Geologic Implications of Aeromagnetic Data in the Pend Oreille Area, Idaho and Montana

GEOLOGICAL SURVEY PROFESSIONAL PAPER 646-D

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By ELIZABETH R. KING, JACK E. HARRISON, *and* ALLAN B. GRIGGS

GEOPHYSICAL FIELD INVESTIGATIONS

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Positive aeromagnetic anomalies identify granodiorite bodies intruded to various levels within a block-mosaic fault terrane

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By ELIZABETH R. KING, JACK E. HARRISON, and ALLAN B. GRIGGS

ABSTRACT

An aeromagnetic survey of about 1,000 square miles of northern Idaho was made to outline intrusive bodies to help provide three-dimensional control for a geochemical study of contact and regional metamorphism in the northern half of the surveyed area. Most of the host rocks in the area are a part of the Belt Supergroup. This report discusses interpretations of the southern 800 square miles of the survey and is confined to tectonic and ore deposit problems.

Positive aeromagnetic anomalies reflect both exposed and buried Cretaceous granodiorite cupolas and stocks. The reticularity of some aeromagnetic contours is related to major block faults that were reactivated during tectonic swelling and emplacement of the granodiorite. Subsequent collapse created a block mosaic of minor faults within the older blocks; geologic maps of the area have a shattered-glass appearance.

One zone of closely spaced high-angle faults (The Magee fault zone), which is about 20 miles long, was caused by collapse of a monoclinal flexure; a long narrow pluton raised and tilted a block bounded on three sides by old major faults. The fourth side formed the monocline which eventually stretched and collapsed.

The aeromagnetic survey does not show any relation between the principal mining areas and the aeromagnetic anomalies.

INTRODUCTION

The U.S. Geological Survey, as part of its program of regional investigations, has conducted geologic studies in the northeastern Washington–northern Idaho–northwestern Montana area for several years. Reasons for the studies include the need for information on the complex tectonics of the area, the need for information on mineral resources including the relation of the mining districts to the broad geology of the area, and the opportunity for examination in detail of some of the less well understood geologic processes displayed in the rocks of the area. This report presents some of the results of these continuing studies.

Among the previous geologic work in the area is the geologic mapping and study of ore deposits by Anderson (1930, 1947) in the Clark Fork district and (Anderson, 1940) in Kootenai County, and by Sampson (1928) in the Pend Oreille district. Gillson (1927) reported on the granodiorites of the area. More recent work includes aeromagnetic mapping by Meuschke, McCaslin, and others (1962), geologic mapping by Harrison and Jobin (1963, 1965), a combination of new mapping and compilation of previous work by Savage (1967), and geologic mapping by Griggs (1968).

The aeromagnetic survey discussed in this report was made in 1959 and covered an area of about 1,000 square miles. About 200 square miles of the survey that covers the Elmira 15-minute quadrangle, which is directly north of Pend Oreille Lake, is excluded from this report. Interpretation of that part of the aeromagnetic data must await completion of a modern geologic map, which is now in progress. A preliminary interpretation of part of the aeromagnetic data was given by Harrison, Jobin, and King (1961). After the preliminary aeromagnetic map was open filed in 1962, Savage (1962) published an interpretation of the data. Unfortunately, his interpretation was made without the benefit of modern geologic maps or measurements of magnetic properties of the rocks.

For this report, King is largely responsible for the various calculations using the magnetic data and for the geophysical interpretation of the aeromagnetic map. Harrison and Griggs share the responsibility for the compilation and interpretation of the geology—Harrison for the north half of the area and Griggs for the south half (fig. 1).

The advice and assistance of J. W. Allingham in the use of computer techniques for calculating suitable models to fit the observed magnetic anomalies are gratefully acknowledged.

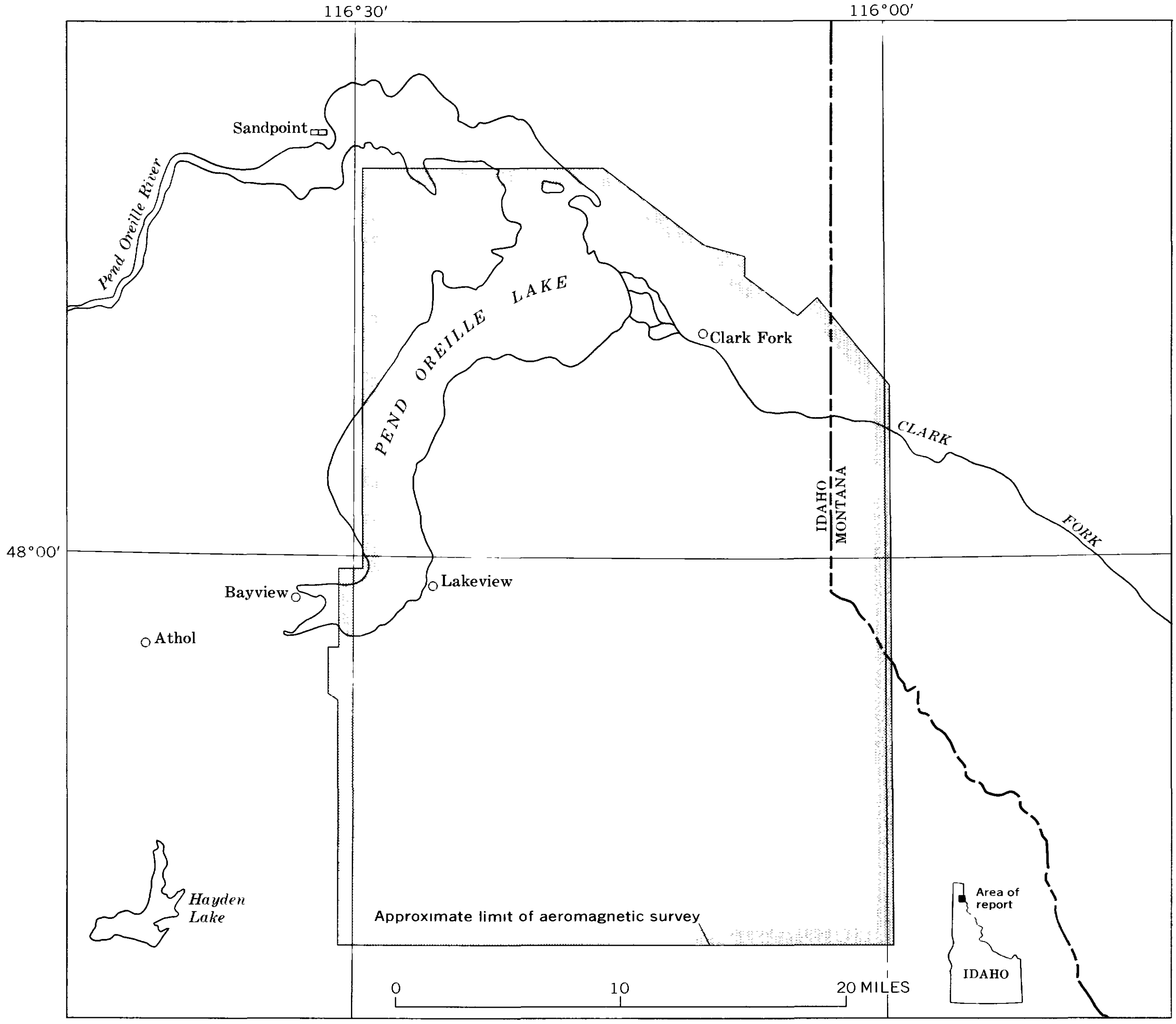

FIGURE 1.—Location of the aeromagnetic survey (pl. 1).

GEOLOGIC SETTING

REGIONAL SETTING

The area covered by the aeromagnetic survey is part of a terrain of highly faulted rocks in a wedge bounded by the Hope fault on the north, the Osburn fault system on the south, and the Purcell trench on the west (fig. 2). These major structures were used by Yates, Becraft, Campbell, and Pearson (1966, fig. 3–1) to divide the region into tectonic subdivisions: (1) a structurally simple area north of the Hope fault and east of the Purcell trench (the Kootenay-Flathead Subprovince), which principally contains Belt rocks; (2) a structurally complex area south of the Hope fault and east of the Purcell trench (the Coeur d'Alene Subprovince), which contains mostly Belt rocks; and (3) a structurally complex area west of the Purcell trench, which contains paragneisses and granitic intrusive rocks, as well as Precambrian and Paleozoic sedimentary and metasedimentary rocks. The area of this report is virtually all within the Coeur d'Alene Subprovince and almost fills the apex of an inverted Y formed by the intersection of the Hope fault and the Purcell trench (fig. 2).

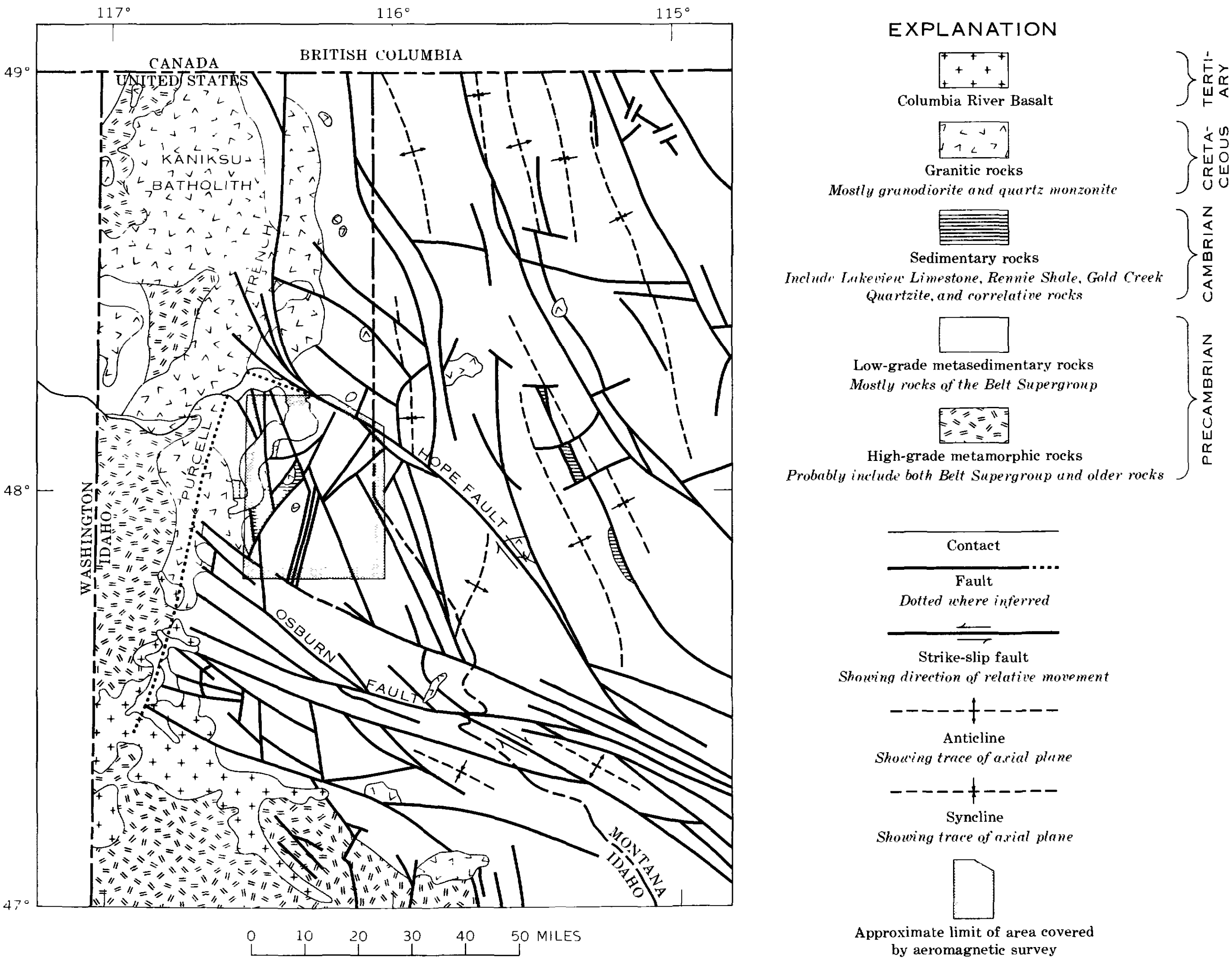

FIGURE 2.—Northern Idaho and northwestern Montana (from Yates and others, 1966, fig. 3–2).

GEOLOGIC HISTORY

The geologic history displayed by the rocks of the Pend Oreille area (pl. 1) began with Precambrian deposition of at least 38,000 feet of fine-grained sedimentary rocks (the Belt Supergroup). During Precambrian time, these rocks were intruded in their lower part by quartz diorite (the Purcell sills) and then were gently folded into broad synclines and anticlines that trended northward. Some faulting during or after the folding disrupted the beds before erosion at the end of Precambrian time had leveled the area and had formed the vast surface of unconformity on which the Cambrian rocks were deposited. As postulated by Hobbs, Griggs, Wallace, and Campbell (1965, p. 125–128), the first movement on the Osburn and Hope faults probably began in Precambrian time. Movement on these major right-lateral strike-slip faults was intermittent throughout much of Phanerozoic time.

In the Paleozoic Era, only Cambrian time is represented by dated rocks in the area. The depositional sequence during early Middle Cambrian time is represented by quartzite, shale, and limestone and dolomite. Another possible representative of Paleozoic time is found just north of the map area in the Purcell trench. This rock of possible Paleozoic age is a poorly sorted conglomerate that is confined to the trench and that contains cobbles and pebbles of only Belt rocks and Purcell sills. The deposit was inferred by Anderson (1930, p. 20–22) to be a fanglomerate of Paleozoic age. This inference seems sound to us, and it requires further tectonism, probably faulting, in and near the trench sometime during the Paleozoic.

The Mesozoic Era is represented in the area by Cretaceous intrusive rocks and mineral deposits. One of the major events in this era was the intrusion of the Kaniksu batholith (fig. 2), of granitic to granodioritic composition. The complex history of the emplacement of the batholith includes (1) early intrusions of dioritic dikes, sills, and small irregularly shaped masses, (2) emplacement of the main mass and stocks, plugs, and dikes of granodioritic rocks satellitic to it, and (3) intrusion of lamprophyres simultaneously with emplacement of lead-zinc-silver deposits in some fractures. These episodes of intrusion were accompanied by a significant amount of new block faulting and a renewed movement on older faults. Thrust faults developed around some of the intrusive masses during and after their emplacement.

A final surge of right-lateral movement along the Hope fault in and near the Purcell trench is here tentatively assigned to the early Tertiary. The event is represented by granodiorite and dacite porphyry dikes (too small to be shown at the scale of pl. 1) that follow faults which cut all other bedrock in the area. These porphyry dikes occur only in the area north and northwest of Pend Oreille Lake. South of the Hope fault, they follow high-angle normal faults; north of the Hope fault and between branches of the Hope (fig. 2), they follow north-trending high-angle normal faults that branch from the Hope fault in and near the Purcell trench. This surge of movement on the Hope fault was accompanied by dilatancy to make room for the porphyry dikes and completed an apparent right-lateral slip of 16 miles, which compares exactly with the maximum amount of apparent right-lateral slip on the Osburn fault (Hobbs and others, 1965, p. 74–83). This event may have been a final phase of the complex intrusion process that accompanied emplacement of the Cretaceous batholith, but it resulted in such a clear-cut and definable geologic event that we prefer to emphasize its importance in the geologic history by identifying it separately and by assigning it a slightly younger age. A radiometric age-determination program now in progress will verify or deny the tentative age assigned here.

The remainder of Tertiary to Holocene time is represented by (upper(?) Tertiary) gravels, a wide variety of glacial and glaciofluvial deposits of Pleistocene age, and alluvium, talus, and other surficial rock debris of Holocene age.

ROCK UNITS

Rocks of the area have been described in detail in several reports. Only brief descriptions will be given here, but the interested reader is referred to Anderson (1930) for petrography of the intrusive rocks in general, to Gillson (1927) for petrography of the granodiorite, to Sampson (1928) for description of the Cambrian sedimentary rocks, to Harrison and Jobin (1963) for descriptions of the Belt rocks, and to Savage (1967) for descriptions of the surficial deposits.

The oldest rocks in the area are low-grade metasedimentary rocks of the Belt Supergroup. These consist principally of quartzites, argillites, and siltites with significant amounts of carbonate-bearing layers in the upper half of the supergroup. The coarsest detrital grain size of these rocks was fine sand, and most of the original sediments were silt or clay. At least 38,000 feet of the supergroup is exposed in the area, and these rocks form by far the largest amount of bedrock in the area (pl. 1).

The Belt Supergroup is unconformably overlain by the Gold Creek Quartzite of Cambrian age. Where exposed, the unconformity shows an angular discordance of about 7°, and Gold Creek Quartzite rests on the middle to upper part of the Wallace Formation; the Wallace rocks are reddish for a few feet below the unconformity, and the Gold Creek Quartzite is conglomeratic in its lower few feet. Overlying the Gold Creek Quartzite is an olive fissile shale—the Rennie Shale—which contains fossils identified by A. R. Palmer, U.S. Geological Survey, as trilobites and brachiopods of early Middle Cambrian age (Harrison and Jobin, 1965). The Rennie Shale is overlain by the Lakeview Limestone, a mottled black to gray dense rock that is largely calcareous in its lower part and largely dolomitic in its upper part. These Cambrian rocks are about 2,500 feet thick.

Other sedimentary rocks in the area include high-level gravels of probable Tertiary age, glacial and glaciofluvial deposits of Pleistocene age, and alluvium, colluvium, talus, and other mass-wasting deposits of Holocene age.

The principal intrusive rocks of the area are dioritic to gabbroic sills of Precambian age (the Purcell sills) and stocks, plugs, and dikes of granodioritic rocks of Cretaceous age. The various bodies of granodiorite shown on plate 1 are remarkably similar in outcrop and generally show only slight differences in texture from body to body. Minor amounts of diorite, lamprophyre, and granodiorite porphyry of Tertiary age form dikes or small plugs, most of which are too small to be shown at the scale of plate 1.

Plate 1 shows the geology of the area simplified primarily through grouping of the rock units into units larger than on the original, more detailed maps. We also have deleted several minor faults not required to show the fault pattern of the area or to justify offset contacts between rock units.

Plate 1 shows a high degree of correlation between positive magnetic anomalies and exposures of the Cretaceous and Tertiary intrusive rocks. Positive anomalies not directly correlatable with such exposures are found over various rock units and obviously correlate with some quality other than simple stratigraphy. Interpretation of these anomalies will be discussed later in this report.

STRUCTURE

The mapped area is one of simple folds but complex and intricate faults. The only major fold is a broad, ill-defined syncline whose axis trends approximately N. 15° E, and plunges gently northeast across the southeastern part of the mapped area (pl. 1). All the area south of the Hope fault and northwest of this fold axis is on the northwestern flank of this syncline. The continuity of beds on this structure is not readily apparent because of the abundant faults and repetition of beds. Other folds do occur in the area, some with wavelengths as much as a mile, but they are all local in extent and are related to dragging and flexing along and between faults or, less commonly, to shouldering aside during emplacement of a few of the plutons.

The fault pattern is complex, and at first glance presents a shattered-glass appearance (pl. 1). The gross pattern can be described briefly as a block-mosaic fault system in which the faults generally step down from east to west. Other important elements include the Hope fault, a major right-lateral strike-slip fault, and the Magee fault zone, a belt of closely spaced high-angle faults that separates an area of more intense block faulting in the southwestern part of the area from an area of less intense block faulting in the southwestern part of the area from an area of less intense block faulting in the southeastern part of the area. Less common elements in the fault pattern include high-angle strike-slip faults and low-angle thrust faults.

Determination of the age and sequence of faulting has been a problem in the area for many years. Sampson (1928) was the first to recognize and map the fault mosaic. He attributed the pattern to crustal breakage and foundering of blocks during intrusion by the granodiorite, and he classed the mosaic faults as "intrusion faults" and "postintrusion faults." This lead was followed by Anderson (1930) for the Clark Fork district and (Anderson, 1940) for Kootenai County with the modification that the major right-lateral strike-slip faults (the Hope and Osburn) were added to the postintrusion fault group. In a later report on the Clark Fork mining district, Anderson (1947) confined his comments to faults within the district but recognized that low-angle thrust faults and minor strike-slip faults also occurred in the area and that the thrusts were cut by high-angle faults.

For the Clark Fork quadrangle, Harrison and Jobin (1963) proposed a general classification scheme of Hope fault, block faults, and mineralized faults. They suggested (p. K28) that this sequence was also probably chronological, from oldest to youngest. Savage (1967) accepted this scheme and applied it to his studies of Bonner County.

Several lines of evidence point to a more complex history of faulting than previously supposed. The horizontal persistence of Purcell sills has been mapped by several geologists. (See Anderson, 1930, pl. 14; Kirkham and Ellis, 1926, pl. 3.) A Precambrian age of faulting is implied by the lack of continuity of Purcell sills across the Hope fault. For example, the various segments of quartz diorite shown in the northwestern part of plate 1, south of the Hope fault, are parts of a single persistent sill that occurs stratigraphically about 4,500 feet below the top of the Prichard Formation. This sill, however, is missing from an equivalent (or even a higher) stratigraphic position on the north side of the Hope fault (north and slightly east of the town of Clark Fork). Direct evidence of faulting prior to deposition of the Cambrian sedimentary rocks can be seen in the Packsaddle Mountain quadrangle (Harrison and Jobin, 1965) in the area of Packsaddle Mountain. Here, on the northwestern slope of the mountain, the Gold Creek Quartzite overlies the middle part of the Wallace Formation with angular unconformity of about 7°. About 2 miles to the southeast across the Packsaddle fault, not only are middle and upper rocks of the Wallace present but also more than 1,000 feet of the Striped Peak Formation which overlies them. Thus, the Packsaddle fault must have been active before the Gold Creek Quartzite was deposited, and the middle and upper parts of the Wallace and the Striped Peak rocks are preserved only because they were below the surface of unconformity on which the Gold Creek was laid down. Although other direct evidence of such old faulting has not yet been found, it seems reasonable to believe that the Packsaddle fault was not unique when formed and that some of the other faults now in the mosaic were also first formed in Precambrian (preunconformity) time.

Paleozoic(?) faulting, as inferred by Anderson (1930, p. 20–22) in accounting for the presence of the Sandpoint Conglomerate in the Purcell trench, may also have contributed to the mosaic. Mapping currently in progress by Harrison has shown that the conglomerate is in fault contact with the granodiorite rather than being intruded by the granodiorite as inferred by Anderson (1930, pl. 14) on his reconnaissance map. The conglomerate, however, contains only cobbles and pebbles of low-grade metamorphosed Belt rocks and Purcell sills, not the higher grade contact-metamorphosed Belt rocks and migmatites of the immediate vicinity that were formed when the granodiorite was intruded. This field relation supports Anderson's interpretation of a pre-granodiorite age for the conglomerate. Pending further study, we have tentatively accepted Anderson's inferred Paleozoic age of tectonism and deposition of the Sandpoint Conglomerate.

Block faulting in Cretaceous time during emplacement of the granodiorite and related rocks was discussed in some detail by Sampson (1928) and by Harrison, Jobin, and King (1961). The basic observations and conclusions of these reports can be summarized briefly as follows:

1. The broad gentle folding of the region can account for only a few thousand of the many thousands of feet of structural rise from east to west across the area.
2. The structural rise is accompanied by stepping down of the blocks in the same direction as the rise.
3. Local folding within some of the keystone blocks must have been in response to an upward push because some of the keystones are bounded by faults that converge upward.
4. Both preintrusion and postintrusion faults are documented in the area.
5. Magma invaded faulted ground; the upward pressure caused a general tectonic uplift in the west and additional uplift of some preexisting fault blocks; a final phase of the process involved collapse in the area of general tectonic uplift.

An expansion of this concept is presented in this report in the section on the relation of aeromagnetic patterns to tectonic features.

The low-angle thrust fault between Packsaddle Mountain and the community of Granite is also probably Cretaceous in age. This fault is best explained as a bedding-plane thrust that resulted from pressures exerted during forceful intrusion of the Packsaddle Mountain Granodiorite body.

Faulting younger than the granodiorite is represented in the mapped area south of the Hope fault by fractures of minor displacement that contain dike rocks (mostly diorites and lamprophyres) and weakly mineralized quartz veins, which at places also fill fractures in some of the granodiorite bodies. These faults commonly extend between faults of the block-mosaic system, as do the fissure veins in the area, although at places the younger faults either cut or are cut by the block faults. The younger faults appear to represent generally late minor adjustments in various blocks of the shattered rocks, but they are of economic significance because they were formed during the ore-deposition stage (Sampson, 1928, p. 23–25; Anderson, 1930, p. 37–39; Harrison and Jobin, 1963, p. K32–K33).

Faults of a still younger surge of movement on the Hope fault are those filled by Tertiary(?) granodiorite porphyry. These are known only in the northernmost part of the mapped area, where they are common in and near the Purcell trench.

One major group of faults, the Magee fault zone, has not been included in the summary given above. The relation of these closely spaced high-angle faults to the regional fault pattern will be discussed under "Fault Control of Emplacement of Granodiorite."

ORE DEPOSITS

Descriptions of the mines and ores of the area were given by Sampson (1928), Anderson (1930, 1947), and Savage (1967). The brief comments made here are largely summaries from those reports.

Ore deposits of the area are primarily narrow fissure veins, which contain ores of silver, lead, copper, and zinc and minor amounts of gold. Zones of altered wallrock rarely extend more than a few feet on each side of the vein.

Although many small mines and prospects are scattered throughout the area, only four small districts have had mines with significant ore deposits. These small districts are near Clark Fork, Talache, Granite, and Lakeview (fig. 4). Neither these small districts nor any other parts of the area show the vast "bleaching" and loss of pigmented minerals (largely iron-bearing ones) so characteristic of the Coeur d'Alene district about 20 miles to the south. (See section by P. L. Weis in Fryklund, 1964.)

METAMORPHISM

Several types of metamorphic effects can be seen in the rocks of the area. The most widespread effect is a regional metamorphism of the Belt Supergroup into the greenschist facies. The upper part of the Belt rocks is in the chlorite-sericite zone; secondary biotite first appears sparsely but consistently in the middle part of the Wallace Formation; and all rocks below the middle part of the Wallace are in the biotite zone of metamorphism. The amount of biotite in rocks of appropriate composition increases progressively with depth in the stratigraphic section, and the Prichard Formation commonly has at least 10 percent of secondary biotite.

The Purcell sills have commonly been altered. The original intrusive rock consisted principally of quartz, calcic plagioclase, hornblende, and pyroxene; it contained minor amounts of magnetite, sulfide minerals, and other common accessories. At many places, particularly near faults, the present rock is largely chlorite, sericite, epidote, sodic plagioclase, quartz, and calcite with some relict hornblende and traces of magnetite, pyrite, sphene, hematite, and leucoxene.

Contact metamorphism is identifiable around many of the intrusive bodies. A zone of hornfels a few feet wide was formed in the Prichard Formation adjacent to the Purcell sills. Younger dike rocks commonly show chill margins against the intruded rocks; and a hornfels zone, if present, is only a few inches wide. The Cretaceous granodiorite bodies caused extensive metamorphism in the Belt Supergroup and in Cambrian rocks adjacent to the intrusive bodies. These effects were described in mineralogic detail by Gillson (1929). Recrystallization of the rock in contact zones has at places increased the magnetite and (or) pyrrhotite content of the rocks, which results in local magnetic effects noticeable in the field through erratic behavior of the compass needle.

Aureoles of contact metamorphism are readily identified within about 2,000 feet of an exposed intrusive body. Limestones and dolomites are marmarized at the outer edge of the aureole, and garnet, diopside, and epidote are conspicuous at the inner edge. The fine-grained argillites and siltites are progressively more gneissoid from the outer to the inner part of the aureole, where clots of microcline, muscovite, and biotite are common and crystals of andalusite are conspicuous in rocks of appropriate composition. Where rocks of the Belt Supergroup above the middle part of the Wallace Formation are near an exposed intrusive, such as the small body near Antelope Mountain (pl. 1), the outer part of the aureole is marked by conspicuous flakes of secondary biotite. This identification of the outer limit of the contact aureole cannot be applied to rocks lower in the Belt Supergroup because the regional metamorphism had already prograded those rocks into the biotite zone. Thus, the ability to recognize the outer limit of contact metamorphism in the field becomes progressively more difficult with depth in the stratigraphic section.

GEOPHYSICAL DATA

THE AEROMAGNETIC SURVEY

The aeromagnetic data were recorded with a fluxgate AN/ASQ–3A magnetometer towed by the U.S. Geological Survey DC–3 aircraft. The flight paths were east-west and spaced 2 miles apart in the southern half of the area and half a mile apart in the northern half of the area, except for a 5-mile strip at the northern end where the flight spacing was 1 mile. The location of flight lines was shown by Meuschke, McCaslin, and others (1962). Flight elevation was 6,000 feet above sea level, except over Packsaddle Mountain where it was increased to 7,000 feet to clear the 6,400-foot summit. The distance of the magnetic detector from the surface varied greatly over short distances (pl. 1; *A*3, *B*3). Pend Oreille Lake is 2,048 feet above sea level, and the lake floor slopes steeply from the shore to depths of over 1,000 feet. The topographic relief of the land surface is rough; many of the higher ridge crests and peaks are at elevations between 4,500 and 5,500 feet. North of the Hope fault, the crest of the mountains ranges from 6,000 to 7,000 feet, and only a small part of this higher area was covered by the survey. The aircraft was equipped with a gyrostabilized continuous-strip camera to provide location control. The data were compiled on the U.S. Geological Survey topographic quadrangle maps of the area at scales of 1:62,500 and 1:125,000; all data were reduced to a scale of 1:125,000 on plate 1. The contour interval is 10 gammas, and the datum is arbitrary. The surveying techniques, instrumentation, and compilation procedures were described by Balsley (1952).

MAGNETIC PROPERTIES

The interpretation of the aeromagnetic data was supported by laboratory measurement of the magnetic properties of rocks in the surveyed area. Sedimentary rocks rarely produce significant positive anomalies, and the flatness of the magnetic map over the larger expanses of Belt rocks shows that these rocks have little or no anomalous character. For this reason, most of the samples were collected from various bodies and kinds of igneous rocks to evaluate them as sources of anomalies.

The properties measured were magnetic susceptibility and magnitude and, for some specimens, direction of the remanent magnetization (table 1). All the measurements were made in the U.S. Geological Survey's magnetic properties laboratory in Silver Spring, Md., by William Huff. An inductance bridge was used for determining the susceptibility, and a motor-driven "spinner" magnetometer (Doell and Cox, 1965) was used for measuring the remanent magnetization.

TABLE 1.—*Magnetic properties of rocks from the Pend Oreille area, Idaho*

[Data obtained from cores of samples; two sets of numbers shown if two cores from the same sample were measured. Magnetic measurements made by William Huff]

Sample[a] No.	Rock type	Magnetic susceptibility (k), in cgs units $\times 10^{-3}$	Remanent magnetization (J), in emu/cm³ $\times 10^{-4}$	Bearing of declination of J[b]	Inclination of J (positive below horizontal)[b]	Königsberger ratio (Q)[c]
	Cretaceous					
1	Granodiorite	0.83	0.78	349	+68	0.16
		.87	.77	338	+67	.15
2	do	.87	.84	19	+60	.17
		.84	.79	28	+59	.16
3	do	1.02	1.25	207	−84	.21
		.94	3.12	257	−51	.57
4	do	.72	39.3	----	----	9.4
5	do	1.47	3.54	128	−69	.42
		1.21	6.20	131	−72	.89
6	do	.89	.30	63	+77	.06
		1.18	.32	14	+78	.05
7	do	.07	.11	----	----	.27
8	do	1.22	1.45	----	----	.20
9	do	1.15	.88	----	----	.13
10	do	1.66	.82	207	+75	.09
		1.45	1.45	324	+63	.17
11	do	1.70	[d]1.07	244	+80	.11
		1.56	2.31	103	+66	.26
12	do	.91	1.87	80	+44	.35
		.91	1.41	74	+48	.27
13	do	.30	[d].27	68	+73	.16
		.30	[d].24	271	+87	.14
14	do	.04	.05	----	----	.22
		.05	.09	----	----	.31
15	do	.55	.30	----	----	.09
		.61	.10	----	----	.03
16	do	.35	.14	----	----	.07
17	Diorite dike	4.46	8.61	----	----	.33
18	Quartz monzonite sill	.06	.05	----	----	.13
19	Lamprophyre dike	2.43	.40	----	----	.03
20	Granophyric granodiorite sill	.07	.08	----	----	.20
	Precambrian					
21	Quartz diorite sill	.11	.04	----	----	.06
		.11	.06	----	----	.09
22	do	.07	.01	----	----	.03
		.07	.02	----	----	.05
23	do	.09	.02	----	----	.04
		.10	.36	----	----	.62
24	do	.09	.63	----	----	1.2
25	do	.11	.06	----	----	.09
26	Prichard Formation, siltite speckled with magnetite.	.97	1.18	----	----	.21
27	Prichard Formation pyrrhotitic argillite	.06	.05	----	----	.16
28	Burke Formation, siltite speckled with magnetite.	.06	.11	----	----	.31

[a] Sample locality shown on plate 1.
[b] Declination and inclination of J shown only for oriented samples.
[c] In Pend Oreille area, $Q = \frac{J}{0.58k}$
[d] Core showed unstable remanent magnetism.

Measurement of the magnetic susceptibility allows comparison of the magnitude of induced magnetization in the present earth's field with the magnitude of remanent magnetization to determine the relative importance of each. Remanent magnetization is acquired largely at the time of crystallization of the igneous rocks, although it may be subsequently modified in various ways including exposure to lightning strikes or chemical alteration. The ratio of remanent to induced magnetization is called the Königsberger

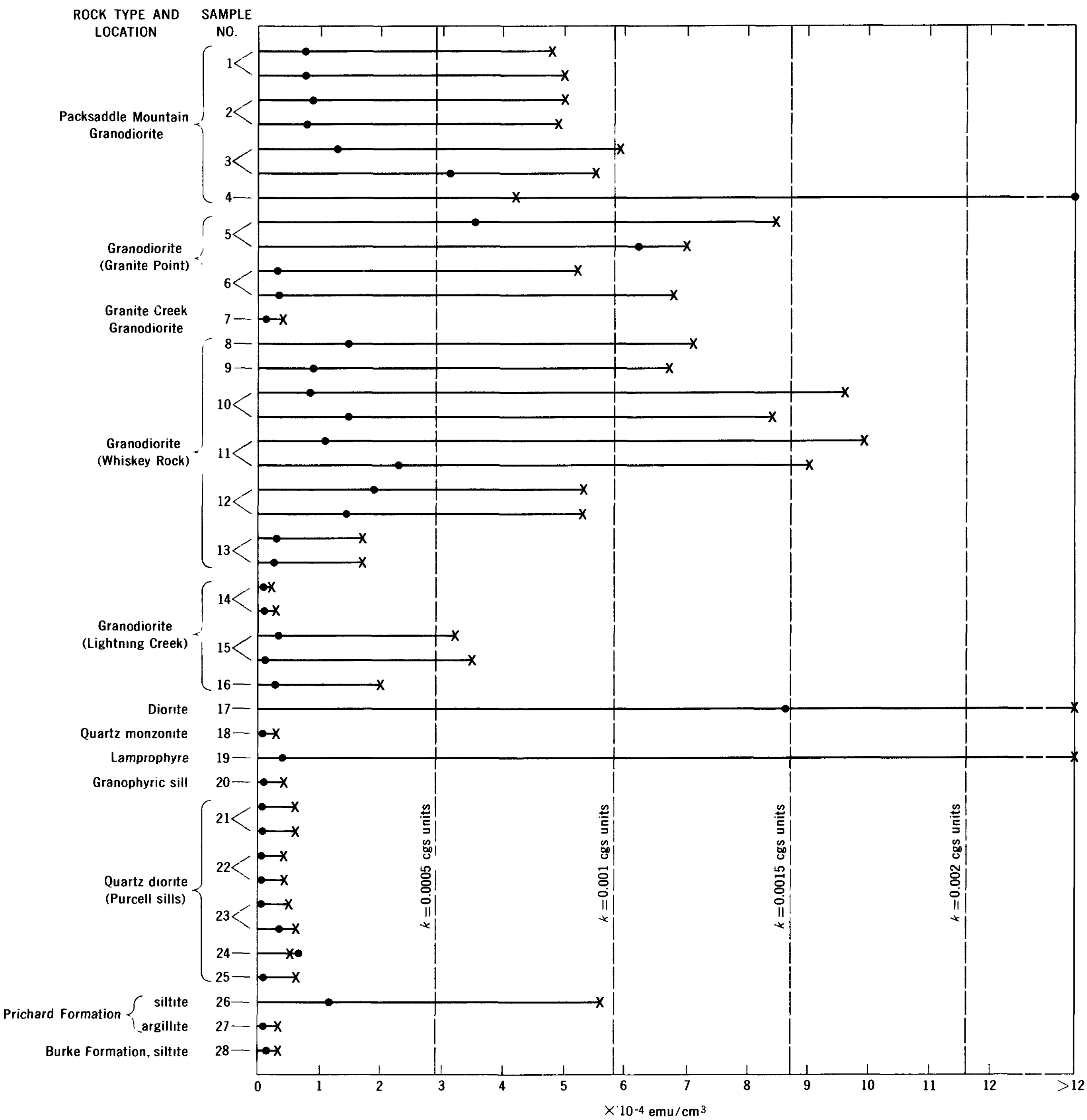

FIGURE 3.—Magnetization of rocks from the Pend Oreille area. ●, remanent magnetization; ×, induced magnetization (in earth's field of 0.58 oersted); *k*, magnetic susceptibility. Sample numbers refer to those given in table 1 and shown on plate 1.

ratio, or Q, which is defined as $Q = \frac{J}{kH}$, where J is the remanent magnetization, H is the earth's field, and k is the susceptibility. Q is independent of the direction of the remanent magnetization and was calculated for all samples (table 1). The direction of remanent magnetization was determined for several of the granodiorites, for which oriented samples were collected in the field. The locations of the samples are shown on plate 1. Figure 3 shows remanent and induced magnetizations for each sample, plotted to the same scale. More than one core was obtained from many of the samples, resulting in the paired measurements.

The results of the laboratory measurements confirm what can be deduced from the aeromagnetic map—that is, the bulk of the magnetic anomalies are produced by the bodies of granodiorite, with which they show an excellent correlation. Other rocks show an appreciable magnetization but occur only in bodies too small to affect the aeromagnetic map.

The Purcell sills in the northern part of the area all have a negligible susceptibility and a remanent magnetization below the detection limit of the equipment. Diorites are usually quite magnetic, but, as previously noted, these Precambrian quartz diorite sills have been subjected to alteration which may have destroyed any initial magnetization.

The rocks of the Belt Supergroup are generally poor in magnetite (3–5 percent combined FeO and Fe_2O_3 for most of the rocks), and the regional metamorphism has not augmented their magnetite content significantly. Samples of a few Belt rocks in which magnetite or pyrrhotite was present in appreciable amounts were measured; only one of these, a Prichard siltite from a tectonically disrupted zone over an intrusive cupola about 5 miles north-northeast of Packsaddle Mountain, was magnetic. A localized increase in magnetization is shown in the field by erratic behavior of the compass needle in areas where some contact metamorphic aureoles are sufficiently high in magnetite or pyrrhotite content. In such places, the anomaly caused by the granodiorite might have been augmented slightly.

Representative samples were measured for most of the bodies of granodiorite in the area. The measurements show that the granodiorite south of the Hope fault tends to have a susceptibility that averages 0.001 cgs (centimeter-gram-second) units. The remanent magnetization is also fairly uniform, with a small Q of not more than 0.2, with only a few exceptions. One unoriented sample from Packsaddle Mountain had a susceptibility in the normal range but a remanent magnetization of nearly 40 emu/cm^3 (electromagnetic units per cubic centimeter). Another oriented sample from the top of Packsaddle Mountain had a slightly higher than normal Q and a remanence in the negative direction—that is, pointing upward. These abnormal magnetizations are the effects of lightning, which is most prevalent on peaks and other exposed locations. These magnetizations are local and random, so that for the body as a whole, the susceptibility is the dominant factor in producing the observed anomaly. The remanent magnetizations are small and, although the azimuths show a wide range, they dip at fairly steep angles and probably slightly enhance the induced magnetization. There were some differences in susceptibility for the various bodies sampled. The Packsaddle Mountain body shows the least scatter in values, which average 0.0009 cgs units. The granodiorite of Granite Point tends to have a slightly higher value, although a sample from the block immediately to the south of Packsaddle Mountain had an abnormally low susceptibility. The Whiskey Rock group of samples shows more scatter in that values of susceptibility range from 0.0003 to 0.0017 cgs units, but the average is 0.001 cgs units. In general, magnetic properties of the granodiorites south of the Hope fault are similar enough to suggest that they have a common source. North of the Hope fault, the granodiorite of Lightning Creek has a relatively low susceptibility and negligible remanent magnetization.

The remaining measurements were of samples from several dikes and sills. A narrow diorite dike from Warren Island was intensely magnetic but was not crossed by a flight line. Two lamprophyre dikes of the ore-stage age also had a high susceptibility and, although too small to have any effect on the aeromagnetic survey, perhaps could be mapped by detailed ground magnetic methods.

INTERPRETATION OF THE AEROMAGNETIC DATA

The contoured aeromagnetic data shown on plate 1 portray large areas of remarkably low gradient upon which a preponderance of positive anomalies with small to moderate amplitudes are superimposed. The pronounced slope of the magnetic surface to the southwest is almost entirely the effect of the earth's main magnetic field, which decreases in this area at a rate of 10 gammas per mile in a direction 36° west of south. Most of the magnetic anomalies are sharp enough so that they are not obscured by this gradient, but a few very gentle variations are brought out by removing this gradient, as shown in figure 4. Removal of the regional gradient brings out a few more small positive magnetic closures in the southeast, as well as emphasizes some broad low areas such as the one south of the Hope fault and those along the Cascade fault and the Magee fault zone.

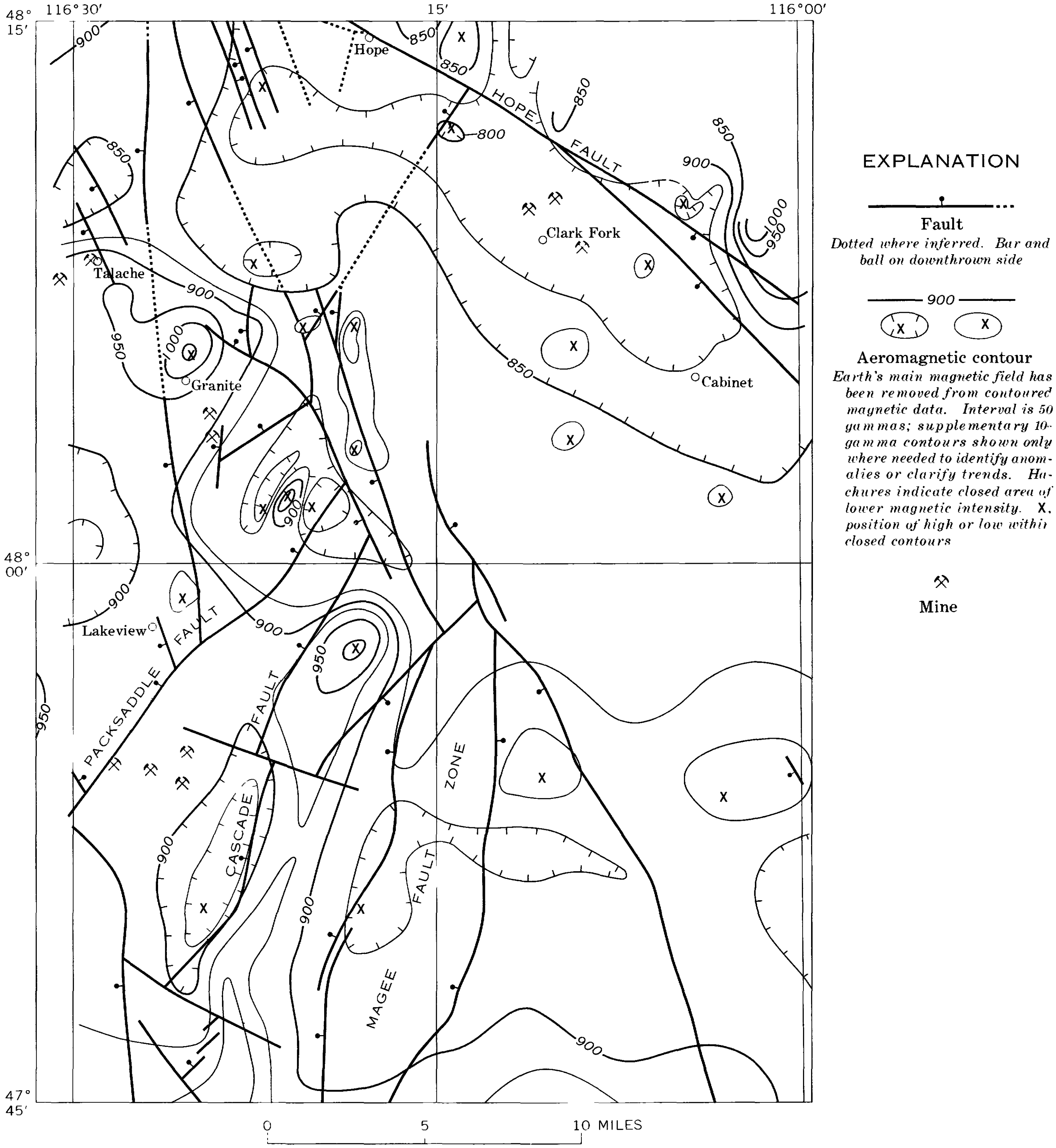

FIGURE 4.—Aeromagnetic anomalies, major faults, and principal mining districts.

The aeromagnetic map shows good correlations between positive anomalies, the intrusive granodiorite bodies, and major faults or fault zones. On the basis of the magnetic pattern, the area can be divided into three parts: (1) the area of limited information northeast of the Hope fault, (2) the nearly flat eastern half of the area, which is punctuated by a number of small circular anomalies in a random pattern and which includes the Magee fault zone, and (3) the western half, which has a strongly reticulate pattern of higher amplitude anomalies.

POSITIVE MAGNETIC ANOMALIES

A preliminary report on the relation between positive magnetic anomalies and geologic features (Harrison and others, 1961) presents discussions on correlations in the northwestern third of the area. That report documents in some detail the close association between positive anomalies and exposures of Cretaceous granodiorite or zones of increased metamorphic grade in the metasedimentary rocks that indicate near-surface bodies of granodiorite. The most prominent of these anomalies is the high associated with the Packsaddle Mountain Granodiorite body. The series of granodiorite bodies exposed along Pend Oreille Lake from Granite Point to Lakeview are indicated by a large magnetic high at Granite Point and a linear anomaly along the lake shore. The small high 3 miles east of Clark Fork is adjacent to the Hope fault and is precisely over a small exposure of granodiorite. The other small highs in the northeastern part of the surveyed area coincide with local zones of higher grade metamorphic rocks. The series of highs north-northeast of Packsaddle Mountain are over an area where the rocks are not only higher in metamorphic grade but tectonically disrupted as well; a sample of Prichard siltite from one of these localities was found to have a relatively high magnetic susceptibility.

These same correlations are recognizable in the remainder of the area south of 48° N. latitude. The only two exposures of granodiorite mapped are marked by well-defined magnetic highs, one northeast of Lakeview and the other southeast of Packsaddle Mountain (pl. 1). When the regional gradient was removed, two positive magnetic closures were isolated in the area east of the Magee fault zone (fig. 4), but they are not as clear cut as those to the north. Perhaps a closer spacing of flight lines in the southern half of the area would have provided detailed data that would have outlined other small anomalies similar to those in the northeastern quarter of the area. The mapping of metamorphic grade was not extended into the southern half of the area; as a result, a correlation with magnetic highs was not possible. However, every known outcrop of granodiorite is accompanied by a clearly defined magnetic high.

The relatively high magnetic susceptibility of the granodiorite (table 1) and the obvious correlation between positive anomalies and exposed granodiorite bodies (pl. 1) give a high degree of assurance to the interpretation of all positive anomalies in the area as reflections of granodiorite masses. This is particularly true when one considers that (1) other principal rocks of the map area have low magnetic susceptibility (table 1), and (2) almost all positive anomalies where no intrusive is exposed are accompanied by an identifiable increase in metamorphic grade (Harrison and others, 1961, fig. 67.2).

RELATION OF AEROMAGNETIC PATTERNS TO TECTONIC FEATURES

The aeromagnetic map pattern also shows some direct relations to the fault pattern (pl. 1; fig. 4). In figure 4, only those faults that have an apparent vertical throw of at least 2,000 feet are shown, with the exception of the Magee fault zone, which has a cumulative stratigraphic throw of several thousand feet on many small faults and which is indicated by delineation of the bounding faults only.

THE HOPE FAULT

The Hope fault is clearly delineated by the contoured magnetic data, which show a very smooth flat plane on the south side juxtaposed with a variable pattern of magnetic anomalies on the northeast (pl. 1). These anomalies are cut off abruptly at the fault. Although magnetic data are limited on the northeast side of the fault, some of the anomalies can be interpreted together with the known geology. The granodiorite along Lightning Creek was found to be less magnetic than the granodiorites south of the Hope fault (pl. 1), and this is reflected by the relatively small magnetic anomaly recorded on the two flight lines that came near the granodiorite body. The anomaly with a narrow crest just east of long 116°15′ W. coincides with one of the exposures of the Purcell sills, but they were found to have negligible magnetic susceptibility (table 1), which suggests that a near-surface body of granodiorite may be responsible. In fact, a granodiorite dike mapped just west of long 116°15′ W. is coincident with a smaller magnetic high. The 1,350+ gamma anomaly at the east edge of the surveyed area is probably a buried intrusive whose surface indications include a fine-grained granodiorite sill and a "bleaching" to pale green of the normally purple St. Regis Formation exposed in the area of the large anomaly. The Hope fault is paralleled on the southwest by a broad low which is roughly coincident with the surficial deposits of the Clark Fork river valley and the adjacent portion of Pend Oreille Lake.

FAULT CONTROL OF EMPLACEMENT OF GRANODIORITE

The correlation of the reticulate pattern expressed in the aeromagnetic map with the complex fault system shown on plate 1 and in figure 4 is striking. Such angularity of contours is unusual and on the basis of that characteristic alone is suggestive of faulted blocks. The excellent correlation of most magnetic highs with exposed granodiorite and the uniformity of magnetic properties for the granodiorite as a whole support the conclusion that the anomaly pattern is primarily influenced by the shape and relative depth to fault-bounded blocks of granodiorite. Both the geologic and the geophysical evidence suggests that granodiorite underlies the entire area and that as the granodiorite pushed upward in a rather viscous state, it elevated some blocks along preexisting faults, and later some of the blocks collapsed into the cooling melt. Subsequent erosion following the structural adjustment has exposed, or nearly exposed, granodiorite in the fault blocks that now give high magnetic anomalies.

The magnetic data facilitate recognition of several of these blocks. A nearly square low that surrounds Packsaddle Mountain indicates a tectonically low block, and this indication from the magnetic data is supported geologically by the preservation of Cambrian sedimentary rocks in this dropped block. Tectonically higher blocks occur to the northwest at Granite Point, to the southeast between the Cascade and Magee faults, to the west at Whiskey Rock Bay, and to the northeast, although this block is more complex than any of the others.

The depth of burial of the granodiorite masses was estimated for individual anomalies by means of the observed profiles and methods described by Vacquier, Steenland, Henderson, and Zietz (1951). These methods assumed that the mass of rock causing the anomaly has a uniform magnetization, is flat topped, and extends downward vertically for a great distance. Under such conditions, the vertical distance from the detector to the top of the body is a function of the horizontal extent of the steepest gradient on the side of the anomaly. The best estimates are made from traverses across the anomaly normal to the gradient, but a correction can be made if the anomaly is two dimensional and has a linear gradient extending for a considerable distance on the map. The granodiorite blocks are almost uniform in magnetization and are nearly vertically sided. However, many blocks do not have flat tops, and the calculated downward vertical extent may be too small if granodiorite underlies the entire region. For bodies that show a small anomaly, estimates of distance from the detector down to the top of the body will be too small.

Error in the estimates of distance from the detector to the top of any particular granodiorite body in the Pend Oreille area ranges from about 10 percent too large an estimate, made from sharp high-amplitude anomalies, to about 35 percent too small an estimate, made on small, low-amplitude anomalies. Percentage of error is based on comparison of calculated elevations and actual elevations of exposed granodiorite bodies. When we take into account these limits of error, we find that with the exception of the Packsaddle Mountain body, all cupolas top out between elevations of 2,000 and 4,500 feet. The ridge of granodiorite between the Cascade fault and the Magee fault zone (pl. 1) is only about 1,000 feet below the present topographic surface for most of the length of the ridge.

The shapes and relative depths of the granodiorite masses were further studied by selecting two representative geologic sections and calculating a theoretical profile to fit the observed data along these sections (pl. 1). Locations of the sections are also shown on plate 1. *A–A′* crosses the Whiskey Rock and Packsaddle Mountain bodies and the small circular anomaly south of Cabinet. *B–B′* crosses the Cascade fault and the Magee fault zone in the southern half of the area. The gradient caused by the earth's main magnetic field has been removed from the second profiles (*A*2, *B*2) shown on plate 1. The theoretical anomaly profiles were computed by use of a FORTRAN program based on a method similar to that used by Talwani and Heirtzler (1964). The calculated magnetic profile fits the positive anomalies quite well when a susceptibility of 0.001 cgs units is used in the calculations. The Packsaddle Mountain Granodiorite (pl. 1) is found to be a narrow body. The fit was improved by allowing for the effect of the sharp crest and steep west wall. The Whiskey Rock block at the west end of section *A–A′* is a nearly flat-topped body about 2 miles wide. The body causing the small anomaly near the east end of section *A–A′* is cautiously estimated to be 3,000 feet wide and 3,500 feet above sea level. The depth of the granodiorite underlying most of the mapped area is difficult to determine. The fit of the calculated anomalies is improved by considering that a floor of granodiorite lies under the area, but the calculations are not very sensitive to changes in the level of this floor, which may be from sea level to several thousand feet below sea level.

A representative magnetic profile *B–B′* across the Magee fault zone and the ridge of granodiorite to the west is shown on plate 1. The granodiorite is probably bounded on the west by the Cascade fault, but it does not extend east as far as the Magee fault zone. A deeper, wider block of granodiorite indicated by the broad low anomaly at the west end of the profile is probably a continuation of the granodiorite at Whiskey Rock.

The Magee fault zone, although formed under a similar environment and during the same period of crustal adjustment as the faults making up the mosaic system, has quite a different structural pattern. It consists of a series of steeply dipping to vertical fault wedges within a distinct structural band 3 to 5 miles wide extending about 20 miles in a north-northeasterly direction. At the north it ends abruptly at the intersection of a group of northwest- and northeast-trending faults, and at the south (just south of the mapped area) it terminates against a series of west-northwest-trending faults. To the east it is bounded by Belt rocks of the same formational units as those in the fault zone, but which are relatively undisturbed and lie within the western limb of the broad gentle north-northeast-trending syncline. To the west the zone is bounded by a tilted fault block in which Belt rocks underlying those in the fault zone dip moderately to steeply to the east.

An incomplete section of Belt rocks about 3,500 feet thick, which includes the uppermost part of the middle Belt map unit and most of the upper Belt map unit, is involved within the fault zone. In general, the strike of these rocks parallels the trace of the faults, which in turn parallels the trend of the zone, although individual fault wedges are discontinuous. From a few hundred to a few thousand feet of section make up each fault block. Typically, from west to east, one finds older to younger rocks interrupted at each fault and then a complete or partial repetition of the same section in the next fault block, with a progression upward through the 3,500 feet of section (pl. 1).

A positive magnetic anomaly of unusual linear extent coincides with the extent of the tilted block that bounds the Magee fault zone on the west. This anomaly has a prominent maximum over a small granodiorite pluton just west of the north end of the fault zone, and tails off gradually to the south.

The juxtaposition of the magnetic anomaly with the tilted fault block and the parallelism of the unique fault zone that bounds them on the east are strongly indicative that these phenomena are related in origin. The anomaly undoubtedly shows the presence of a buried intrusive whose upper surface is a ridge trending slightly east of north. The ridge either slopes gradually to the south or is downfaulted in two steps from north to south. The small pluton at the north is a cupola of this intrusive body and the only exposure of it at the surface. During its emplacement, this granitic mass shouldered up a part of the section of Belt rocks forming the tilted block. The Cascade fault is the major break bordering this tilted block on the west, and the apparent vertical throw along it amounts to as much as 12,000 feet. The Cascade fault nearly parallels the Packsaddle fault and has the same relative direction of movement as does the Packsaddle. The Cascade fault may have had its beginning in Precambrian time also, but much of the movement is most logically related to the intrusive period. The Magee fault zone on the east is most plausibly explained as a block that foundered in relation to the tilted block. A sharp monoclinal flexure formed along the Magee fault zone during emplacement; and as tilting of the block to the west continued, successive wedges foundered from the east margin of the tilted block.

The postulated origin of the Magee fault zone is shown in figure 5. At the inception of the tilting of the block and the formation of the monocline, the forces were most logically compressional (fig. 5*B*, *C*), but during the period of collapse and the foundering of the wedges they were tensional (fig. 5*D*). Scattered through the zone are small fault blocks made up of rocks younger than those in the wedges that bound them. In some blocks, the strata dip at moderate to low angles in contrast to the near-vertical attitude of the beds in the bounding wedges. One of the more unusual of the blocks, which lie along the east margin of the zone, is an isolated exposure of Cambrian Gold Creek Quartzite at the surface, which there probably lies on the upper part of the Striped Peak Formation or on the lower part of the Libby Formation. The process of formation of the Magee fault zone represents in miniature the process believed responsible for the block-mosaic pattern of the entire western half of the area (compare fig. 5 of this report and fig. 67.3 of Harrison and others, 1961).

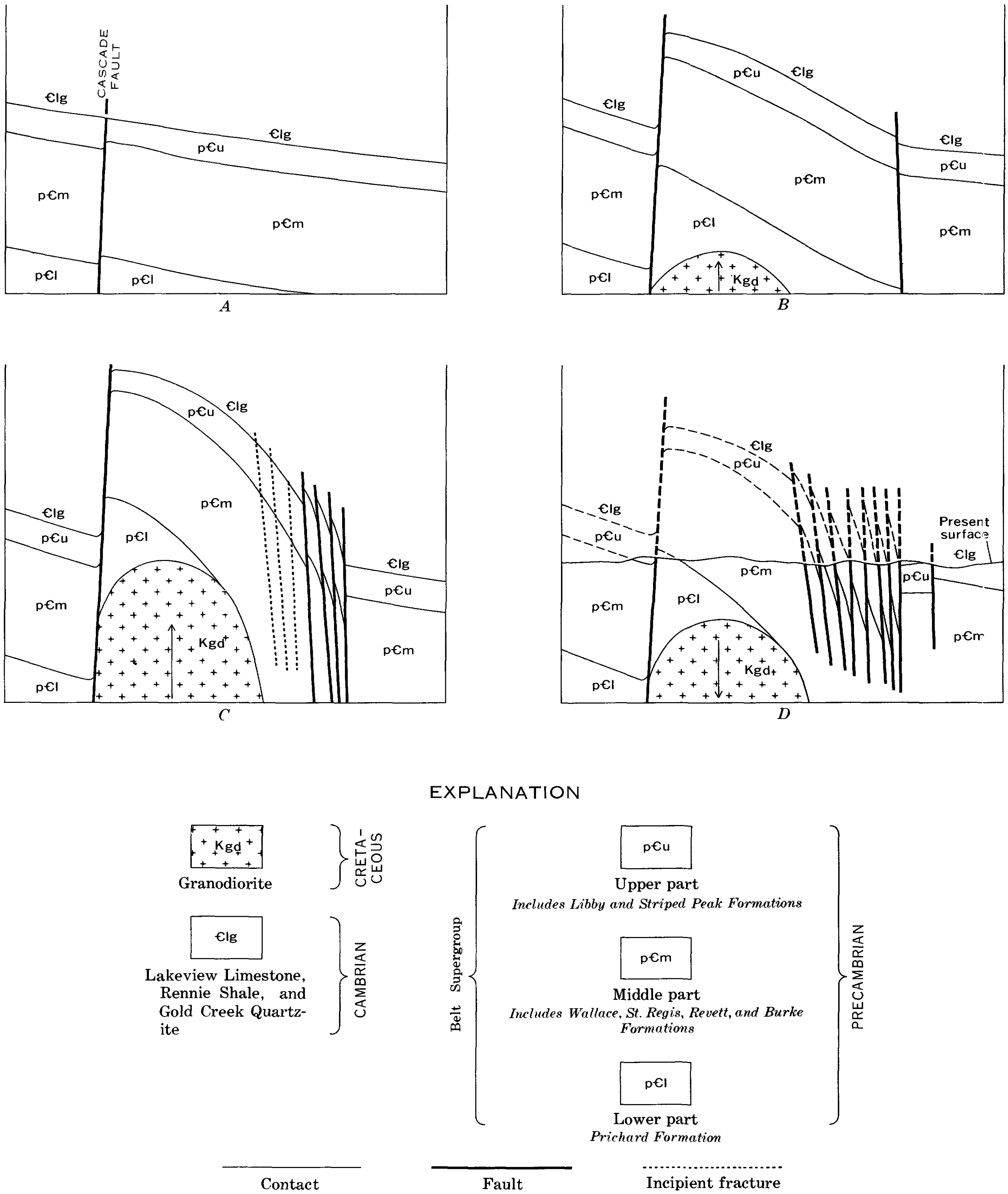

Figure 5.—Postulated origin of the Magee fault zone.

AEROMAGNETIC DATA AND THE MINING DISTRICTS

The principal mines of the area are shown in figure 4. These generally are grouped into four small mining areas near Clark Fork, Talache, Granite, and Lakeview. Many small prospects exist in the area, but the mines indicated in figure 4 are those described by Savage (1967, p. 81–98) as having had significant amounts of ore shipped from them. We can find no detailed and specific relation between either positive or negative anomalies and the mining areas. This is disappointing but not suprising. None of the ores contain sufficient magnetic minerals to have caused a positive anomaly in the airborne survey, and the altered zones are too small to have caused a negative anomaly recognizable in the survey.

CONCLUSIONS

Aeromagnetic anomalies in the Pend Oreille area are principally a reflection of the greater magnetic intensities of surface and near-surface granodiorite masses. Positive anomalies reflect exposed or buried cupolas and stocks from a larger mass inferred to extend under most of the area. The location of the cupolas and stocks is related to major faults, most of which are believed to have been in existence at the time of the intrusion. These major faults are part of a north-trending zone of weakness that corresponds in part with the Purcell trench, and the zone has served to help localize intrusion as well as later erosion that exposed some of the intrusives. Many of these major faults are reflected in the magnetic pattern by elongate lows.

The intrusive process included tectonic raising and forceful invasion of magma into a previously faulted segment of the earth's crust. The western part of the area rose considerably more than the eastern. Tilting and gross flexing accompanied intrusion, and a mosaic of minor block faults formed as the tectonically raised area collapsed into the underlying magma. Among the more spectacular features that were formed was the Magee fault zone. It was caused by an elongate cupola that lifted and tilted a block bounded on the west by the Cascade fault. As the block continued to rise, a monoclinal flexure formed a few miles to the east beyond the edge of the cupola. This flexure eventually stretched, shattered, and collapsed to form the Magee fault zone.

The complete lack of granodiorite dikes along the faults indicates that the whole process of uplift, intrusion, and collapse did not cause sufficient tensional stresses to allow dike intrusion. Several factors were probably involved: (1) the granodiorite was cool and viscous, as suggested by the small contact-metamorphic zones and the almost total lack of pegmatite or aplite in the bodies, (2) the regional stresses at the time of magma upwelling may have been compressional and thus aided forceful intrusion and uplift of the blocks, and (3) collapse of the blocks may have followed relaxation of regional stress and may have occurred after partial cooling of the melt.

Ore deposits are probably related in time to the intrusive process, but the known deposits are not reflected by the aeromagnetic data. Because the widespread buried granodiorite masses are reflected by the aeromagnetic data and because the intrusive process took advantage of preexisting faults, aeromagnetic surveys of the faulted Belt terrane to the east of the Purcell trench might reveal areas of buried granodiorite associated with old fractures that could be broad target areas worthy of exploration for ore deposits.

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