

PSEUDO-RHYTHMIC LAYERING IN THE SQUARE BUTTE ALKALI-GABBRO LACCOLITH

JOSEPH J. BEALL, *Department of Geology, University of Montana,
Missoula, Montana 59801*

ABSTRACT

Square Butte is a conspicuously layered 250+ foot thick, alkali rich, gabbroic laccolith at the northern end of the Big Belt Mountains of Montana. A pair of layers consists of a subequal thickness of lighter colored, less resistant rock, grading downward into darker, more resistant rock. Both types of layers contain diopsidic augite phenocrysts in essentially constant amounts. The layering results from groundmass alteration of feldspars to zeolites in the lighter layers. Analyses of these rocks indicate no significant chemical variation between light and dark layers. It is suggested that the layering was caused by multiple injections of magma, each 14 to 16 feet thick, with successive injections thermally metamorphosing the upper half of the subjacent injection.

Square Butte laccolith is similar in chemistry and thickness to Shonkin Sag laccolith, located about 60 miles to the east in the same alkalic province. The differentiation so evident in Shonkin Sag laccolith is missing from Square Butte, adding credibility to the hypothesis.

INTRODUCTION

Square Butte is a conspicuously layered 250+ foot thick, alkali-rich-gabbroic laccolith at the northern end of the Big Belt Mountains of Montana. The feeder dike for this laccolith is exposed and cuts across Cretaceous sediments for twelve miles south of Square Butte. This dike, terminated at its northern end by Square Butte, is part of a radial dike swarm which radiates from the Three Sisters stock, located twenty-two miles south of Square Butte in the center of the Adel Mountain volcanics. Although this study concentrated specifically on the layering in Square Butte, there are three other laccolithic intrusions (Cascade, Fort Shaw, and Crown Buttes) within ten miles of Square Butte that are similarly layered. Lyons (1944) described the general geology and igneous rocks of the region.

GENERAL DESCRIPTION

The lower contact of the laccolith is exposed in several places. Although no sediments remain above the laccolith, the upper chill zone is still present in two small outcrops making it possible to vertically sample the entire laccolith. Columnar jointing is well developed in the steep butte walls, the columns extending throughout the thickness of the butte. One very conspicuous feature, best viewed in fresh outcrops, is a set of semi-continuous, horizontal veins of alkali-syenite. In the

chill zone, these veins are very thin (1 mm.) and closely spaced (1 cm.). With increasing distance from the chill zone the veins become gradually farther apart and thicker, attaining a vertical separation of three to four feet and a thickness of 1.5 inches in the upper middle of the intrusion. The veins cut cleanly across the columnar joints without injecting into them. The similarity between the vein material and the groundmass, subtle mafic selvages adjacent to the veins, and the lack of any signs of forceful injection, strongly suggests that the veins are formed by concentration of material from the groundmass of the immediately adjacent rock. The cause of this veining is unknown although it may be related to the horizontal jointing sometimes found in the entablature of lava flows (*eg.*, Lefebvre, 1970), the cause of which is also unknown.

PETROGRAPHY

The rock is porphyritic (with the exception of the vein material) with unzoned diopsidic augite ($\text{Ca}_{46.5}, \text{Mg}_{37.3}, \text{Fe}_{16.2}$) uniformly comprising about 24 percent by volume of the rock. Magnetite and apatite are commonly included in the pyroxene phenocrysts. A few, usually highly altered, plagioclase (An_{65}) phenocrysts, are generally present.

Chilled Margin

The very fine grained nature of the chilled margin gradually disappears through the lower fifty feet of the laccolith, as indicated by a gradual increase in the size of anorthoclase crystals in the groundmass. The increase in grain size away from the upper chill zone occurs over a much smaller distance. The groundmass consists mainly of anorthoclase laths which give it a felty texture. Magnetite forms about 10 percent of the rock. It occurs in two distinct sizes, the larger commonly forming inclusions in the pyroxene phenocrysts. Biotite, which forms about 5 percent of the rock, is present in two varieties, a fresh, euhedral type, with x = light yellow and z = dark green, and an altered anhedral type with x = red and z = brown. Also present in small amounts are small pseudoleucite phenocrysts, zeolites, calcite, and apatite.

Alkali Gabbro

The diopsidic augite (salite) phenocrysts in the bulk of the laccolith are set in a groundmass dominated by anorthoclase in euhedral to subhedral crystals. Plagioclase (An_{60}), generally in small crystals, constitutes about one-fourth of the groundmass and occurs both interstitially and embedded in the larger anorthoclase crystals. The plagioclase

clase shows incipient alteration to thomsonite and albite. A small amount of olivine is altered to iddingsite along cracks but the former presence of more olivine is evidenced by pseudomorphs of red to orange biotite and iddingsite. Biotite also occurs as euhedral crystals with x = light yellow and z = red to green (edges distinctly more green). Magnetite, as in the chilled zone, occurs in two distinct sizes and forms 10 percent of the rock. Clinopyroxene (optically identical to the phenocrysts), pseudoleucite, zeolites, and apatite complete the groundmass.

Veins

The veins are typically equigranular with a diabasic texture imparted by anorthoclase laths which form most of the vein. Anorthoclase shows varying degrees of alteration to natrolite and analcite. Also present in small amounts are: euhedral biotite with x = light yellow and z = dark green to brown, subhedral to anhedral diopsidic augite with narrow green rims of aegerine augite, and magnetite.

LAYERING

The layering is recognized as alternating light and dark bands, each 6 to 8 feet thick. A pair of these layers, sharply bounded on top and bottom, consists of a subequal thickness of lighter colored, less resistant rock grading downward into a darker colored, more resistant rock. In fresh outcrop this is seen only in subtle color changes. In weathered rock, however, the darker layers stand out in relief whereas the lighter layers weather back, giving the butte walls a stairstep effect (Fig. 1).

Close examination of a pair of layers reveals that the darker layer is massive in its lower part. Abruptly at the base of a dark layer, the upper part of the underlying light layer is seen to be weathered along closely spaced fractures which are, in general, at a large angle to the essentially horizontal layering. The boundary between the bottom of a light layer and the top of a dark layer is gradational over a few feet as the rock grades from the closely fractured to the massive state described above (Fig. 2).

In thin section the boundary between the bottom of a dark layer and the top of an underlying light layer is a more gradual one. First, the groundmass plagioclase crystals begin to alter to zeolites (mainly thomsonite) and/or become less calcic with little change in the anorthoclase. With increasing alteration most of the plagioclase is altered to thomsonite with some replacement of plagioclase by biotite. The center of a light layer is characterized by alteration so intense that relict crystals of plagioclase are unrecognizable. Anorthoclase shows

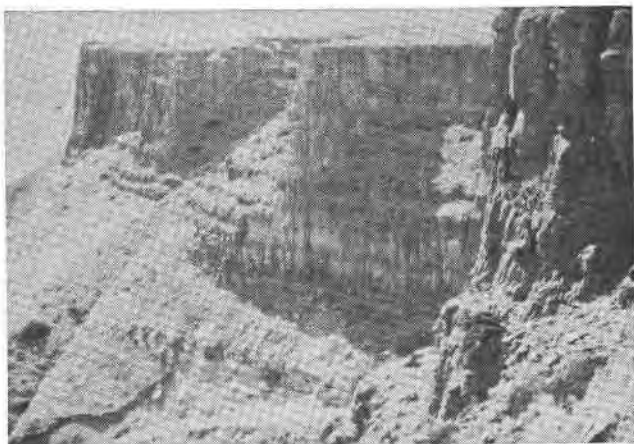


FIG. 1. Layering of Square Butte as seen from the south. Photograph shows the color banding evident in fresh outcrops (lower cliff face) and the stairstep effect of more weathered layering.

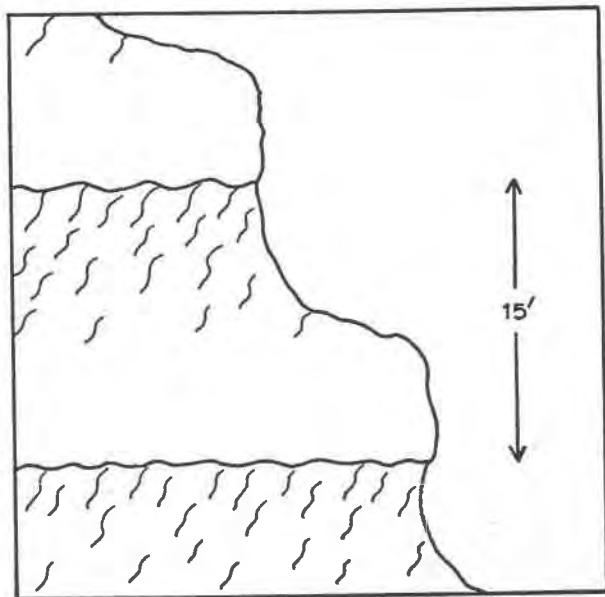


FIG. 2. Schematic cross section through a pair of light and dark layers. Diagram shows the fractured nature of the light layers, the massive nature of the dark layers, the sharp boundary at the base of dark layers, and the gradational boundary at the base of light layers.

intense alteration to zeolites (natrolite, analcite, thomsonite) and to a lesser extent biotite. Lyons (1944) noted a gradual change in specific gravity to lower values toward the middle of light layers as would be expected from the alteration described above.

The nature of the layering is therefore expressed both in terms of the physical properties of the rock and in the mineralogy. The fact that the change in physical properties is rather abrupt at the base of dark layers, whereas the mineralogy changes over a distance of several feet requires additional consideration.

In view of the pronounced differences between the light and dark layers in terms of resistance to erosion, mineralogy, and color, it seemed likely that chemical analyses of samples with close vertical spacings might provide a key to the origin of the layering. Eighteen chemical analyses of the eight major oxides indicate no significant variation between light and dark layers (Fig. 3). Similarly, there is no variation in the percentage or composition of the diopsidic augite phenocrysts between the layers. These phenocrysts are present in constant amounts throughout the intrusion.

Lyons (1944, p. 458) suggested that: "Hess' 1938 proposal of (1.) relative density differences between each of the two main constituents settling and (2.) disturbance of the normal state of quiescence by short epochs of mild but irregular turbulence . . ." might have caused the layering. He offered as an equally reasonable alternative, that each pair of one light and one dark layer resulted from a separate injection of magma which differentiated to form a light and a dark band. These schemes, however, would necessarily involve chemical variations which can now be shown not to exist. The present author agrees with multiple injection of magma in layers 14 to 16 feet thick as the major cause of layering. It is probable, however, that the only differentiation to occur within each injection was the movement of volatiles (mainly water) into the upper half of the injected layer. The alternation of light and dark layers was probably caused by each successive higher injection of magma thermally metamorphosing the upper and probably more hydrous half of the subjacent injection.

Square Butte laccolith is similar in chemistry and thickness to Shonkin Sag laccolith which is located about 60 miles to the east in the same alkalic province (Larsen, 1940; Barksdale, 1937; Hurlbut and Griggs, 1939; Osborne and Roberts, 1931; Nash and Wilkinson, 1970). Since the differentiation so clearly evident in the Shonkin Sag laccolith is altogether missing in the Square Butte laccolith, it was thought that a comparison might shed some light on the layering of Square Butte. For comparison purposes the chilled zone is considered representative

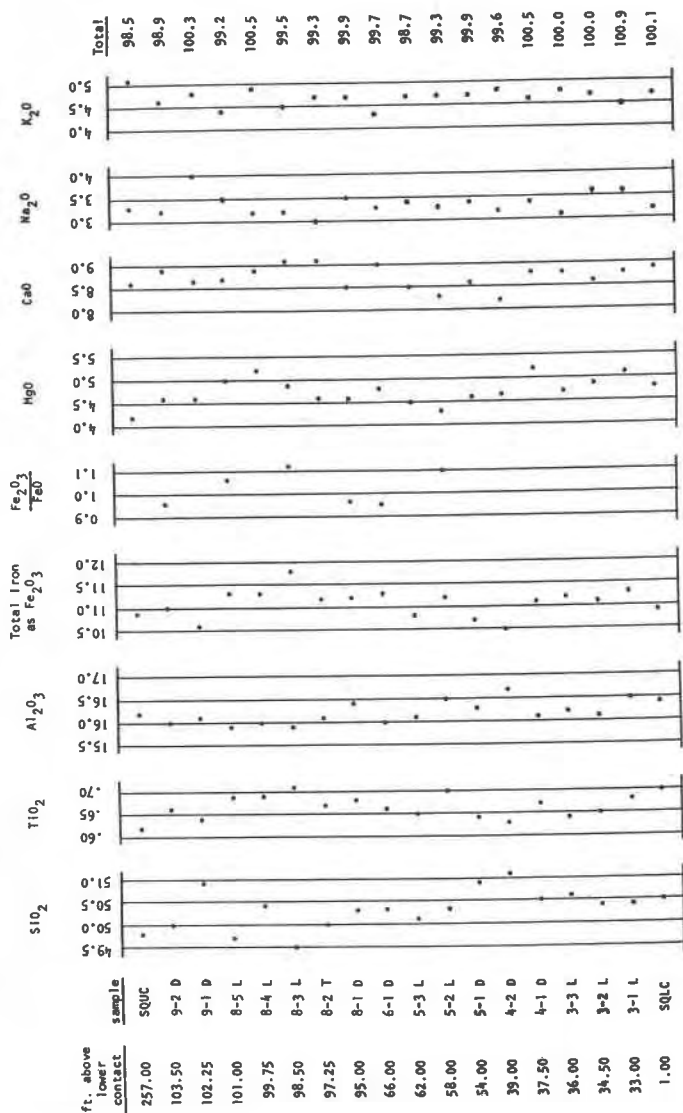


FIG. 3. Chemical analyses of Square Butte laccolith. First digit of sample number gives the number of dark layers between the bottom contact and the sample. Samples from light and dark layers indicated by "L" and "D" respectively. "T" indicates transitional rock between lower light layers and upper dark layers. "SQUC" and "SQLC" denote respectively the upper and lower chill zones.

of an approximate average Shonkin Sag composition. Both laccoliths are undersaturated in SiO₂, low in TiO₂, and high in total alkalis with K₂O > Na₂O. Square Butte is generally about 3 percent higher in Al₂O₃ and 4 percent lower in MgO than Shonkin Sag.

Multiple injection of magma to form the layering of Square Butte requires a mechanism to propel pulses of magma at regular intervals.

This could be accomplished by the buildup of vapor pressure in a magma chamber, injection of a layer of magma with a resultant drop in pressure in the magma chamber, renewed buildup of pressure, etc. If this mechanism was responsible, certain petrochemical consequences of the proposed mechanism can be used as a partial test of its validity.

P_{O_2} in basaltic magmas depends primarily on the equilibrium $2H_2O \rightleftharpoons 2H_2 + O_2$. Kennedy (1948) has calculated that at $1000^\circ C$ this dissociation results in an increase in P_{O_2} from 9×10^{-6} to 9×10^{-4} bar when P_{H_2O} is raised from 1 to 1000 bars. P_{O_2} differences of this magnitude thus imply large differences in P_{H_2O} and cause significant changes in the crystallization paths of basaltic magmas. The effect of a high P_{O_2} on basaltic melts is to increase the Fe_2O_3/FeO of the system and remove iron early in the crystallization process by precipitation of magnetite. Low P_{O_2} leaves the iron in the ferrous state and allows it to remain longer in the melt and be incorporated into ferro-magnesian minerals later in the crystallization process (Osborn, 1962).

The proposed injection mechanism therefore demands that a rather large and uniform amount of magnetite appear as an early phase in all layers. Such is the case for Square Butte. Shonkin Sag samples by comparison are quite low in magnetite as shown by modal percentages of opaque minerals (Nash and Wilkinson, 1970).

Six FeO analyses were done on representative samples from Square Butte to compare Fe_2O_3/FeO with samples from Shonkin Sag. As shown in Figure 2, Square Butte rocks have a nearly constant Fe_2O_3/FeO at about 1.0. Fe_2O_3/FeO is slightly lower in samples from dark layers (e.g., 6-1D, 8-1D, 9-2D) and higher in samples from light layers (e.g., 5-2L, 8-3L, 8-5L) as might be expected from the suggested origin of the layering. Table 1, using data from Nash and Wilkinson (1970), shows that Fe_2O_3/FeO in Shonkin Sag is generally much lower than in Square Butte. Only in the highly differentiated syenitic rocks does Fe_2O_3/FeO reach 1.0. This correlates with anomalously high magnetite content for that part of Shonkin Sag (Osborne and Roberts, 1931). The high and relatively constant Fe_2O_3/FeO for Square Butte rocks may reflect the proposed injection mechanism.

Although Fe_2O_3/FeO cannot reasonably be used to assess quantitatively the P_{H_2O} in a magma, the relationship between P_{H_2O} , P_{O_2} , and the early precipitation of magnetite suggests that each injection of magma into Square Butte was subjected to high P_{H_2O} prior to injection. The much lower Fe_2O_3/FeO and magnetite content for Shonkin Sag laccolith as a whole, suggests that it was subject to significantly lower P_{H_2O} prior to being intruded. This is further suggested by what are apparently very different modes of intrusion of two laccoliths of

Table 1. $\text{Fe}_2\text{O}_3 / \text{FeO}$ for Shonkin Sag rocks. Data from Nash and Wilkinson (1970).

Sample Location	$\text{Fe}_2\text{O}_3 / \text{FeO}$
Upper Chill Zone	0.08
Upper Shonkinite	0.60
Main Syenite	0.72, 0.94
Syenite Pegmatite	1.08
Lower Shonkinite	0.62, 0.63, 0.27
Lower Chill Zone	0.18

similar size and overall chemistry, located in the same alkalic province of Central Montana.

$\text{Fe}_2\text{O}_3/\text{FeO}$ values for samples of either laccolith are presumably not those of the magma at the time of intrusion. The above argument, however, depends only on the relative difference between these values, which may be smaller now than at the time of intrusion. As would be expected from the volume of magma intruded at one time in the Shonkin Sag laccolith, $\text{Fe}_2\text{O}_3/\text{FeO}$ increases with differentiation (Table 1). This correlation strengthens the above argument. Although many surface rocks are weathered, very fresh samples were available for chemical analyses of Square Butte laccolith due to recent blasting. The amount of weathering oxidation in the rocks used is therefore minimal.

SUMMARY AND CONCLUSIONS

Several lines of evidence point to multiple injection of magma, with each successive injection thermally metamorphosing the top half of the subjacent injection, causing alternating light and dark layers in the Square Butte laccolith.

- (1) Abrupt change at the bottom of dark layers from massive, resistant rock to less resistant, fractured rock, probably as a result of reheating of volatiles in the next lower layer by the succeeding injection.
- (2) Gradual change, over several feet, from light colored, intensely fractured rock, to darker colored more massive rock below.
- (3) Extreme degree of alteration in the groundmass of the light layers.
- (4) Lack of chemical variation in the eight major oxides in closely spaced samples, within layers, between layers, and throughout the laccolith as a whole.

- (5) High and relatively constant ratio of $\text{Fe}_2\text{O}_3/\text{FeO}$ as compared with the chemically similar Shonkin Sag laccolith suggests a high $P_{\text{H}_2\text{O}}$ which could reflect the mechanism responsible for repeated pulses of magma injection at regular intervals.
- (6) Correlation of somewhat higher $\text{Fe}_2\text{O}_3/\text{FeO}$ with light layers also suggests a reheating of the upper and probably more hydrous half of the subjacent injection with a concurrent increase in the amount of Fe_2O_3 .

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