided joints formed predominantly in the more massive granitic rocks. Fourth, a system of four joint sets was formed that locally cuts Precambrian rocks but not the Tertiary rocks that intrude them. Joints of this system were locally followed by Tertiary dikes, and therefore can be dated in outcrop only as post-Precambrian but pre-Tertiary. The conformity of the system with that expected from arching of the Front Range highland leads us to conclude that the post-Precambrian system probably is Laramide in age.

INTRODUCTION

The Central City-Idaho Springs area is about 30 miles west of Denver and is a small part of the Front Range of Colorado (fig. 1). The area was mapped in detail during the field seasons of 1952–54 as part of the U.S. Geological Survey's studies on behalf of the Division of Raw Materials of the U.S. Atomic Energy Commission. The principal purpose of the study was an exhaustive investigation of the geology of the uranium-bearing veins, and this report presents only a small part of the data gathered during the investigation.

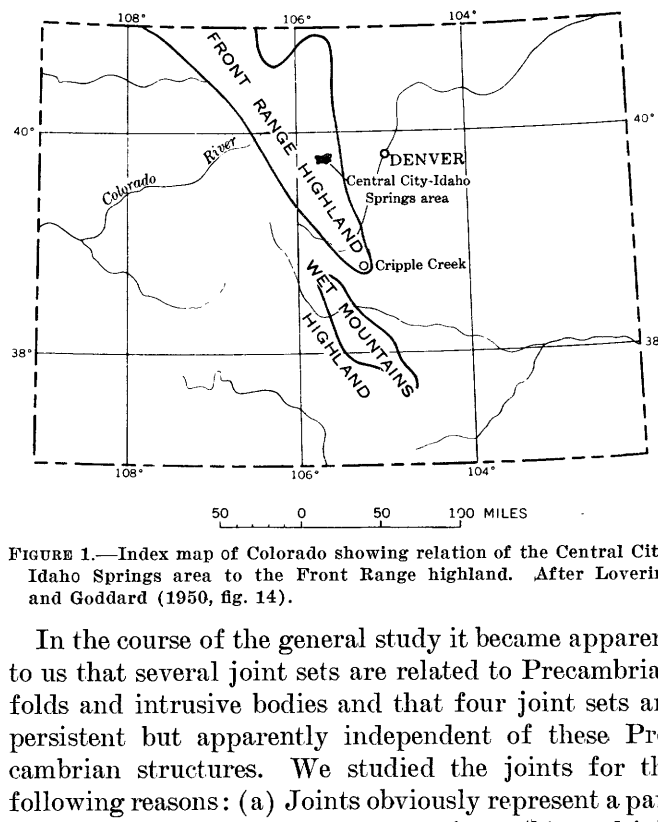

Figure 1.—Index map of Colorado showing relation of the Central City-Idaho Springs area to the Front Range highland. After Lovering and Goddard (1950, fig. 14).

In the course of the general study it became apparent to us that several joint sets are related to Precambrian folds and intrusive bodies and that four joint sets are persistent but apparently independent of these Precambrian structures. We studied the joints for the following reasons: (a) Joints obviously represent a part of the geologic history of any region; (b) multiple joint sets in rocks of complex structural history have, in our opinion, been ignored too often or dismissed as too complicated to interpret; (c) this discussion may encourage other geologists working in the Front Range to test an hypothesis set forth here concerning a regional joint system; and (d) a comprehensive knowledge of this proposed regional joint system may lead to a better understanding of Front Range tectonics.

The data presented in this report have been drawn from our work and from that of seven of our colleagues. We sincerely thank A. E. Dearth, A. A. Drake, Jr., C. C.

Hawley, F. B. Moore, P. K. Sims, E. W. Tooker, and J. D. Wells for their generous contributions of data and stimulating discussions of the problem. Many details of the geology of the area have been summarized from data compiled by us and by our colleagues. For the interpretations of the data we, however, accept full responsibility.

The general geology of the area has been described previously in several reports, the most comprehensive of which are three U.S. Geological Survey Professional Papers (Spurr and others, 1908; Bastin and Hill, 1917; and Lovering and Goddard, 1950).

GENERAL GEOLOGY

The Precambrian bedrock in the Central City-Idaho Springs area consists of a generally conformable series of folded metasedimentary gneisses, metaigneous rocks, and igneous rocks. The Precambrian rocks have been faulted and intruded during Tertiary time by a series of calc-alkalic to alkalic porphyry dikes and small plutons. As this report concerns only the Precambrian rocks, no extensive discussion of the Tertiary intrusive rocks will be given.

A generalized summary of the Precambrian geologic history in the area shows the following events:

1. Precambrian sediments were deeply buried and reconstituted into high-grade gneisses.
2. The foliated metasedimentary rocks were plastically deformed into major folds with north-northeast-trending axes. The deformation was accompanied by the intrusion of granodiorite, and then minor amounts of quartz diorite and associated hornblendite.
3. Biotite-muscovite granite was intruded near the end of the period of plastic folding.
4. Uplift and erosion of several thousand feet of cover.
5. The Precambrian rocks were deformed locally. Where deformed, the more massive rocks were crushed and granulated; the more foliated gneissic rocks were formed into small terrace, monoclinal, or chevron folds; also some foliated metasedimentary rocks were cataclastically deformed.

The major post-Precambrian folding, faulting, and intrusion in the Front Range were strongly influenced by the structural framework established during the Precambrian. The post-Precambrian geologic history, as summarized from Lovering and Goddard (1950, p. 57–63), shows the following principal events:

1. A regional Precambrian anticline was gradually worn down, and sediments accumulated in basins to the east and west. Minor uplift of the arch occurred several times during the Paleozoic, in greatest amount during the Pennsylvanian. During much of the Late Cretaceous epoch, all the Front Range was submerged.
2. The present Front Range was uplifted and arched, generally along the old Precambrian anticline; the arching began in Late Cretaceous time and culminated during the early Tertiary. The bedrock was folded along the margins, faulted, and intruded by porphyry stocks and dikes during early Tertiary time. Mineralization of the Colorado mineral belt accompanied and followed emplacement of most of the intrusive rocks.
3. Minor renewed movement along some of the early Tertiary faults and continued erosion bring the geologic history up to date.

PRECAMBRIAN ROCKS

The Precambrian rocks in the Central City-Idaho Springs area are an interlayered and generally conformable sequence of metasedimentary gneisses, gneissic metaigneous rocks, granite, and pegmatite (fig. 2).

The oldest rocks are metasedimentary gneisses, which are principally biotite-quartz-plagioclase gneiss, sillimanitic biotite-quartz gneiss, and microcline-quartz-plagioclase-biotite gneiss. Minor amounts of lime-silicate gneiss, cordierite-bearing gneiss, quartz-magnetite gneiss, and amphibolite are also found in the area, and these form lenses or pods in the more abundant biotite-rich gneisses and microcline-bearing gneiss. The mineral assemblages in the metasedimentary gneisses are those described by Turner (1948, p. 76–88) for several subfacies of the amphibolite facies.

The granite gneiss and pegmatite unit consists principally of granite and granite pegmatite that grade into each other and into the metasedimentary gneisses. The unit is virtually conformable and forms large mappable units as well as thin layers in the biotite-rich metasedimentary gneisses. This unit is probably of metasomatic origin.

The metasedimentary gneisses and the granite gneiss and pegmatite are cut by a series of younger intrusive plutons, sills and dikes. The oldest of this series, a medium- to coarse-grained granodiorite, is correlated with the Boulder Creek granite of Lovering and Goddard (1950, pl. 2). The next younger intrusive rock, quartz diorite and associated hornblendite, is fine grained to coarse grained and forms scattered small bodies and dikes. Much of the granodiorite and quartz diorite has undergone some retrograde metamorphism. The youngest intrusive Precambrian rocks are the biotite-muscovite granite and its associated pegmatites. The biotite-muscovite granite is a fine- to medium-grained and seriate biotite-muscovite granite that is probably correlative with the Silver Plume granite, the

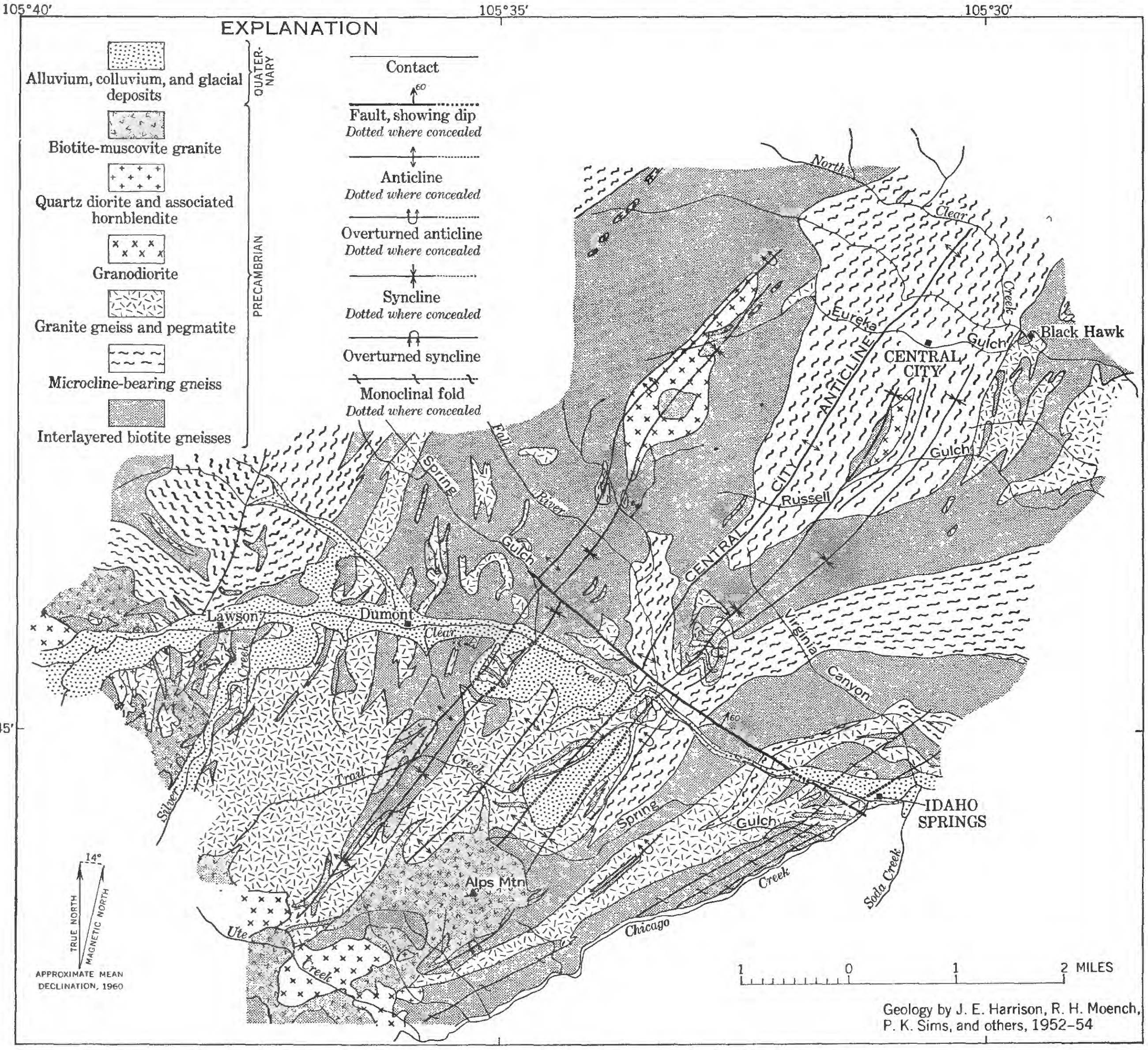

FIGURE 2.—Generalized geologic map of Precambrian rocks, Central City-Idaho Springs area, Colorado.

type locality of which is at Silver Plume, Colo., 6 miles southwest of the area shown in figure 2. The sills, dikes, phacoliths, and small irregular plutons of biotite-muscovite granite and pegmatite exposed in the mapped area (fig. 2) apparently are satellitic to the main batholith (Lovering and Goddard, 1950, pl. 2).

TERTIARY ROCKS

A series of calc-alkalic to alkalic porphyritic intrusive rocks that form small plutons and dikes was emplaced into the Precambrian host rocks during early Tertiary time. A description of the porphyritic rocks and their probable mode of emplacement is presented in a paper by J. D. Wells (1960). One of the striking features of the dikes is their rectangular grid pattern in many parts of the area. (Wells, 1960, pl. 19.) This is particularly true in the Central City area where the dikes clearly are in joints in the microcline-bearing gneiss, and many of the joints in the gneiss are in sets that belong to a regional joint system (near northward- and near westward-striking, steeply dipping fractures).

FOLDS

Two periods of Precambrian deformation can be recognized in the rocks of the Central City-Idaho Springs area. First was plastic folding, during which the metasedimentary rocks were recrystallized, the biotite gneisses migmatized, a series of plutons and sheets were intruded, and the more mafic members of the igneous series were locally retrograde metamorphosed. These older folds are now outlined by the lithologic units. The second deformation was largely cataclastic and less pervasive than the earlier major deformation. It was most intense in a narrow belt that trends northeastward through the town of Idaho Springs (fig. 2). This deformation produced small folds and zones of granulation which were superposed on the previously foliated and folded rocks.

Folds of the two stages are distinguished by their trends and type. The older folds are dominantly open, upright, doubly plunging folds, but some are tight folds that are upright to overturned and recumbent. The largest of these folds has a wavelength of about 1½ miles and can be traced along its axis for about 12 miles. The fold axes are sinuous in both a map and a long-section view, but on the average they trend about N. 30° E. and commonly plunge gently northeast or southwest. The plunge of the folds is markedly steeper than the average in the area along the southwestern part of Chicago Creek (fig. 2).

The younger folds are terrace, monoclinal, and chevron structures on the older larger folds; the largest of the younger folds has a wavelength of about 300 feet. These folds trend N. 55° E. and are remarkably straight. They plunge at different angles, depending upon their position on the older, larger folds. The younger folds have steep axial planes and consistently show an asymmetry that indicates the northwest side moved up. This second folding was accompanied by granulation which was most severe in the igneous rocks and in the poorly foliated metasedimentary rocks.

FAULTS

Most of the faults in the area are early Tertiary in age, although a very few may be Precambrian faults along which Tertiary movement has occurred. A thorough study of the faults has been prepared by Sims and others (written communication, 1959) and the following statements are based largely on that report.

The abundant Tertiary faults, many of which have been mineralized, generally follow preexisting planes of weakness in the Precambrian host rocks. Among these planes of weakness are axial planes of tight folds, contacts between rock units, foliation in the gneissic units, and joints. The predominant movement along the Tertiary faults is a few feet to a few tens of feet of strike slip, though some faults have a small component of dip slip. The subsidiary fractures associated with the faulting are also surfaces of shear, and few if any joints seem to have been formed during this period of deformation.

JOINTS

Considering the long and complex history of the area, it is to be expected that all the rocks would be jointed intensely. Most outcrops in the area show at least 3 distinct joint sets, and 5 or more joint sets in a single outcrop are common. With few exceptions we have related each of the many joint sets to one of several processes—the flow and cooling of the Precambrian and Tertiary igneous rocks, the two Precambrian foldings, or the Laramide deformation of the Front Range. To decipher these relations requires a detailed knowledge of the structural geology; only with this knowledge is it possible to suggest that some joint sets are related, for example, to the second Precambrian fold system, whereas others are persistent from area to area, show little regard for structural variations, and therefore constitute a regional joint system. The remainder of this report will concern the methods of gathering and plotting the data on the joints, and the interpretation of the joint patterns disclosed.

ACCUMULATION AND INTERPRETATION OF THE JOINT DATA

About 9,000 readings of joint attitudes were collected in a 50-square-mile area during this investigation. Joints in the two main Precambrian intrusive bodies (granodiorite and biotite-muscovite granite) were plotted on Schmidt equal-area nets, and joints in the Precambrian metamorphic rocks were plotted on 10 Schmidt nets that represent 10 divisions of the entire area. The 10 areas were selected to correspond with areas for which lineation diagrams showing bearing and plunge of the Precambrian folds were available. The joint plots were then counted and contoured using the standard 1-percent area-counting device (see Billings, 1942, p. 117–122, for a simple explanation of the technique).

The interpretations presented are based on the premise that joints should and can be related to major geologic events in the area. The genetic relations of joints to geologic events can be recognized only locally in the field; dikes related to an intrusive body may appear in a limited number of joint sets within the intrusive mass, or a joint at rights angles to the plunge of folds may remain at right angles although the bearing and (or) plunge of the folds may vary as much as 30° from area to area. Persistent joint sets are recognized on joint contour diagrams, and their genetic relations are inferred from their fit with ideal joint sets that would be related to known folds. At a few places in the field, inferred ages of joints can consistently be checked against their actual age relations in the rocks. In addition, the patterns seem to be widespread, for some persistent patterns emerge on each diagram even though 9 individuals working independently collected the data, and no individual contributed data to more than 2 diagrams.

We conclude that each of the principal Precambrian magmatic rocks contains joints formed in response to stress during cooling and that the Precambrian metamorphic rocks contain joints related to folding of those rocks during the two periods of deformation. Some of the joints formed during each period of Precambrian folding have been superposed on the Precambrian intrusive rocks. A widely distributed "regional" joint system seems to have been superposed on all Precambrian rocks, possibly during Laramide time.

METHODS AND PROBLEMS OF INTERPRETATION

Both field and office interpretations of joints of several ages are difficult. Where a younger joint system includes joints that are virtually parallel to older joints it may be difficult or impossible to determine whether a given joint is new, or whether it represents reopening or extension of the older joints.

To interpret Schmidt net diagrams we look for individual concentrations of poles (highs) on the contoured diagrams. If only 1 or 2 joint sets exist in a rock and they are separated by many degrees in both strike and dip, then the recognition of the individual highs is simple and direct—no overlap of poles belonging to either joint set occurs. However, in a rock that has six or more joints (as do most rocks in this area), none of which can be identified on the basis of some intrinsic geologic characteristic as clearly belonging to one set or another and some of which are only a few degrees apart in the strike and (or) dip, overlap is likely, and some of the highs become difficult to identify. Under these circumstances the system of taking overlapping averages in a 1-percent area used to count the points on a Schmidt net plot necessarily results in points belonging to one set also being counted with those of an adjacent set. If the two sets are about the same strength (have the same number of points), then the area of overlap may contain as many, or even more, points than either of the true highs. The similarity between this problem and those of bimodal distributions in histograms will be apparent to some readers. The result on the contoured Schmidt net diagram is a long narrow high if the overlapping area contains about as many points as each of the true highs, or a single false high if the two true highs are so closely spaced that the overlapping area contains a higher concentration of points than either of the true highs. The single false high is near the true highs, and perhaps for purposes of joint interpretation is adequate if used as a single high. The long narrow high can sometimes be recognized as two highs by making closely spaced contours (thus making slight differences in point concentration or "relief" more apparent), but some long narrow highs are so nearly level along their crestlines that separations into two highs can be done only by assuming that the long high represents an unusual spread of joint directions in the rocks (based on experience) and therefore probably represents two closely spaced joint sets rather than one exceptionally dispersed set. If two adjacent elements differ greatly in strength, the stronger high may distort the weaker high's true location or even mask it. The weaker high may show only as a small closed contour or as a deflection of the otherwise smooth contours around the stronger high, but the significance of such a small closed contour or deflection may be doubtful.

A single joint set may generate two distinct highs on a contour diagram. For example, a joint set perpendicular to fold axes is common in this area. The bearing of the older Precambrian folds is reasonably constant in the area covered by each of the contour diagrams, but in several of the areas the plunge of the folds has a range of as much as 40°. A joint set perpendicular to these fold axes has a nearly constant strike, but it has a 40° spread in dip. Because these folds are commonly double or asymmetrically plunging, a single joint set may show a double high, a more prominent high for the most common plunge and a less prominent high for the less common plunge of the fold system. Joint sets that may represent such dispersions in dip are not abundant in the area; the few examples of such dispersions are noted in the last two columns of table 1 as "spread from" the possible related high.

Despite the many problems in interpretation, the contour patterns do show many distinct highs as well as several deflections that probably indicate highs. Although we cannot explain to our own satisfaction every high on every diagram, we can relate to folds all the highs on many diagrams and most highs on the remainder.

PRECAMBRIAN JOINTS IN IGNEOUS ROCKS

The joints of Precambrian age include two types, primary joints in intrusive igneous rocks and joints related to two periods of Precambrian folding. Primary joint sets in igneous rocks are identified if dikes related to the igneous mass are found parallel to (following) joints in that mass. (See Balk, 1937, p. 27–42.) If the dike rock is not related to the intrusive mass in which it occurs, then joints parallel to it may be primary joints that were reopened at a later time, or joints formed at a later time.

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Primary joints in igneous granodiorite and Silver Plume granite commonly contain dikes of pegmatite, or light-colored granodiorite. The attitudes of joints in the granodiorite and of dikes in it are shown in figures 3 and 4. The dikes are of two ages; some are light-colored granodiorite that is related to the grano-

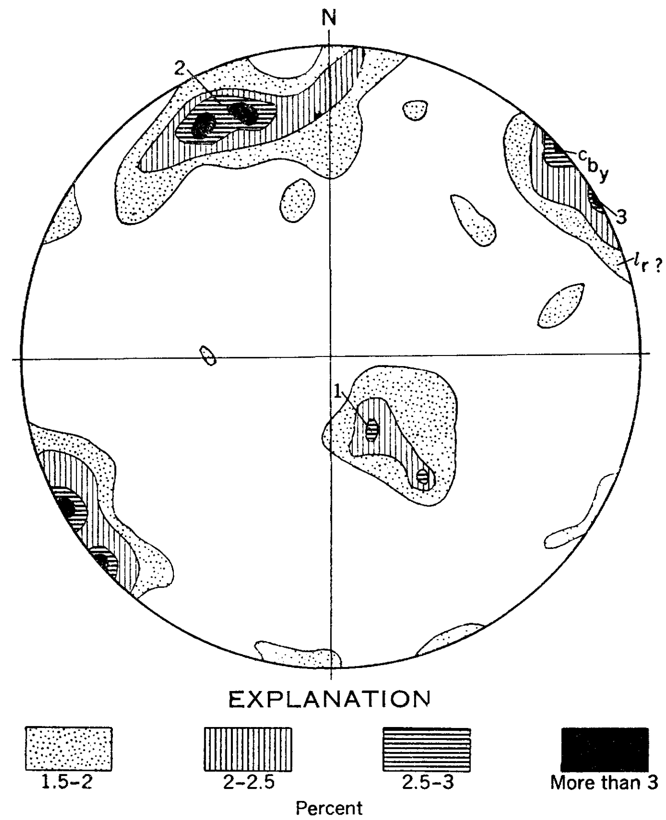

FIGURE 3.—Contour diagram of joints in granodiorite along Ute Creek, upper hemisphere plot of 751 poles. After Harrison and Wells (1959, fig. 13).

diorite (Harrison and Wells, 1959, p. 13), and others are biotite-muscovite granite and its associated pegmatite. The light-colored granodiorite dikes are confined to the granodiorite, are commonly about 2 inches wide, and at places form a grid pattern in outcrop. The steeply dipping joints (sets labeled 2 and 3 on fig. 3) are parallel to the dike grid pattern of the light-colored granodiorite, although it is apparent in the field and on the contour diagram (fig. 4) that more dikes are parallel to the joint set labeled 2 than to the set labeled

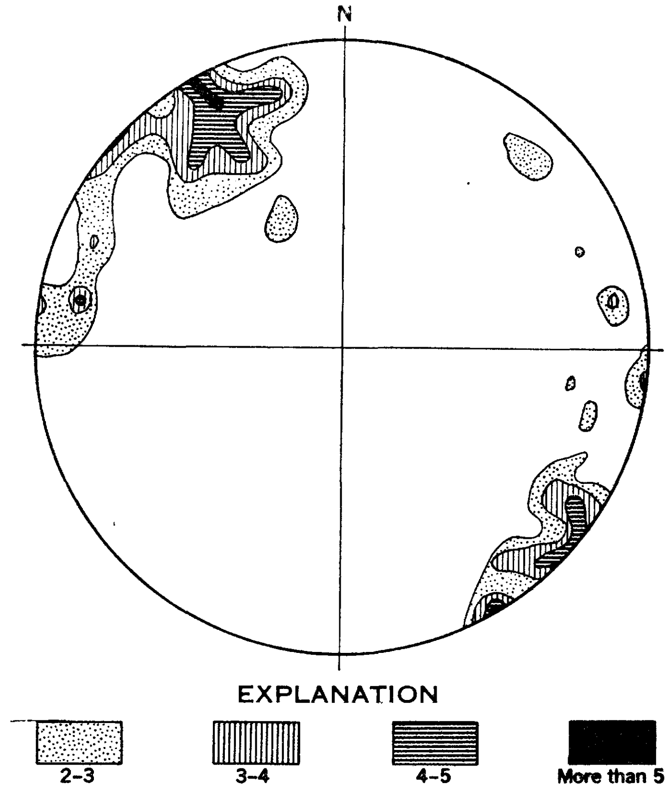

FIGURE 4.—Contour diagram of attitudes of Precambrian biotite-muscovite granite and associated pegmatite, and light-colored granodiorite dikes in granodiorite along Ute Creek, upper hemisphere plot of 153 poles. After Harrison and Wells (1959, fig. 14).

3. This set labeled 2 also is parallel to dikes of biotite-muscovite granite and its associated pegmatite. Both of these sets are interpreted as primary joints, some of which were reopened and filled during emplacement of biotite-muscovite granite. Balk (1937, p. 27–42) also describes and defines the primary fracture system in an igneous rock in relation to the flow lines in the rock. The granodiorite has been deformed and recrystallized in part, and the original flow lines cannot be determined with accuracy at most places; therefore, direct comparisons with Balk's terminology and conclusions are not possible. However, the two steeply dipping primary joint sets plus the principal flat-lying joint set (1 on fig. 3) form a conjugate system typical of the primary joint systems that have been thoroughly studied and described by Balk.

The granodiorite was intruded during the period of older folding, but no joints clearly identifiable as belonging to that series of folds have been impressed on the granodiorite (compare fig. 7, diagrams 7 and 10). The younger period of folding, however, seems to have left a mark because a joint set (labeled c_{b_y}) on figure 3 is almost exactly parallel to a joint set in the folded metamorphic rocks that is related to the younger period of Precambrian deformation.

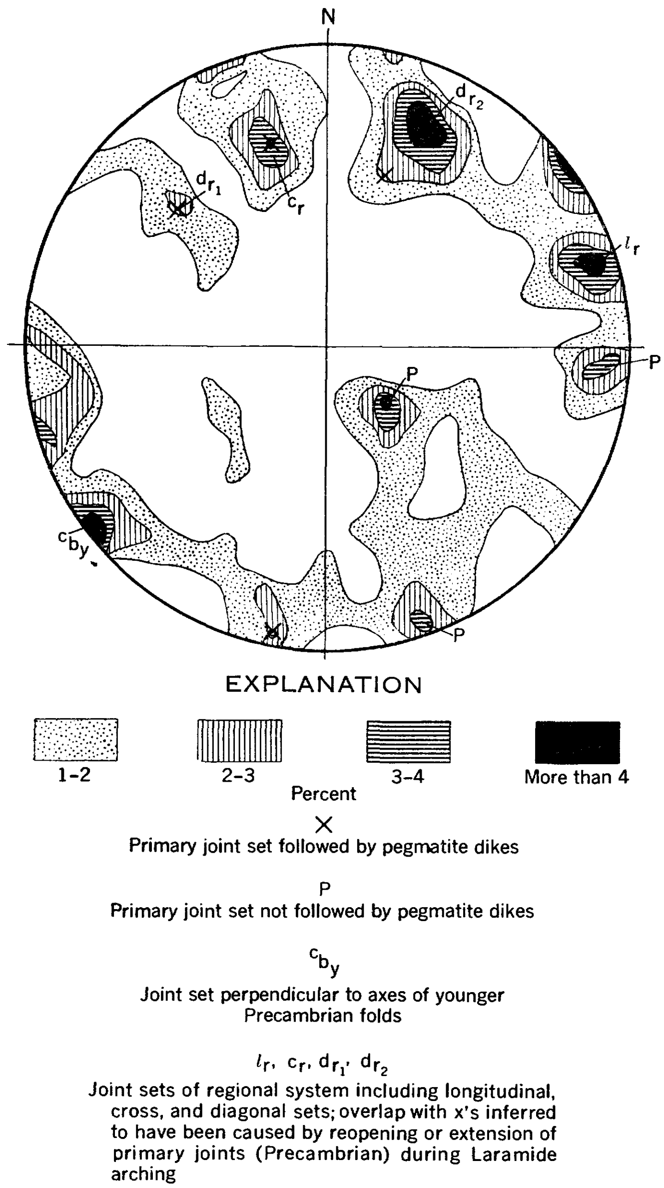

Figure 5.—Contour diagram of joints in the Alps Mountain stock of biotite-muscovite granite, upper hemisphere plot of 175 poles.

The other principal Precambrian intrusive body is the biotite-muscovite granite, which is most extensively exposed in the Alps Mountain stock (fig. 2). The granite was intruded late in the period of older folding and was apparently deformed very slightly or not at all by the older stresses at the time of intrusion (Harrison and Wells, 1959, p. 20). The granite in the southern and southeastern part of the area was cataclastically deformed during the younger period of Precambrian deformation and, at many places, zones of closely spaced slickensided fractures trending N. 55° E. cut across the flow lines in the granite; the fractures commonly show striations identical in direction and type with *a* lineations in the cataclastically deformed metamorphic rocks—cataclasis that occurred during the younger deformation. Mortar texture is present in the granite at outcrops where the slickensided fractures occur. These slickensided fractures form a set that differs from all other joints; they will be discussed in a later part of this report and are not included on the joint diagram for the Alps Mountain stock.

The Alps Mountain stock contains a group of primary joints as well as joints that are inferred to be younger than the stock. Figure 5 is a contour diagram of joints in the stock. Those joint sets marked with an X are parallel to dikes of pegmatite related to the biotite-muscovite granite; they are inferred to be primary joints in the granite. The joint sets marked with a *P* are also inferred to be primary because diagrams of surrounding rocks do not contain these sets (compare diagrams 7, 8, and 10, figs. 6 and 7). The joint set labeled c_{b_y} on Figure 5 is common to all agneous and metamorphic rocks in the Alps Mountain area, does not parallel dikes of pegmatite related to biotite-muscovite granite either inside or outside of the stock, and is at right angles to the axes of the younger Precambrian folds or zones of cataclasis. It is inferred to be a joint related to the younger period of Precambrian deformation. The joints labeled l_r, c_r, d_{r_1}, and d_{r_2} on figure 5 are probably new or reopened joints formed during post-Precambrian time and will be discussed in the section on post-Precambrian points.

PRECAMBRIAN JOINTS IN METAMORPHIC ROCKS

Many joints in the metamorphic rocks apparently formed during one or the other of the two periods of Precambrian deformation. Diagrams of joints in the metamorphic rocks are shown on figure 6 where each diagram has been plotted in the approximate center of the geographic area that it represents. Figure 7 shows the same joint diagrams without the contours but with the positions of the highs indicated. The positions of joint sets shown on figure 7 are given in table 1.

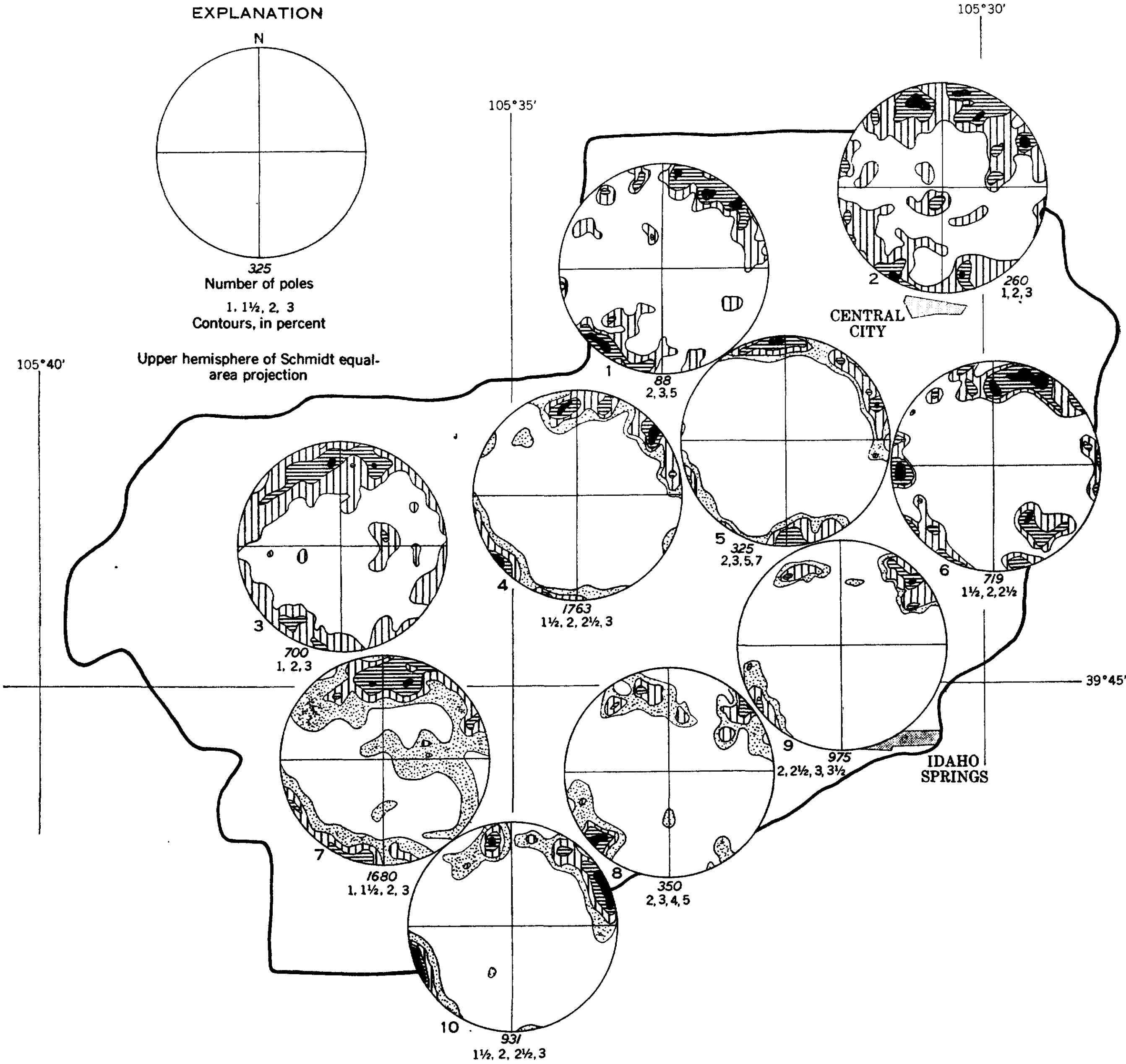

FIGURE 6.—Contour diagrams of joints in metamorphic rocks.

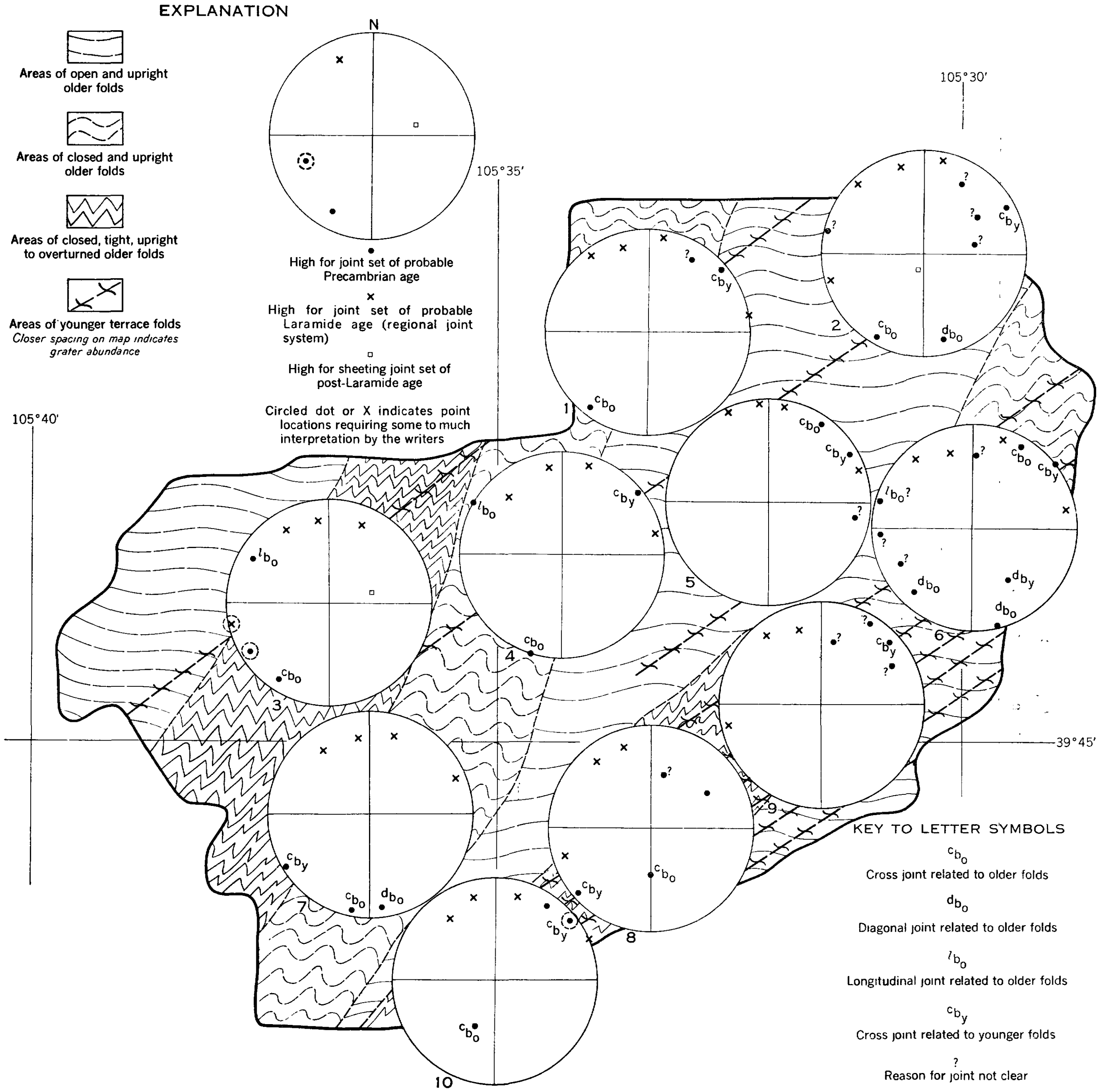

FIGURE 7.—Diagrams showing highs interpreted from contour diagrams, inferred ages of joint sets, and types of Precambrian folding.

TABLE 1.—*Summary of attitudes of joint sets in metamorphic rocks*

[For explanation of symbols, see list at end of table]

Net[1]	Number of poles (total 7,791)	Average attitude of axes of older folds (b_o)[2]	Theoretical cross joint related to b_o	c_{b_o} (joint measured from Schmidt net)	Average attitude of axes of younger folds (b_y)[2]	Theoretical cross joint related to b_y	c_{b_y} (joint measured from Schmidt net)	Attitude of regional joint system (joints measured from Schmidt net)				Other joints	Interpretation of other joints
								l_r	c_r	d_r	d_r		
		1	2	3	4	5	6	7	8	9	10	11	
1	88	8°, N. 32° E.	N. 58° W., 82° SW.	N. 55° W., 83° SW.	Horizontal, N. 54° E.	N. 36° W., vertical.	N. 39° W., 82° NE.	N. 12° W., 88° NE.	N. 75° E., 78° NW.	N. 78° W., 82 NE.	N. 53° E., 78° NW.	N. 60° W., 70° NE. N. 10° W., 41° NE.	
2	260	8°, N. 41° E.	N. 49° W., 82° SW.	N. 62° W., 86° SW.	Horizontal N. 58° E.	N. 32° W., vertical.	N. 28° W., 80° NE.	N. 17° W., 83° SW.	N. 77° E., 77° NW.	N. 77° W., 82° NE.	N. 48° E., 83° NW.	N. 62° W., 67° NE. N. 35° W., 54° NE. N. 13° E., 87° NW. N. 76° E., 72° SE.	Spread from c_{b_o}. Diagonal joint related to b_o.
3	700	22°, N. 22° E.	N. 68° W., 68° SW.	N. 57° W., 79° SW.	19°, N. 55° E.	N. 35° W., 71° SW.	N. 33° W., 81° SW.	N. 13° W., 86° SW.	N. 82° E., 72° NW.	N. 69° W., 75° NE.	N. 58° E., 74° NW.	N. 68° W., 14° SW. N. 14° W., 38° NE. N. 30° E., 78° NW.	Sheeting. Do. Longitudinal joint related to b_o.
4	1,763	6°–2°, N. 13°–30° E.	N. 60°–77° W., 84°–88° SW.	N. 73° W., vertical.	Horizontal, N. 56° E.	N. 34° W., vertical.	N. 37° W., 85° NE.	N. 22° W., 83° NE.	N. 80° E., 75° NW.	N. 73° W., 80° NE.	N. 47° E., 67° NW.	N. 30° E., vertical.	Do.
5	325	Horizontal, N. 30° E.	N. 60° W., vertical.	N. 55° W., 82° NE.	Horizontal, N. 57° E.	N. 33° W., vertical.	N. 30° W., 83° NE.	N. 20° W., 85° NE.	N. 83° E., 87° NW.	N. 80° W., 85° NE.	N. 65° E., 85° NW.	N. 12° E., 78° SE. N. 25° W., 70° SW.	
6	719	Horizontal, N. 27° E.	N. 63° W., vertical.	N. 59° W., 85° NE.	Horizontal, N. 55° E.	N. 35° W., vertical.	N. 35° W., vertical.	N. 12° W., 78° NE.	N. 73° E., 66° NW.	N. 72° W., 80° NE.	N. 48° E., 77° NW.	N. 43° W., 75° SW. N. 88° W., 63° NE. N. 3° W., 80° SW. N. 58° E., 50° SE. N. 76° E., 88° SE.	Diagonal joint related to b_o. Spread from l_r? Diagonal joint related to b_y. Diagonal joint related to b_o.
7	1,680	27°, N. 20° E.	N. 70° W., 63° SW.	N. 77° W., 82° SW.	Horizontal, N. 55° E.	N. 35° W., vertical.	N. 32° W., 85° SW.	N. 22° W., 79° NE.	N. 82° E., 62° NW.	N. 74° W., 68° NE.	N. 56° E., 63° NW.	N. 14° E., 86° NW. N. 83° E., 78° SW.	Longitudinal joint related to b_o? Diagonal joint related to b_o.
8	350	41°, N. 12° E.	N. 78° W., 49° SW.	N. 90° E., 40° S.	10°, N. 55° E.	N. 35° W., 80° SW.	N. 40° W., 85° SW.	N. 18° W., 79° SW.	N. 69° E., 75° NW.	------------	N. 50° E., 75° NW.	N. 35° W., 60° NE. N. 80° W., 50° NE.	Spread from c_{b_y}. Parallel to one set of Precambrian faults?
9	975	54°, N. 26° E.	N. 64° W., 36° SW.	------------	27°, N. 55° E.	N. 35° W., 63° SW.	N. 41° W., 79° NE.	N. 13° W., 82° SW.	N. 73° E., 67° NW.	------------	N. 52° E., 72° NW.	N. 77° W., 52° NE. N. 27° W., 68° NE. N. 58° W., 82° NE.	Do. Spread from c_{b_o}?
10	931	62°, N. 23° E.	N. 67° W., 28° SW.	N. 68° W., 41° SW.	Horizontal, N. 55° E.	N. 35° W., vertical.	N. 37° W., 84° NE.	N. 20° W., vertical.	N. 76° E., 72° NW.	N. 77° W., 73° NE.	N. 56° E., 62° NW.	N. 53° W., 78° NE.	Do.

[1] Corresponds with diagrams on figures 6, 7, and 8.
[2] Data compiled by R. H. Moench, J. E. Harrison, and P. K. Sims.
b_o, axis of older Precambrian folds.
b_y, axis of younger Precambrian folds.
c_{b_o}, cross joint related to older Precambrian folds.
c_{b_y}, cross joint related to younger Precambrian folds.
l_r, longitudinal joint of regional joint system.
c_r, cross joint of regional joint system.
d_r, diagonal joint of regional joint system.

A brief review of joints expected on fold structures (fig. 8) seems warranted. In either plastic or virtually

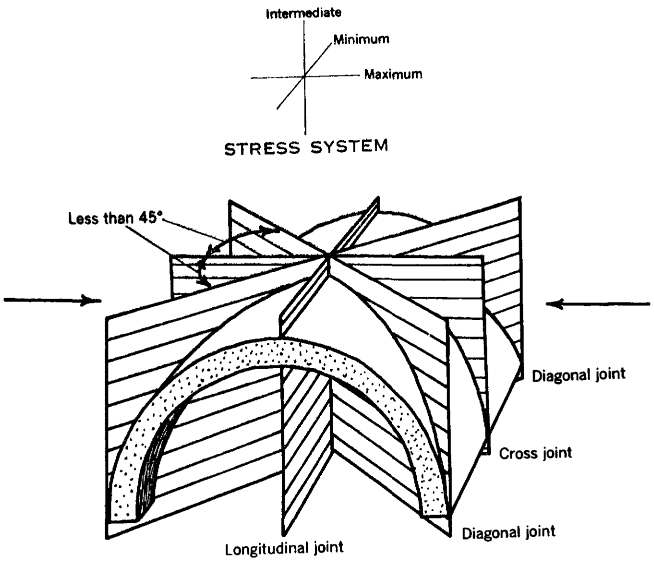

FIGURE 8.—Theoretical joints along a fold formed at depth by horizontal compression. After Willis and Willis (1934, fig. 47).

nonplastic deformation, a joint set may form parallel to the fold axis and one set perpendicular to it. "Release tension-joints" (DeSitter, 1956, p. 131) or "release joints" (Billings, 1942, p. 125) may form parallel to the axial plane of a fold owing to release of the principal stress. Tension joints may also form parallel to the axial plane in the upper part of the fold owing to stretching of the beds or layers across the top part of the fold. A set of joints at right angles to the fold axis (and at right angles to the release joints) may form during elongation of the fold ("extension joints" of Billings, 1942, p. 125). Similarly, a doubly plunging fold may have tension joints formed perpendicular to the axis of the fold owing to stretching of the beds on the crest of the doubly plunging anticline. Shear joints (here called diagonal joints), in addition to longitudinal and cross joints, may form in symmetrical positions about the direction of principal stress. Anderson's studies (1951, p. 15) indicate that the angle between the greatest compressive principal stress and the surfaces of shear will be less than 45°. Both directions of shear are not necessarily expressed by strain in the rocks. In theory shear joints should have slickensided surfaces, but the deformation may show as a fracture along which movement was so slight as to be indiscernable. Hills (1953, p. 100–101) expresses the problem as follows:

> Shear joints are either shearing planes along which the differential slip has been of microscopical amount, or potential shearing planes which have become visible as a result of readjustments taking place in the deformed rocks as a result of weathering, or of fatigue under alternating stress.

Fractures which have the correct relative position to be shear joints but which show no discernible movement along them are called diagonal joints in this report. An ideal system of joints related to a fold formed by the stress system shown in figure 8 would consist of a release tension joint parallel to the axial plane of the fold (a longitudinal joint), a release tension joint perpendicular to the axis of the fold (a cross joint), and two shear joints (diagonal joints) symmetrically disposed at less than 45° about the cross joint (which is parallel to the direction of maximum stress). The longitudinal, cross, and diagonal joints should have a common line of intersection, which would be parallel to the intermediate axis of stress.

The older Precambrian folds do seem to have a joint system of cross, diagonal, and longitudinal joints. Cross joints are the easiest ones to recognize. The theoretical position of cross joints can be calculated from the average plunge of the folds in a given area and compared to joint-set positions measured from Schmidt net diagrams of the same area; close agreement can be found, as is shown on table 1, columns 2 and 3. The marked variation in bearing and plunge of axes of the older fold system, particularly in the southern part of the area, can be related to a shift in a joint set shown on the diagrams (table 1 and fig. 7). This shift is noticeable in the field where the gradual change in the plunge of the older folds from outcrop to outcrop is accompanied by a gradual shift in one of the more conspicuous (closely spaced) joint sets; the joint set is consistently almost exactly at right angles to the bearing and plunge of the older folds as measured from outcrop to outcrop. When we consider that the bearing and plunge of the fold axis that is used to compute the theoretical cross joints is an average of a variable structure, and the attitude of joint sets as read from a Schmidt net is an average whose position may be modified by any or all of the factors previously discussed, then we are surprised at how good a match can be made.

Less easy to recognize are joints inferred to be longitudinal or diagonal joints related to the older fold system. No field evidence was found to show a clear relation between these joints and the older fold system. The joint sets given in table 1, column 11 and shown on figure 7 as diagonal (d_{b_o}) or longitudinal joint sets (l_{b_o}) related to the older fold system are so named because they correspond approximately in position with the theoretical positions of joint sets on the older folds that can be calculated with some fair degree of accuracy. If these diagonal joints do belong to the stress system prevailing at the time of the older folding, then the intermediate axis of stress at the time of the jointing must have been vertical. The character of the older folds suggests that the intermediate axis of stress was horizontal at the time of the folding.

The stress system prevailing in the Central City-Idaho Springs area was apparently the same at the time of the younger Precambrian folding and at the time of the jointing. The character of the younger folds suggests that the intermediate axis of stress was horizontal rather than vertical; diagonal (shear) joints formed in such a stress system should strike parallel to the younger fold axes and dip about 45° (compare fig. 8; Billings, 1942, fig. 108B). Release tension joints parallel to the fold axes (longitudinal joints) and perpendicular to them (cross joints) would have the same relations as shown in figure 8.

Diagonal joints related to the younger folding are clearly shown in biotite-muscovite granite and in granite gneiss and pegmatite. These joints (fig. 9) contain

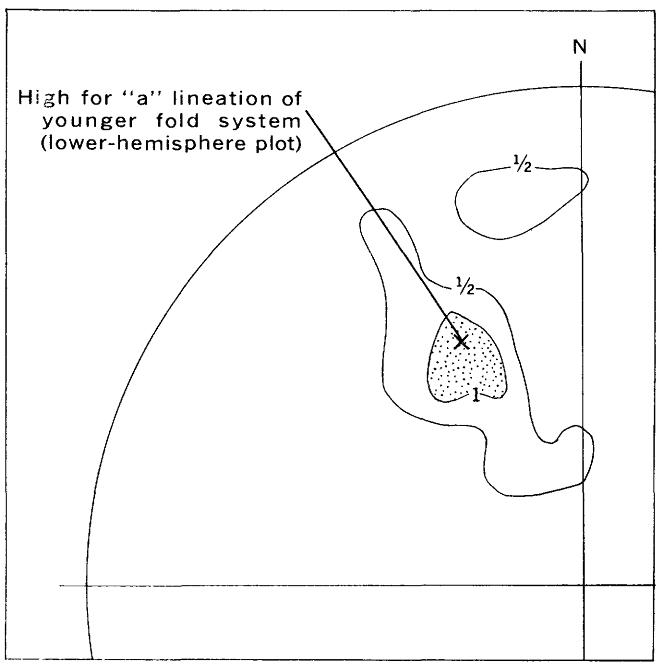

Figure 9.—Contour diagram of shear joints in biotite-muscovite granite and in granite gneiss and pegmatite, upper hemisphere plot of 63 poles, in percent.

slickenside lineations that are parallel to *a* of the younger fold system. Only 1 of the 2 possible shear joints has formed in the rocks, and therefore, only 1 quadrant of the Schmidt net is required to show their concentration. Apparently the stress was entirely taken up along 1 of the 2 possible directions of shear. Only very small offsets (generally less than one-tenth of an inch) have been observed on the shear joints. Some of these slickensided joints also appear in the metasedimentary rocks where they commonly are along northwestward-dipping layers (P. K. Sims, oral communication, 1958).

Joints related to the younger period of folding include cross joints and diagonal joints. The nearly constant bearing and plunge of the younger fold axes are reflected in the nearly constant strike and dip of a cross-joint set that appears on all Schmidt net diagrams (figs. 3, 5, and 7). The nearness of this joint set to the strike and dip as calculated from the bearing and plunge of the younger fold axes is shown by comparing column 5 with column 6 on table 1. This joint set occurs in all Precambrian igneous and metamorphic rocks, which suggests that it is either late Precambrian or post-Precambrian in age. Areas of more intense younger Precambrian folding generally show a more intense high on the contour diagram at the location of the theoretical cross joint that would be related to that folding (figs. 3, 5, 6, and 7). This correlation of more intense jointing with more intense folding also supports the idea that the joints and folds are genetically related.

POST-PRECAMBRIAN JOINTS

Joints that are younger than Precambrian include those formed by sheeting and those belonging to a regional joint system. Sheeting joints form by release of pressure due to erosion of overlying rocks and are flat-lying joints. (See Chapman and Rioux, 1958, for a recent study of sheeting joints.) Such joints are visible in most parts of the area. Because these joints are both irregular and flat, (commonly dipping less than 10°), their true attitude in the field is difficult to determine accurately. The result on a Schmidt net is that the poles of flat joints are dispersed and do not necessarily show as a concentration on the contour diagram. Only on two of the contour diagrams of the metamorphic rocks (2 and 3 on fig. 6) are they sufficiently concentrated to form a distinct high. If sheeting has formed in the intrusive rocks, it probably has accented the highs for the flat-dipping primary joints marked 1 on figure 3 and *P* on figure 5.

A group of four joint sets has been superposed on the Precambrian rocks. We propose to demonstrate that this group of four joints is a joint system formed by a single stress system. The age of the joint system probably is Laramide.

The group of joint sets appears on all diagrams (figs. 3, 5, 6, and 7). In the granodiorite, all four positions occupied by this group of younger joint sets nearly or exactly coincide with the positions of primary joint sets. Three of the joint sets, where they exist, would appear in the diagram in the area covered by the 2–2.5 percent contour around the high labeled 2; the fourth set (labeled l_r on fig. 3) may be represented by the elongated high around the primary joint labeled 3. Similarly, in the Alps Mountain stock (fig. 5), 2 of the 4 joint sets (d_{r_1} and c_r) locally were followed by pegmatite and are primary directions of weakness that may have opened or become emphasized during a subsequent period of stress. The other two joints (d_{r_2} and l_r) were not followed by pegmatite, and at places they cross contacts between the stock and the enclosing metamorphic rocks. The deflection on the southwest side of d_{r_2} (fig. 5) represents a joint set that is followed by pegmatite. We suggest that if d_{r_2} were primary to the granite as is the joint set indicated by the small deflection on its side, then d_{r_2} should also be followed by pegmatite, because the strike and dip of planes having this general attitude obviously were favorable for emplacement of pegmatite during emplacement of the Silver Plume granite.

The group of joint sets appears consistently in all metamorphic rocks regardless of their structure (fig. 7), whereas the joint sets related to the Precambrian folding change in direction and (or) intensity with changes in direction or intensity of the Precambrian folds.

To determine whether these joints form a genetically related system, we plotted the four joint sets on stereographic diagrams (fig. 10) which were then compared visually with the ideal system described on page 11 and illustrated on figure 8. Each diagram approaches the ideal system reasonably closely; the solid

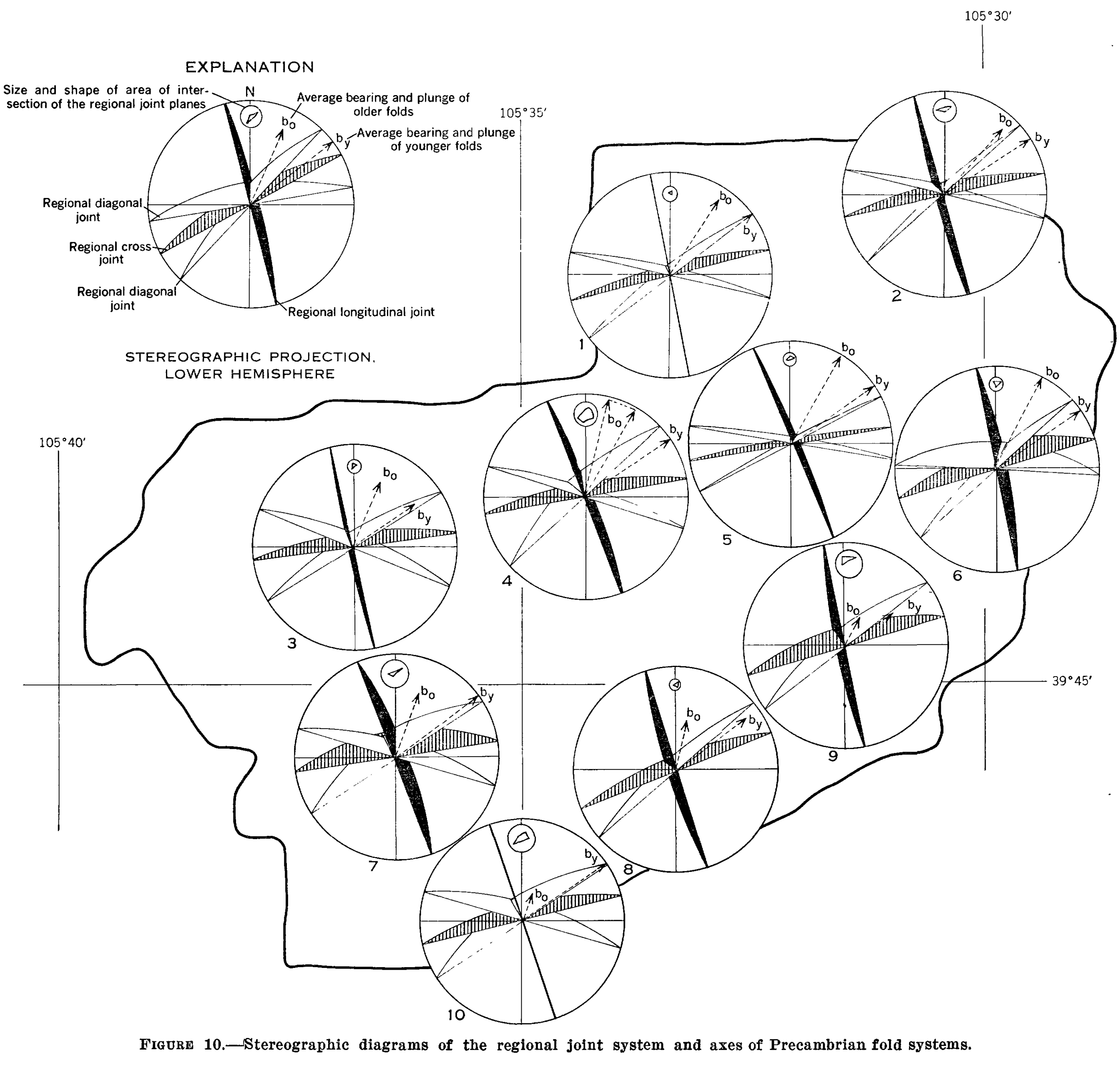

FIGURE 10.—Stereographic diagrams of the regional joint system and axes of Precambrian fold systems.

black plane and the vertically lined plane are almost exactly at right angles; the unpatterned planes are nearly symmetrically disposed at less than 45° about the vertically lined plane. In most diagrams the four planes intersect in what we consider to be a relatively small volume of error, which projects onto the diagram as an "area of error," instead of a straight line as the ideal system shows. If we consider all the possible errors, and thus the limit of exactness in the position of the attitudes obtained from the Schmidt net diagrams, it seems surprising that these joint sets so nearly approach an ideal system. Our conclusion is that these 4 joints do form a system expressed as a longitudinal and a cross joint, and 1 or 2 diagonal joints. But to what stress system do these joints belong?

The joint system apparently has no systematic relation to either of the Precambrian fold systems. Shown on figure 10 in each diagram are the average bearing and plunge for each of the Precambrian fold systems in the areas covered by the diagrams. On diagram 4 of figure 10 the bearing of the older fold system is shown as a range because the diagram covers an area where the older fold system gradually changes bearing from one side of the area to the other, hence for this area the range is more descriptive than the average. If the joint system is related to either Precambrian fold system, then the longitudinal joint sets (black planes on fig. 10) should contain the axis of one of the Precambrian fold systems. It does not; therefore we infer from this lack of concordance with Precambrian folds and from the appearance of the system in the youngest Precambrian intrustive rock (biotite-muscovite granite) that the system is either very late Precambrian or post-Precambrian. As the system also postdates the youngest Precambrian folding, we infer that it is most likely post-Precambrian in age.

The uplift and arching of the Front Range highland (Lovering and Goddard, 1950, p. 57–63) constitute the only major post-Precambrian geologic episode affecting the area to which this joint system could logically belong. The highland was arched during Paleozoic time and again during Laramide time. These disturbances formed the arch or regional anticline outlined in figure 1. The Laramide disturbance seems to have been more pronounced than any of the Paleozoic disturbances, and the weight of evidence suggests that the regional joint system is Laramide rather than Paleozoic in age. We suggest that stresses which were strong enough to cause Laramide folding and thrusting along the edge of the Front Range and to help elevate the highland arch surely would leave some mark on the crystalline core of the arch. The trend of the arch is about N. 15° W. near the Central City–Idaho Springs area, and this direction is reasonably near the trend of the regional longitudinal joint (column 8, table 1). The highland disappears to the south near Cripple Creek, Colo., which indicates that the arch plunges gently to the south. A highland arch cross joint in the Central City–Idaho Springs area theoretically should dip steeply to the north-northwest to be at right angles to the axis of the gently plunging arch, and actually it does (column 8, table 1). We infer that the regional joint system was formed during the arching and is Laramide in age.

The existence of a regional joint system of Laramide age is an hypothesis based on the study of a small part of a large area, but it can be tested by geologists who are working or plan to work in parts of the Front Range where Paleozoic sedimentary rocks overlap Precambrian crystalline rocks. If the hypothesis is found to be true, then we have another tool that will aid in the unscrambling of the complex geologic history of the Front Range.

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