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Petrology and Rb-Sr Studies of Precambrian Granitic Rocks at Rose Dome, Woodson County, Kansas

ABSTRACT

The granitic rocks exposed on Rose Dome, Woodson County, Kansas are of Precambrian age. Rb-Sr isotope studies show that they originally crystallized between 1100 and 1300 m.y. ago. Field, drill-core, mineralogic, and petrographic studies show that the granitic rocks were emplaced as inclusions of Precambrian basement in a mica peridotite magma that intruded the Pennsylvanian section of Rose Dome during Cretaceous time.

High temperatures of the alkaline ultramafic magma (probably greater than 800°C) led to metamorphism of the granitic inclusions and the formation of high sanidine and high albite from original microcline and albite. Contact metamorphic effects include the development of buchitelike sanidine-magnesian biotite hornfels from Weston Shale (Pennsylvanian) that was intruded by the mica peridotite. That the high temperatures of the peridotite magma also led to partial melting of the granitic rocks is indicated by a quartzofeldspathic matrix that shows abundant volcanic textures and binds mineral and rock fragments together to produce the varied range of textures and structures shown by the granitic xenoliths.

Partial melting of the granitic rocks also accounts for those features that led earlier workers to conclude the "granite" on Rose Dome had intruded the Pennsylvanian section. Those features include intrusive relationships between the granitic rocks and metamorphosed Weston Shale and inclusions of hornfels entrapped within the granitic material.

The spread of isotope ratios found in the Rb-Sr studies of the granitic rocks may stem partly from partial melting and exchange of ions between the "granite" and the mica peridotite magma, or from the "sampling" of different levels of granitic crust by the upwelling peridotite magma.

INTRODUCTION

Weathered boulders of granitic rock are found in and near a clump of sumac and bittersweet in a hayfield in the SE 1/4 sec. 13, T. 26 S., R. 15 E., Woodson County, Kansas (Fig. 1, 2). Additional boulders are found in the adjoining SW 1/4, sec. 18, T. 26 S., R. 16 E.. The boulders are near the apex of Rose Dome, a breached anticlinal structure that shows more than 15 m (50 ft.) of closure on top of subsurface Mississippian and Pennsylvanian beds (Hambleton and Merriam, 1965, Plate 2). Bedrock exposed in sec. 13 is of Pennsylvanian age and includes the Weston Shale Member of the Stranger Formation (Virgilian) and the underlying Stanton Limestone (Missourian). Alkaline mica peridotite has been known to intrude the Paleozoic section in the subsurface of Rose Dome for a number of years (Twenhofel and Bremer, 1928; Knight and Landes, 1932), but the occurrence of mica peridotite in the shallow subsurface was reported only recently (Franks, 1966). Similar alkaline mica peridotite also intruded the Pennsylvanian section and is exposed at the surface at Silver City Dome, which lies about 8 km (5 mi) southwest of the apex of Rose Dome (Fig. 1) (Wagner, 1954; Franks, 1959). The mica peridotite of Woodson County, however, is petrographically unlike the kimberlitic ultramafic rock of Riley County, Kansas (Fig. 1) (cf. Franks, 1966; Brookins, 1967; Rosa and Brookins, 1966).

Figure 1. Map of Kansas showing the locations of outcropping igneous rocks. The rocks in Woodson County include alkaline mica peridotite and altered "granite;" those in Riley County are kimberlite. Data for Riley County are from Byrne and others (1956) and Brookins (1970).

Figure 2. Simplified geologic map of sec. 13, T. 26 S., R. 15 E., Woodson Co., Kansas, showing location of diamond-drill holes and line of cross-section W-E shown in Figure 3. Rock units in order of increasing age are: Kmp, Cretaceous mica peridotite (checked pattern); Pd, Douglas Group, Pennsylvanian (ruled lines); Psw, Weston Shale Member, Stranger Formation, Douglas Group, Pennsylvanian (unpatterned or stippled where hornfels); Pst, Stanton Limestone, Pennsylvanian (cross-hatched); pCrg, chiefly Rose "granite" and granitic rubble, Precambrian (unpatterned). Contacts dashed where approximately located, short dashes where inferred. Geology by H. C. Wagner and P. C. Franks, 1951, 1964.

A variety of ideas have been advanced over the years to account for the occurrence of what seem to be outcrops of "granite" in eastern Kansas.[1] One idea entertained by Twenhofel (1917, 1919) was that the boulders were products of Pleistocene glaciation. However, he discounted that thesis partly because the "granite" occurs so far south of the southern limit of Pleistocene glaciation (120 km or 80 mi.). Instead, he proposed that the boulders were rafted to their present stratigraphic and geographic position by ice during Pennsylvanian time. Subsequently, evidence favoring an intrusive origin for the "granite" was reported (Twenhofel and Edwards, 1921; Twenhofel, 1926). An intrusive origin for the "granite" generally has been accepted since the work of Twenhofel (1926) and Knight and Landes (1932). More recently, however, Merriam (1963, footnote, p. 154) suggested that the "granite" boulders might be xenoliths of Precambrian rock caught up in an ultramafic intrusive. Wheeler (1965) proposed that the "granite" on Rose Dome is the allocthonous product of large-scale overthrusting, and a variety of individuals have entertained the thought that the "granite" boulders on Rose Dome may have been brought to the surface by meteorite impact.

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[1] The term "granite" is placed in quotation marks to emphasize that most samples do not show typical granitic textures and structures and that the structural state of feldspar in the rock departs from that expected in most granite. Except for these peculiarities, the rock might be described as leucogranite.

Shallow diamond-drill holes[2/] put down by the State Geological Survey of Kansas in 1964 penetrated as much as 5.6 m (18.5 ft) of granitic residuum

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2/ Copies of the logs of the diamond-drill holes can be obtained from the State Geological Survey of Kansas, Lawrence, Kansas, or from Paul C. Franks. The core and samples are stored at the State Geological Survey.

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and also granitic material that is admixed with grayish-yellow to pale-olive clayey and micaceous weathering products derived from mica peridotite. The holes then passed either into metamorphosed sedimentary rock belonging to the normal Pennsylvanian section or into sill-like bodies of mica peridotite (Fig. 3). The ultramafic and granitic rocks of Rose Dome seem to intrude the Weston Shale Member of the Stranger Formation near its contact with the underlying Stanton Limestone. Twenhofel (1926, p. 404-405 and Fig. 2, p. 407) reported discovery of the contact between the granitic rocks and the enclosing shale near the center of the east line, sec. 13, T. 26 S., R. 15 E.. A trench dug by one of us (P.C.F.) in the same locality in the grader ditch of U.S. Highway 75 also exposed what seems to be the contact between highly weathered granitic rock and shale much altered by contact metamorphism (Fig. 2). Moreover, Franks (1965) found a boulder of weathered granitic rock with inclusions of hornfels and what appears to be baked Weston Shale clinging to it (Fig. 4). It is not surprising that an apparent post-Pennsylvanian granitic intrusive in this part of the North American stable interior has provoked much interest, especially when a Precambrian isotopic age was reported for the "granite" (R.E. Denison, 1963, oral communication to P.C. Franks; Merriam, 1963, p. 154; Muehlberger and others, 1966; Muehlberger and others, 1967).

Figure 3. Cross-section W-E of igneous, metamorphic, and sedimentary rocks on Rose Dome based on drilling by State Geological Survey of Kansas. Short dashes indicate inferred geologic contacts and correlations. Dashed portions of drill holes indicate those parts of logs based on cuttings rather than core. Rock units in order of increasing age are: Kmp, Cretaceous mica peridotite; Psw, Weston Shale Member, Stranger Formation, Pennsylvanian; Pst, Stanton Limestone, Pennsylvanian; Psv(?), Vilas (?) Shale, Pennsylvanian; pЄrg, chiefly Precambrian Rose "granite" and granitic rubble but also includes admixed, weathered mica peridotite. Vertical exaggeration, X 10.

Figure 4. Boulder of Rose "granite" near cen. E 1/2 E 1/2 sec. 13, T. 26 S., R. 15 E.. Note fragment of hornels (H) adhering to relatively flat surface on the boulder. Scale, which is about 15 cm (6 in) long, lies along the same surface. Opposite side of boulder not visible in photograph also is a relatively flat surface to which hornfels adheres. The two opposed flat surfaces are suggestive of an original dikelike or sill-like form for the "granite." Small inclusions of hornfels (HI) are partly enclosed by "granite" in right-hand part of photograph.

Age and Emplacement Problem

The Rb-Sr age of K-feldspar from one sample of Rose Dome "granite" that was reported several years ago (Muehlberger and others, 1966, 1967) was measured in the laboratories of the U.S. Geological Survey. The age obtained was 1293 m.y. ($Rb^{87} = 1.39 \times 10^{-11}$ yrs.$^{-1}$). This age seemed anomalous inasmuch as the "granite" apparently had intruded sedimentary rock of Pennsylvanian age; the unusual thermal history of the granitic rocks that is indicated by the presence of high sanidine also cast some doubt on the validity of a single Rb-Sr age determined from feldspar. On the basis of this age Muehlberger and others (1966) assigned the Rose Dome rocks an age of 1272 m.y. and believed them to be derived from a rather large terrane of rocks of similar age. Muehlberger and others (1966, p. 5420-5421) referred rocks of this terrane to the "Spavinaw igneous activity," originally defined as the period between 1150 and 1300 m.y. ago. Muehlberger and others (1967, p. 2364) later redefined the Spavinaw igneous activity as an event occurring 1200 m.y. ago on the basis of an isochron plot of 11 samples. More recently, Denison and others (1969, p. 127) have again redefined the Spavinaw igneous activity as an event occurring 1250 ± 20 m.y. ago; this latest definition is based on an isochron plot of 33 samples from the Precambrian basement of southeastern Kansas and northeastern Oklahoma.

Zartman and others (1967) determined that the mica peridotite associated with Rose "granite" was formed about 88 m.y. ago by means of a K-Ar age determination on phlogopite. Thus the granitic rocks on Rose Dome have yielded a Precambrian Rb-Sr age from separated K-feldspar, apparently intrude Pennsylvanian sedimentary rocks, and are closely associated with an 88 m.y. old peridotite intrusive.

ACKNOWLEDGMENTS AND WORK RESPONSIBILITIES

Pei-lin Tien, formerly with the State Geological Survey of Kansas, took the photographs of the core and hand samples. He also helped in the gathering of some of the x-ray diffraction data as did Catherine Frank and John Schloderer, New York University. Gary Stewart, Kansas Geological Survey, helped to clear the drill sites and in plane-table surveying of the drill-hole locations.

, The University of Kansas, did some of the drafting. We also want to acknowledge the value of discussions and correspondence with several individuals who have done isotopic and petrographic work that touched on Rose Dome. Those people include M.N. Bass, R.E. Denison, A.V. Heyl, E.G. Lidiak, R.M. Muehlberger, and R.E. Zartman. Bass was among the first to suggest that some of the feldspar in Rose "granite" might be of high-temperature origin. Mr. and Mrs. Maynard Stockebrand allowed us easy access to the exposures on Rose Dome and graciously permitted the State Geological Survey of Kansas to drill the locality. Costs of preparing some of the illustrations were defrayed partly by the Graduate School of Arts and Science, New York University. The isotopic studies were supported by

. Davis Young, New York University, reviewed parts of the rough draft of the manuscript.

The information presented in this report was gathered over a number of years. Wagner did geologic mapping in the Rose Dome area during 1950 and 1951 and part of that work is used here. Later field work was done by both Franks and Wagner. Franks oversaw the drilling on Rose Dome that was done by the State Geological Survey of Kansas in 1964 and logged the core. Franks also is responsible for the bulk of the petrographic and mineralogic data, many of which were gathered between 1960 and 1966 while he was with Kansas Geological Survey.

were made by Bickford, Mose, and Wetherill between 1965 and 1968. About half of the age measurements reported here were done in the Institute of Geophysics at the University of California, Los Angeles, during the summer of 1965; the other measurements were made at the University of Kansas.

Although many of the petrographic, mineralogic, and chemical data in the report are of a preliminary nature, those data are included because of the dearth of descriptive information that has been published on the igneous and metamorphic rocks of Rose Dome. Plans are to prepare a comprehensive report on the petrology of the ultramafic and metamorphic rocks of both Rose and Silver City Domes in the future.

PETROGRAPHY

Granitic Rocks

The boulders of Rose "granite" and the material penetrated in the drill holes show surprising textural and structural heterogeneity even though most of the rock is composed of approximately 30 percent light-gray to bluish-gray quartz that has a faint but distinctly opalescent luster, 45 percent potash feldspar, and 25 percent albitic plagioclase. Dark minerals, chiefly much weathered biotite, are scarce and amount to less than one percent of most samples. Accessory minerals include trace amounts of zircon and apatite as inclusions in the much altered biotite. Scarce calcite and pyrite fill veinlets and form replacement patches that are less than 1 mm across. Most of the feldspar is turbid and has been subjected to varying degrees of argillic alteration. Many of the "granite" boulders and some of the core samples contain irregularly shaped vugs that measure as much as 2 cm in long dimension. The vugs are lined with stumpy quartz crystals that are as much as 2 mm across and that seem to be of bipyramidal rather than rhombohedral habit. Moreover, nearly equant anhedra of andalusite that measure as much as 0.35 mm across and that are enclosed completely by vug-filling quartz were found in thin sections of two of the core samples.

Texturally the "granite" ranges from a very coarse grained, inequigranular, nearly pegmatitic rock (Fig. 5) in which individual grains of subhedral potash feldspar are as much as 5 cm long to an equigranular fine-grained aplitic rock in which all grains are less than 1 mm across. Some phases of the "granite," however, are of porphyritic appearance, especially those samples that show flow structure that is imparted by subparallel alignment of angular to rectangular fragments of feldspar and angular to rounded fragments of quartz that are embeded in a fine-grained quartzofeldspathic matrix (Fig. 5).

Figure 5. Sawed face of sample from cen. E line sec. 13, T. 26 S., R. 15 E., showing textural extremes of Rose "granite." Rock in lower right part of sample is hypidiomorphic granular and very coarse grained. Fine-grained apparently porphyrytic rock in upper left part of sample shows flow structure. Arrow indicates weathered inclusion of hornfels entrapped by the fine-grained "granite."

In the field there is little evidence to indicate the relationships between the several types of granitic rocks or their mode of occurrence. Some boulders show rounded masses of coarse-grained "granite" enclosed in fine- to medium-grained rock that may or may not show flow structures; still other boulders show rounded inclusions of aplitic rock embedded in medium-grained granitic rock; and some boulders are composed of what seems to be nearly pegmatitic rock that not only shows flow layering but also contains rounded masses of equally coarse material that shows normal granitic textures (Fig. 6). The granitic materials that show flow structures, however, do contain inclusions of most of the other textural varieties of the "granite" and therefore seem to be younger than the other textural and structural phases. Regardless of the textures and structures, however, the rock is rich in potassium and could be described as a leucogranite (Table 1).

Nearly all thin sections of the granitic rocks yield evidence of brecciated to porphyritic textures and structures. A very fine grained to cryptocrystalline matrix of quartz and feldspar that locally contains small amounts of amphibole, biotite, or chlorite not only encloses aggregates of grains of coarser quartz and feldspar, but also binds coarser granulated and fractured grains of quartz and cleavage fragments of feldspar. Moreover, the fragments of quartz and feldspar entrapped in the matrix commonly show a seriate range of grain sizes. Individual grains in the quartzofeldspathic matrix mostly measure less than 0.02 mm in long dimension, and very few of the grains exceed 0.3 mm in length. The matrix amounts to as much as 10 or 15 percent of many samples, but in those phases of the rock that show distinct flow structure (e.g., that in Fig. 5), the quartzofeldspathic matrix may amount to as much as 30 percent of the rock. Some samples of the coarse-grained "granite," however, contain only sparse quartzofeldspathic matrix. But even in these rocks, the coarse subhedra of potash and plagioclase feldspar have been broken along cleavage planes and the

Figure 6. Close-up of sawed interior of boulder shown in Figure 4. Note flow structure imparted by large cleavage fragments of feldspar and rounded mass showing normal granitic textures.

Table 1. Representative chemical analyses of selected samples of igneous, metamorphic, and sedimentary rocks from Rose Dome, Woodson County, Kansas, and vicinity, (1) coarse-grained "granite," surface boulder; (2) fine-grained "granite" showing flow structure, surface boulder; (3) calcareous mica peridotite containing limestone xenoliths, drill hole 3, 53.0 ft; (4) non-calcareous mica peridotite, Silver City Dome, drill hole no. 2M, 59.3 ft; (5) Weston hornfels, grader ditch, U.S. Highway 75; (6) unmetamorphosed Weston Shale, cen., N line, sec. 13, T. 26 S., R. 15 E., Woodson Co.. Analyst, George Shimer, State Geological Survey of Kansas.

fragments of the original subhedra, many of which still are in approximate optical continuity, are cemented by secondary quartz and feldspar. Quartz grains in those granitic rocks that contain but small amounts of matrix material commonly show quartz overgrowths that are in optical continuity with the original grains of quartz and many of the quartz overgrowths extend between adjoining grains of feldspar as well as penetrate the feldspar along cleavage directions.

Most of the quartz and feldspar in the matrix forms aggregates of anhedra, but in some thin sections the matrix is composed of fibrous intergrowths of quartz and feldspar similar to those seen in some volcanic rocks. Locally, the fibrous intergrowths tend to be arrayed normal to the margins of the enclosed coarse fragments of quartz and feldspar. The fibrous nature of some parts of the matrix is enhanced by oriented needles of pleochroic amphibole that measure less than 0.15 mm long and less than 0.02 mm across. Interfering spherulitic growths of feldspar were seen in three thin sections (Fig. 7A). Some spherulites have nuclei of minutely embayed single grains of quartz; other spherulites are enclosed in whole or in part by later generations of quartz that also form overgrowths on primary quartz grains. Other phases of the quartzofeldspathic matrix show textures similar to the interstitial, nearly graphic quartz-sanidine intergrowths in boulders of granodiorite entrapped in pyroclastic deposits and volcanic breccias in central North Island, New Zealand, (Ewart and Cole, 1967, Fig. 11, p. 42). Such intergrowths of quartz and feldspar in the matrix of Rose "granite" form as extensions of quartz overgrowths.

The volcanic aspect of the brecciated and prophyritic phases of the "granite" is augmented by the resorbed appearance of many of the fragments of quartz entrapped within it (Fig. 7B). Much of the quartz in the rock, both primary quartz and later generations of quartz, also is characterized by the straight or nonundulose extinction commonly shown by quartz phenocrysts in volcanic rocks. Locally, fragments of feldspar enclosed in the matrix also show sign of resorption.

Figure 7. Photomicrographs of Rose "granite" showing volcanic textures in the quartzofeldspathic matrix. A. Sanidine spherulites in matrix of surface boulder near cen. E line sec. 13, T. 26 S., R. 15 E. Dark gray to black areas enclosing spherulites are chiefly sanidine. Q_1, fragment of original or first generation quartz enclosed by matrix; Q_2, second generation quartz forming part of the matrix; F_1, fragment of primary feldspar entrapped in matrix. B. Resorbed first generation quartz grain embedded in microgranular quartzofeldspathic matrix, surface boulder near cen. S 1/2 SW 1/4 sec. 16, T. 26 S., R. 16 E.. Crossed polarizers.

Much of the feldspar in the matrix is altered at least partly to clay. However, a small part of the more granular matrix is composed of albitic plagioclase that shows albite twinning and has indices of refraction below that of Canada balsam. Most of the matrix feldspar, however, seems to be sanidine. X-ray powder photographs of minute quantities of feldspar scraped from the matrix of the sample containing spherulites (Fig. 7A) have a $\bar{2}01$ spacing near 4.22A (21.01°2θ) and indicate that the feldspar is potassium rich (about 90 percent $KAlSi_3O_8$) (Wright, 1968; Jones and others, 1969). Attempts to determine the structural state of the feldspar by the x-ray method outlined by Wright (1968) were not wholly satisfactory owing to the poor quality of the films that was induced by the small amount of interstitial feldspar that could be recovered from the sample. The major difficulty was in the certainty of identification of the $\bar{2}04$ diffraction and in the discrepancy between the $\bar{2}01$ spacing and the values of the 060 and $\bar{2}04$ diffractions. The 2θ values of the 060 and $\bar{2}04$ diffractions (41.72° and 51.07° 2θ respectively) are in accord with a high sanidine whose $\bar{2}01$ diffraction should be closer to 21.6°2θ (Wright, 1968, Fig. 3). Thus, the powder data indicate that much of the generation feldspar that forms the matrix of Rose "granite" is potassium rich, but may also mean that the structural state lies between that of orthoclase and high sanidine depending on the validity of identification of the $\bar{2}04$ spacing.

The medium- to coarse-grained nonmatrix (or primary) feldspar in the several phases of Rose "granite" is in a variety of structural states. The potash feldspar ranges from microcline to high sanidine and both low and high albite are present. Some of the medium- and coarse-grained potash feldspar shows microcline twinning; some shows combined microcline and carlsbad twinning; much of it shows only carlsbad twinning; and some is untwinned. Most of the feldspar that shows microcline twinning is perthitic whereas most of the feldspar that shows only carlsbad twinning or is untwinned seems to be nonperthitic.

The orientation of the optic plane in potash feldspar that shows microcline twinning is nearly normal to the trace of 010 cleavage; universal stage measurements of $2V_x$ yield values in the range from 60 to 70°. The microcline is in a structural state that is intermediate between so-called maximum microcline and orthoclase (MacKenzie and Smith, 1956; Wright and Stewart, 1968).

Many, if not all, of the medium to coarse grains of potash feldspar that either show no twinning or carlsbad twinning only have the optics of high temperature feldspar in that the optic plane is parallel to (010) and $2V_x$ is in the range from 26 to 55° (Tuttle, 1954). Such grains occur not only in those phases of the rock that contain large amounts of quartzofeldspathic matrix but also in those phases that contain only small amounts of matrix. Much of the feldspar that shows high temperature optics also has slightly anomalous bluish to brownish interference colors in orientations that are close to extinction. Many of the untwinned grains possess borders in which extinction angles differ slightly from those of the cores and $2V_x$ in the border zones approaches 55° whereas $2V_x$ measured in the cores is closer to 30 or 40°. The cores of the grains also have a mottled appearance between crossed nicols and $2V_x$ varies from one mottle to the next.

X-ray powder diffraction studies of selected grains of the coarse potash feldspar are in keeping with the high-temperature optics shown by much of the primary feldspar. Figure 8A is a diffractometer trace obrained from the powder of a potash feldspar phenocryst in a coarse-grained sample of the granite. The merging of the 111 and $1\bar{1}1$, 130 and $1\bar{3}0$, and 131 and $1\bar{3}1$ diffractions is in accord with the monoclinic symmetry inferred from universal stage measurements (Goldsmith and Laves, 1954; MacKenzie, 1954). An approximation of the composition of the potash feldspar was determined by measuring the angular separation between the $\bar{2}01$ diffraction of the feldspar and the 100 diffraction of quartz

Figure 8. X-ray diffraction traces of packed samples of high-temperature feldspar in Rose "granite," nickel-filtered copper radiation, scan rate of 0.5°2θ per minute. A, potash feldspar picked from coarse-grained boulder near cen. N 1/2 SE 1/4 sec. 13, T. 26 S., R. 15 E.; $2V_x$ about 35° parallel to (010). B, plagioclase from same boulder; $2V_z$ about 180°.

before and after homogenizing the feldspar at temperatures of 900°C and 1100°C for periods of 2 and 8 hours respectively. Slight expansion of the $\bar{2}01$ spacing on heating has been noted by various workers (e.g., Hewlett, 1959), and similar expansion was noted for the feldspar in Rose "granite" after heating at 900°C. The maximum shift observed was about 0.03°2θ in the low-angle direction after heating at 1100°C. Comparison of the position of the $\bar{2}01$ spacing (4.17A before heating, 4.18A after heating for most of the feldspar) with the work of Tuttle and Bowen (1958), Wright (1968), and Jones and others (1969) indicates that the feldspar contains some 30 to 35 percent sodic plagioclase. Chemical analyses of one sample of potash feldspar (10.96 percent K_2O, 3.68 percent Na_2O, and 0.41 percent CaO, or about 65 percent $KAlSi_3O_8$) are in fair agreement with the diffraction data. The 2θ values of the 060 and 204 diffractions, although not in good agreement with the position of the $\bar{2}01$ diffraction in the work of Wright (1968, Fig. 3), are in accord with a high-temperature structure for the potash feldspar.

The variation of $2V_x$ from values as small as 26° to 40° in the cores of some of the grains of potash feldspar and to values as large as 55° in the fringes of some of the same grains indicates that many of the coarse phenocrysts in the "granite" have been transformed from microcline to feldspar belonging to the high-sanidine series of Tuttle and Bowen (1958) and that most intense thermal modifications of structure in the potash feldspar took place in the outer parts of the grains where the grains are in contact with the late-stage quartzofeldspathic matrix that is present in most samples of Rose "granite."

The composition of plagioclase in Rose "granite" was determined by both flat-stage techniques and the Rittman zone method. The measurement of extinction angles indicates a range of composition from about $Ab_{94}An_6$ to $Ab_{92}An_8$. Measurements of $2V_z$ range from about 80° to 123° and indicate variations in the structural state from so-called plutonic low albite to states approaching those of volcanic or high albite (Slemmons, 1962, Plate 11). X-ray diffractometer studies of powders obtained from selected coarse grains of plagioclase in Rose "granite" generally are in accord with the optical studies. However, the position of the $\bar{2}01$ diffraction of high-temperature plagioclase near 21.9°2θ indicates that the plagioclase may contain appreciable $KAlSi_3O_8$ component, perhaps as much as 15 percent (Tuttle and Bowen, 1958; Carmichael and MacKenzie, 1964; Wright, 1968; and Jones and others, 1969). Figure 8B is an x-ray diffraction trace of one of the samples of plagioclase feldspar. The diffraction characteristics seem to be compatible with those of heated natural plagioclase or plagioclase from volcanic rocks rather than the diffraction characteristics of synthetic (maximum high temperature) plagioclase (Smith, J.R., 1958; Smith and Yoder, 1956; and Smith, J.V., 1956) in that the separation of the 131 and $1\bar{3}1$ diffractions is about 1.5°2θ and the separation of the 111 and $1\bar{1}1$ diffractions is about 0.65°2θ.

Petrographic studies show that most of the granitic rock penetrated in the shallow subsurface of Rose Dome (Fig. 3) does not differ appreciably from the "granite" found in the boulders except that some of the buried "granite" has undergone less intense weathering and argillic alteration than the surface material. Some of the granitic rubble penetrated near the tops of the drill holes, however, was much admixed with grayish-yellow to pale-olive clay containing abundant mica similar to the bleached phlogopite formed by weathering of the ultramafic rocks at Silver City and Rose Domes. Moreover, some of the matrix

Figure 9. Photomicrograph of chertlike inclusion in fine- to medium-grained sample of granitic rock from SE 1/4 sec. 13, T. 26 S., R. 15 E.. Note variations in grain size of the quartz in the inclusion. The "granite" shows some sign of cataclasis and contains some finely crystalline quartzofeldspathic matrix. Crossed polarizers.

material in the "granite" recovered from the drill holes contains appreciable iron-rich chlorite and perhaps also biotite as irregularly arrayed flakes and aggregates of flakes measuring less than 0.04 mm long. Unfortunately, the rubbly nature of much of the "granite" and the shallow depth of occurrence prevented coring of much of the shallow material and observations for the uppermost 10 to 24 feet of the drill holes are based chiefly on rotary cuttings (Fig. 3).

Inclusions of metamorphosed sedimentary rock have been found in a few samples of Rose "granite" that either show flow structures or a high degree of brecciation. What seems to be a rounded inclusion of chert was transected by one thin section cut from a highly brecciated surface sample (Fig. 9). The xenolith is composed of quartz anhedra that measure less than 0.06 mm long and are much clouded by minute inclusions, but some of the quartz recrystallized to form anhedral grains that are as much as 1.5 mm long. Moreover, a few boulders of highly fractured and somewhat recrystallized chert also have been found among the boulders of "granite" at the surface of Rose Dome, but the quartz in the chert boulders is relatively free of inclusions. Franks (1965) briefly described a boulder of the "granite" that not only contains inclusions of hornfels in its outer parts, but also shows flow structure and has two relatively flat opposed surfaces to which metamorphosed shale adheres (Figs. 4 and 6). X-ray diffraction studies show that potash feldspar and biotite are the chief components of the hornfels and that it does not differ significantly from metamorphosed Weston Shale on Rose Dome. The part of the sample shown in Figure 5 that shows flow structures also holds an inclusion of metamorphosed shale.

Ultramafic Rocks.--- The ultramafic rocks of Rose Dome are petrographically and chemically similar to the alkaline mica peridotite that is found on Silver City Dome (Wagner, 1954; Franks, 1959, 1966). The two bodies of mica peridotite are thought to be genetically related. Zartman and other (1967) reported the results of K-Ar age determinations on two samples of "biotite" (phlogopite) from Silver City Dome and one sample from the drill core taken on Rose Dome. The sample from Rose Dome was dated at 88 ± 4 m.y.; a core sample from Silver City Dome was dated at 90 ± 5 m.y.; and a somewhat weathered outcrop sample from Silver City Dome was dated at 91 ± 5 m.y. (Zartman and others, Table 2, p. 852). The K-Ar ages seem to be in good agreement at about 90 million years (Zartman and others, p. 857) and substantiate the mid- to late Cretaceous age of intrusion of the ultramafic rocks that had been inferred on other grounds by Wagner (1954).

Much of the mica peridotite drilled on Rose Dome is like the bulk of the peridotite at Silver City Dome and contains about 25 percent phlogopite and less than 10 percent each of olivine remnants, diopsidic augite, and pleochroic, pale reddish-brown amphibole as phenocrysts in a serpentinized groundmass. The phenocrysts of phlogopite measure as much as 2 mm in long dimension whereas the phenocrysts of pyroxene and amphibole mostly measure less than 0.5 mm long. Rounded aggregates or "eyes" of serpentine that contain relict fragments of olivine locally measure as much as 4 mm in long diameter. Minor constituents include apatite, magnetite, and iron-rich chromite. No pectolite, perovskite, or melilite was found in the peridotite on Rose Dome although these minerals occur in some phases of the peridotite at Silver City (Franks, 1959). Some parts of the peridotite, however, are what might be described as "mica rock." They are composed almost completely of phlogopite phenocrysts set in a matrix of fine-grained phlogopite. Remnants of olivine, phenocrysts of augite and amphibole, and the various accessor minerals generally amount to less than 10 percent of the

ultramafic rocks in which the groundmass is composed chiefly of fine-grained phlogopite.

The phlogopite in all phases of the peridotite characteristically shows reversed absorption (X>Y>Z) and x-ray diffraction characteristics of the 1M or 3T polymorph (Yoder and Eugster, 1954). Hogarth (1964) has suggested that reverse pleochroism in biotite and related micas stems from the occupation of tetrahedral sites by Fe^{+3}. The strong reddish brown pleochroism of the mica may also mean that it contains appreciable titania (Deer, Howie, and Zussman, 1962, vol. 3, p. 49). The x-ray method of Gower (1957) was used to estimate the proportions of iron and magnesium in octahedral coordination in samples of phlogopite from both Silver City and Rose Domes. The intensities of the 004 and 005 diffractions indicate that the phlogopite may contain as much as 20 percent Fe in octahedral coordination. The similarity of x-ray and optical characteristics of the phlogopite at Rose and Silver City Domes also points to a common magmatic source for both ultramafic intrusives.

One thin section cut from core recovered at a depth of 27 feet in drill hole 4 (Fig. 3) transected an eyelike aggregate of quartz anhedra that contains andalusite. The quartz aggregate is similar to the vuglike aggregates of quartz that contain andalusite in some samples of Rose "granite." The elliptic aggregate of quartz is about 3 mm in long diameter and is composed chiefly of quartz anhedra that are less than 0.3 mm long. The several grains of andalusite are concentrated near the center of the aggregate, measure less than 0.02 mm across, and are highly irregular in shape.

Where the mica peridotite on Rose Dome has been altered intensely by weathering, the bulk of the serpentine has been converted to grayish-yellow and pale-olive clay that is composed chiefly of nontronite. The reddish-brown phlogopite has been bleached and altered to very pale yellowish-orange vermiculite and mixed-layer vermiculite-mica structures. Clayey material of this type is admixed with the granitic rubble in the upper parts of most of the drill holes.

The peridotite at Rose and Silver City Domes is highly alkaline (Table 1). Chemical analyses commonly report between 5 and 6 percent K_2O, and the percentages of K_2O vary in accord with the proportions of phlogopite in the rock. Na_2O is present in amounts less than 2 percent. CaO is a scarce component in most samples (generally less than 4 percent), but samples that contain xenoliths of recrystallized limestone as well as veinlets and replacement patches of calcite contain appreciable CaO (Table 1). The calcite veinlets generally are less than 2 mm thick. One core sample taken near the contact between the peridotite and Stanton Limestone contained 10.15 percent CaO. Much of the calcite in the peridotite occurs as irregularly shaped aggregates of grains that have replaced parts of the serpentinized groundmass as well as the "eyes" of serpentine that formed by the alteration of olivine phenocrysts.

In contrast to the mica peridotite at Silver City Dome, that drilled on Rose Dome contains a variety of xenoliths. The xenoliths include not only fragments of recrystallized limestone, but also fragments of hornfels and "granite" (Fig. 10). Most of the inclusions of limestone, which measure as much as 2 cm in diameter, are rounded, but their borders are highly irregular in detail and grade abruptly into the serpentinized or mica-rich groundmass of the peridotite. Their texture is crystalline like that of marble and individual grains of calcite measure as much as 1 mm across. Inclusions of recrystallized limestone are most

abundant in peridotite that is close to the contact with Stanton Limestone and most of them probably were derived from that formation.

The xenoliths of hornfels in the peridotite mostly are tabular in shape. The length of some of them exceeds the diameter of the BX core (about 5 cm) and are as much as 2 cm thick. Most of the mineral grains within the shale xenoliths are finer than 0.002 mm in diameter, but the shale inclusions are impregnated with mica that has optical properties similar to those of the phlogopite in the peridotite and that forms anhedral porphyroblasts measuring as much as 1 mm in long dimension. The porphyroblasts grade downward in size to become indistinguishable from the micaceous component in the groundmass of the hornfels. Porphyroblasts of phlogopite amount to as much as 15 percent of some of the xenoliths and tend to be concentrated along relict bedding planes in the inclusions. Little or no quartz is present in the inclusions and an appreciable portion of the groundmass may be feldspar. Thermally metamorphosed inclusions of shale are most abundant in peridotite that is closest to contacts with Weston Shale country rock. The hornfels xenoliths probably were derived from the Weston Shale.

Granitic inclusions are relatively scarce in core samples of the peridotite, but one measuring about 8 cm long was found in drill hole 3 (Fig. 10). Like the other smaller inclusions of granitic rock, that one is rounded and shows an outer greenish-gray alteration zone that was produced by reaction with the peridotite. Thin sections of the granitic xenoliths reveal textures and structures much like the complex array already described for Rose "granite." Most of the inclusions also contain varying proportions of late-stage quartzofeldspathic matrix, but the matrix in the outer parts of the inclusions contains appreciable fine-grained ferromagnesian minerals, at least some of which is green biotite. The optical properties of potash and plagioclase feldspar in the granitic inclusions are

Figure 10. Core sample of mica peridotite containing inclusion of granitic rock, diamond drill hole 3, depth 9.3 m (30.5 ft). Note zonation of inclusion produced by reaction with the mica peridotite. Small inclusions are fragments of recrystallized limestone (white) and of shale (medium gray).

similar to those of the high-temperature feldspars in Rose "granite." Feldspar in the outer parts of the xenoliths is intensely altered to clay and to what may be epidote.

Contact Metamorphic Rocks

The contact metamorphic rocks exposed on Rose Dome and drilled in the shallow subsurface include hornfels derived from Weston Shale and recrystallized Stanton Limestone. X-ray diffraction studies show that the clay fraction of unmetamorphosed Weston Shale is composed largely of illite and kaolinite, but it also contains appreciable chloritic or vermiculitic clay as well as expansible mixed-layer clay (Fig. 11). The nonclay fraction is composed chiefly of quartz, detrital mica, and some feldspar. Chemical analyses (Table 1) show that most Weston Shale is relatively poor in potassium.

Contact metamorphism has baked some of the Weston Shale only mildly to form a brittle hornfels that maintains much of the fissility of the original shale and still is medium gray. Some of the shale, however, was intensely metamorphosed. Most intense metamorphism is apparent where the shale overlies granitic material or peridotite in and near the drill holes or is close to large amounts of granitic rubble, as in the grader ditch along U.S. Highway 75 near the center of the east line of section 13 (Fig. 1). There the shale has been converted to a dense, nearly glassy, buchitelike black hornfels. Locally some of the hornfels has been brecciated and shows sign of flowage. Such hornfels has been bleached and altered either by weathering or by hydrothermal action to a streaked and mottled yellow-brown, gray, and very light gray feldspathic rock.

Figure 11. X-ray diffractograms of selected samples of Weston Shale and hornfels, nickel-filtered copper radiation, scan rate 1°2θ per minute. A. Oriented mount, fraction finer than 2 μ, Weston Shale near cen. N line sec. 13, T. 26 S., R. 15 E.. C, chlorite; I, illite; K, kaolinite; M-L, mixed-layer clay; Q, quartz; underlining indicates major component contributing to diffractions. B. Packed sample of unfractionated Weston Shale, same locality as A. F, feldspar; M, mica; other symbols as for A. C. Packed sample of buchitelike hornfels from grader ditch near cen. E line sec. 13, T. 26 S., R. 15 E. M indicates mica diffractions; other diffractions from sanidine. D. Hornfels from surface of "granite" boulder shown in Figure 4. E. Hornfels inclusion from same boulder.

Optical and x-ray diffraction studies of the buchitelike hornfels show that the rock is composed almost completely of anhedral feldspar and mica. The hornfels contains but few relict silt-sized grains of quartz and nearly all feldspar and mica anhedra are finer than 2 microns in long dimension. As much as 2 precent pyrite was seen in two thin sections of the hornfels. They form irregularly shaped blebs and patches that measure less than 1 mm long as well as minute veinlets up to 0.5 mm wide that fill closely spaced fractures in the hornfels. Chemical analyses (Table 1) show that the buchitelike hornfels is much richer in K_2O than unmetamorphosed Weston Shale.

Nearly identical x-ray diffractograms were obtained from packed samples of the buchitelike hornfels in the grader ditch of Highway 75 in the drill core, and from the fragments of hornfels in and adhering to the boulder shown in Figure 11. The x-ray traces show that the feldspar has diffraction characteristics like those of the K-rich sanidine synthesized by Donnay and Donnay (1952, Fig. 2, p. 123). The $\bar{2}01$ diffraction at 20.1°2θ showed no shift on heating to 1150°C for 8 hours and indicates that the feldspar contains on the order of 95 percent $KAlSi_3O_8$ (Tuttle and Bowen, 1958; Wright, 1968; and Jones and others, 1969). Merging of the 111 and $1\bar{1}1$, 130 and $1\bar{3}0$, and 131 and $1\bar{3}1$ diffractions at 22.55°2θ, 23.45°2θ, and 29.8°2θ respectively demonstrates the monoclinic symmetry of the feldspar (Goldsmith and Laves, 1954; MacKenzie, 1954). The positions of the 060, $\bar{2}04$, and $\bar{2}01$ diffractions (41.6°2θ, 50.8°2θ, and 20.1°2θ) are in keeping with the diffraction characteristics of high-temperature sanidines studied by Wright (1968, Fig. 3, p. 92) and approximate those of K-exchanged Puye high sanidine studied by Wright (1968, Fig. 3) and by Wright and Stewart (1968, Table 2, p. 51). If the presence of high sanidine can be used to assign the hornfels to a metamorphic facies, the rock belongs to the sanidinite facies of Turner and Verhoogen (1960) or Turner (1968).

The mica in the hornfels probably belongs to the phlogopite-biotite series, but the diffraction data do not permit precise identification. The mica has a prominent 001 diffraction at 8.8°2θ, a weak 002 peak near 17.7°2θ, and a 003 peak near 26.6°2θ that is merged with the 220 feldspar diffraction at 26.8°2θ. The low intensity of the 002 mica diffraction indicates that the mica belongs to the biotite-phlogopite series. The 004 diffraction, which should appear near 35.9°2θ, is not readily distinguishable in the diffraction traces (Fig. 11), implying that the intensity of the peak is low compared to the 001 diffraction and that the mica should relatively rich in magnesium (Brown, 1961, Fig. V.7, p. 220). The presence of an iron-rich phlogopite or magnesian biotite would be in keeping with chemical analyses of the rock (Table 1) if much of the iron oxide reported in the analyses can be assigned to the pyrite that was noted in thin sections of the hornfels.

Contact metamorphic effects on Stanton Limestone are not as striking as those on Weston Shale. Normally finely crystalline light- to medium-gray limestone has been converted to a nearly white vuggy marble in which individual grains of calcite measure less than 2 mm across. Some of the limestone cored in the drill holes is penetrated by irregularly shaped finger-like apophyses of mica peridotite that measure as much as 3 cm in diameter. Some of the recrystallized limestone is impregnated with minute flakes of phlogopite that impart a brownish tone to the rock. Pyrite is a common accessory mineral in some of the recrystallized limestone and quartz crystals line some of the vugs. No calcsilicate minerals were observed in thin sections, but one thin section of marble from a depth of 15.15 m (49.7 ft) in drill hole 2 contained rounded and interfering aggregates of scaly brucite measuring as much as 1 mm in diameter. The brucite is about 1.6 m below a sill-like layer of peridotite that is 1.5 m thick.

Rb-Sr STUDIES

Rb-Sr ages were measured for 16 whole-rock samples of Rose "granite" and for mineral separates obtained from three of those samples. Analytical data are given in Appendix I. In calculating isochron ages, $\lambda_{Rb^{87}}$ was taken to be 1.39×10^{-11} yrs.$^{-1}$. The isochron ages were not determined by least-squares methods for reasons that will be discussed below. Rather the isochrons are the result of a visual best fit to the data. Bickford and others (1969, p. 1669-1672) have discussed laboratory procedures, errors, and precision for laboratory work done at the Institute of Geophysics, the University of California, Los Angeles, and at the University of Kansas during the period that these measurements were made.

Figure 12 shows the Rb and Sr isotopic analyses of the whole-rock samples plotted on a Sr^{87}/Sr^{86} versus Rb^{87}/Sr^{86} diagram. The total collection of analyzed samples does not yield a distinct isochron, suggesting that for at least some of the samples the criteria of closed chemical system and/or common initial Sr^{87}/Sr^{86} ratio have not been met; we did not feel justified in applying least-squares curve-fitting methods to these data. However, each of the samples yields a calculated Rb-Sr age that is Precambrian, and if the obvious breccias or samples containing appreciable late-stage quartzofeldspathic matrix (8 samples, open boxes in Fig. 3) are eliminated from consideration, all but one of the remaining samples lies on an isochron indicating an age of 1190 m.y. with an initial Sr^{87}/Sr^{86} of 0.706. The fit of these analytical points to the isochron is rather poor, and it is difficult to determine the error in age, but it is certainly not greater than $\pm$100 m.y.. Thus it is clear that the samples studied are of Precambrian age, and that their age is quite probably between 1100 and 1300 m.y..

Figure 12. Rb^{87}/Sr^{86} and Sr^{87}/Sr^{86} diagram for 16 whole-rock samples of Rose "granite." Size of boxes indicates errors of measurement. Solid boxes, samples showing granitic textures; closed boxes, samples containing abundant quartzofeldspathic matrix or showing obvious brecciation.

We studied minerals separated from three of the whole-rock samples, hoping that mineral re-equilibration had occurred during emplacement of the granitic rocks, and that Rb-Sr isochrons derived from isotopic analysis of the minerals would reveal the age of emplacement. Figure 13 shows an isochron plot of minerals from Sample RDH-3. The whole-rock sample, K-feldspar, and plagioclase determine a 1176±50 m.y. isochron with initial Sr^{87}/Sr^{86}=0.7072, but two separate analyses of biotite are each different and fall well below the isochron. The biotite in the whole-rock samples is highly weathered and it is not surprising that the biotite does not lie on the isochron. Because biotite is a minor constituent of the "granite", one can assume that little of the original Rb and Sr of the rock samples was in biotite. Thus the plagioclase-whole-rock-K-feldspar isochron age may be close to the true age; both the K-spar analysis and the plagioclase analysis plot on the whole-rock isochron in Figure 12, although the whole-rock analysis for RDH-3 lies slightly above the isochron.

Figure 14 shows analyses of minerals from Sample RDH-4. These samples, which include only K-feldspar and plagioclase, do not form an isochron when plotted with the whole-rock analysis. The whole-rock and plagioclase analyses lie on the whole rock isochron in Figure 12. Hence it seems likely that the K-spar sample has not remained a closed system to Rb and Sr; however other interpretations are possible and the meager data do not permit any definite statements.

Mineral separates from Sample RD-51, including K-feldspar, plagioclase, and a mineral mixture with densities lying between 2.64 and 2.90, are plotted with the whole-rock in Figure 15. A 1309±50 m.y. isochron, with initial Sr^{87}/Sr^{86}= 0.702 may be drawn through the K-spar, whole-rock, and mineral mixture analyses, but this isochron does not pass through the plagioclase analysis. Both the whole-rock and the K-feldspar analyses lie on the whole-rock isochron in Figure 12, and it is possible that the mineral mixture and the plagioclase analyses really lie below the true isochron.

Figure 13. Rb^{87}/Sr^{86} and Sr^{87}/Sr^{86} diagram for whole rock and mineral separates from "granite" sample RDH-3, drill hole 3, depth 6.7 m (22 ft).

Figure 14. Rb^{87}/Sr^{86} and Sr^{87}/Sr^{86} diagram for whole rock and mineral separates from "granite" sample RDH-4, drill hole 4, depth 4.9 m (16 ft).

Figure 15. Rb^{87}/Sr^{86} and Sr^{87}/Sr^{86} diagram for whole rock and mineral separates from "granite" sample RD-51, surface boulder near cen. N 1/2 NE 1/4 sec. 13, T. 26 S., R. 15 E..

Our results on the mineral separates are poor because of weathering or recrystallization, or both. However, it is clear that some of the mineral separates yield ages which are about the same as the whole-rocks. There certainly was no systematic re-equilibration of the minerals during post-Pennsylvanian time.

DISCUSSION

Age and Emplacement of Rose "Granite"

The Rb-Sr analyses of whole-rock samples and mineral separates verify that boulders of granitic rock on Rose Dome are of Precambrian age and that they originally crystallized between 1100 and 1300 m.y. ago. The small inclusions of granitic rock in cores of the 90 m.y. old mica peridotite together with the close association of granitic rubble with argillaceous weathering products derived from the mica peridotite indicates that the boulders of "granite" were transported to their present stratigraphic position as inclusions in the ultramafic magma during Cretaceous time. The position of the granitic materials on the outcrop and in the drill core (Fig. 2, 3) is in keeping with emplacement of the "granite" as relatively light inclusions in a relatively dense magma so that the granitic materials became concentrated near the top of the mica peridotite intrusive. The granitic rocks also show the effects of thermal metamorphism by the ultramafic magma and thus contain potash feldspar and albitic plagioclase that range in structural state from low-temperature to high-temperature feldspar. White (1962), for example, found both high- and low-temperature feldspar in granitic and gneissic xenoliths in diabase in the Tortilla Mountains of Arizona. Granitic rocks entrapped in volcanic breccias and pyroclastic deposits in central North Island, New Zealand, also contain high temperature feldspar (Ewart and Cole, 1967).

The granitic rocks of Rose Dome were transported upward through about 760 m (2500 ft) of sedimentary overburden to become emplaced near the contact of the Weston Shale with the Stanton Limestone. The range of Rb-Sr ages (1100 to 1300 m.y.) is in rough accord with the 1250±20 m.y. age assigned by Denison and others (1969) to the "Spavinaw igneous activity," to which the basement rocks of Woodson County have been assigned (Muehlberger and others, 1966, 1967; Denison and others,

1969). However, the granitic rocks on Rose Dome are not hornblende granophyre like the Spavinaw Granite of Oklahoma (Merritt, 1960) and care must be taken in attempting to draw genetic relationships between the granitic materials of Rose Dome and the granophyric rocks of Spavinaw, Oklahoma. Moreover, although there are general textural and mineralogic similarities between the granitic rocks of Rose Dome and basement samples from the Woodson County Granite of Muehlberger and others (1966, 1967), there also are dissimilarities. Of the 24 thin sections of Rose "granite" examined for this study, only a few of the Precambrian clasts embedded in the quartzofeldspathic matrix of the "granite" in three thin sections showed graphic, micropegmatitic, or myrmekitic intergrowths of quartz and feldspar. Muehlberger and others (1967) noted that basement samples of the Woodson County Granite commonly show micrographic textures, and myrmekitic intergrowths of quartz and plagioclase also are common in the basement samples from that terrain. Also, potash feldspar in the basement rock samples invariably is pink in contrast to the light-gray to nearly white potash feldspar of Rose "granite." The difference in color, however, could reflect reduction of iron induced by the ultramafic magma.

Thus, the granitic rocks of Rose Dome actually may represent a wider range of Precambrian ages and rock types than those included in the Woodson County Granite by Muehlberger and others (1967) depending on the thickness of granitic crust "sampled" by the ultramafic magma. However, as was noted in the preceding section, the range of ages may also mean that the Rb-Sr system was partly open during emplacement of the granitic inclusions at Rose Dome.

Temperature and Pressure during Emplacement of Mica Peridotite and "Granite"

Several features indicate that the igneous rocks of Rose Dome were emplaced under conditions of high temperature and low pressure. They include the presence of high sanidine and albite in the "granite;" the grains of andalusite in vug-like aggregates of quartz both in the "granite" and in the mica peridotite; the stumpy quartz crystals that have habits suggestive of high quartz in the vugs in the granitic rocks; the development of sanidine-bearing hornfels from Pennsylvanian shale; and the formation of brucite-bearing marble from Pennsylvanian limestone if the brucite formed by alteration of pre-existing periclase. The vugs in the granitic rocks and sanidinite facies metamorphism of Weston Shale are especially suggestive of low pressures.

The 90 m.y. age of the mica peridotite (Zartman and others, 1967) allows estimation of overburden thickness and pressures at the time of intrusion of the peridotite. If the stratigraphic thickness of post-Weston Paleozoic and Cretaceous rocks elsewhere in Kansas is a reasonable guide and if the eastward truncation of Permian rocks by the Permian-Cretaceous unconformity is taken into account, the igneous rocks on Rose Dome may have been overlain by some 900 to 1200 m (3000 to 4000 ft) of sedimentary rock, chiefly sandstone and shale at the time of intrusion of the mica peridotite. Assuming an average density of about 2.5 g/cc for the overlying sedimentary rocks, load pressures may have been as low as 225 to 300 bars (Fyfe, Turner, and Verhoogen, 1958, p. 34). Fluid pressures at the time of emplacement may have been of the same order of magnitude if fluids were not allowed easy escape through the enclosing argillaceous rocks of the Pennsylvanian System.

The presence of vuggy growths of quartz, the abundance of phlogopite in the mica peridotite, the extend of contact metamorphism, the abundance of mica in Weston hornfels, the presence of late calcite and pyrite veinlets and replacements in the granitic rocks, the mica peridotite, and the country rock all indicate that the system was wet during intrusion of the mica peridotite. In a similar fashion, the enrichment of Weston hornfels in K_2O compared to unmetamorphosed Weston Shale (Table 1) suggests that potassium not only was a highly mobile constituent in the peridotite magma, but that ample water was available in the system to permit easy transport of postassium to the country rock. Thus P_{H_2O} may have been close to P_{total}. The extent to which CO_2 influenced the system through release of the gas from limestone country rock during intrusion is difficult to evaluate, but the small amounts of calcite in most of the peridotite, granitic rock, and hornfels suggests that carbon dioxide did not play a major role.

A temperature-pressure diagram (Fig. 16) of the stability fields of some of the minerals in the igneous and metamorphic rocks of Rose Dome allows insight into the temperatures that prevailed during emplacement of the mica peridotite and Rose "granite," and during contact metamorphism of the Pennyslvanian country rock. Maximum temperatures are limited approximately by the andalusite-sillimanite join, but problems are encountered in attempts to establish the lower limits of temperature of the peridotite magma and contact metamorphism. The magnesian nature of the phlogopite in the peridotite and of the biotite-series mica in the hornfels indicates that temperatures should have been well above the upper stability limit of annite. The formation of a sanidine-magnesian biotite assemblage from Weston Shale is in keeping with the relatively low temperatures of muscovite-quartz reactions and the uppermost limit of muscovite stability. If

Figure 16. Temperature-pressure diagram showing equilibrium curves for various minerals that are present in the igneous and metamorphic rocks on Rose Dome. Circle indicates inferred realm of temperature and pressure that obtained during intrusion and metamorphism. Data from Eugster and Wones (1962), Evans (1965), Luth and others (1964), Richardson and others (1969), Tuttle and Bowen (1958), Velde (1966), Winkler (1967), Wones (1967), Yoder and Kushiro (1969).

low fluid pressures in the range from 200 to 300 bars are reasonable, magmatic temperatures and temperatures of metamorphism may well have been in the range from 700° to 840°C during intrusion of the mica peridotite. This temperature range is in keeping with what seem to be pseudomorphs of low quartz after high quartz in the vugs in Rose "granite." The temperatures and pressures inferred also are in rough accord with those indicated for sanidinite facies metamorphism by Turner and Verhoogen (1960) and Turner (1968). Further insight into the conditions of temperature and pressure, however, can be gained from the evidence that indicates partial melting of Rose "granite."

Partial Melting of Rose "Granite"

Partial melting of Rose "granite" during its emplacement as xenoliths of Precambrian basement rock in the alkaline ultramafic magma is indicated by the volcanic textures of the quartzofeldspathic matrix which permeates much of the rock. Especially significant are the spherulitic growths of sanidine in the matrix (Fig. 7A); the resorption textures shown by fragments of original granitic quartz and feldspar that are entrapped in the late-stage quartzofeldspathic matrix (Fig. 7B); and the development of oriented quartz overgrowths that are in optical continuity with the original quartz grains of the granite, that penetrate grains of feldspar along cleavage directions, and that locally form optically oriented intergrowths with matrix feldspar. The minimum melting curves for granite of Tuttle and Bowen (1958) and Luth, Jahns, and Tuttle (1964) then indicate that temperatures in the mica peridotite magma may well have exceeded 800°C if fluid pressures were in the range from 200 to 300 bars (Fig. 16). Thus, the circle in Figure 16 may encompass the range of temperature and pressure that obtained during intrusion and metamorphism on Rose Dome.

Such high temperatures exceed those estimated for most alkaline peridotite magma from their contact-metamorphic effects (Clegg, K.E., 1955; Crelling and Dutcher, 1968; Ghosh, 1967; Parham, 1963). Most alkaline peridotite in eastern North America is thought to have been emplaced at temperatures of 600°C or appreciably less (Watson, 1967, p. 320-321, 322). The low temperatures associated with most mica peridotite intrusives, however, may reflect partly the kimberlitic nature of many of them as well as the small size of most of the intrusives. Jaeger (1957) pointed out that contact metamorphic effects depend not only on the temperature of the magma, but also on the latent heat of crystallization. The amount of heat evolved during crystallization is a strong function of the size of an intrusive.

Although the composition of the matrix formed by partial melting and rapid low-pressure cooling of the granitic xenoliths could not be determined with any degree of precision, most the matrix feldspar seems to be K-rich sanidine. A melt composed largely of the materials needed to form potassium-rich feldspar and derived by partial melting of granitic rock that has potash feldspar and quartz as its major constituents seems to be in accord with the experimental and theoretical work of James and Hamilton (1969) on the melting of granitic materials.

High-temperature emplacement of the peridotite magma and consequent partial melting of the inclusions of Rose "granite" allows clarification of many of the enigmatic features of the granitic rocks, namely the flow structures shown by much of the "granite," the inclusions of hornfels and recrystallized chert in some phases of the "granite," the intrusive relationships reported by Twenhofel (1926) and deduced by Franks (1965), and perhaps also the scatter of Rb-Sr isotope ratios in the granitic rocks. Partial melting during emplacement not only would have entailed upward rafting of the granitic inclusions by the ultramafic magma,

but also the development of a mush of crystals and rock fragments in a melt that ultimately cooled to form the late-stage quartzofeldspathic matrix. The upwelling mica peridotite magma apparently shoved mushy masses of the granitic material into the enclosing Pennsylvanian sedimentary rocks with consequent alignment of the long dimensions of crystal fragments in the mush and the entrapment of broken fragments of country rock by the granitic material (Figs. 4, 5, 6, 8). The two opposed, relatively flat surfaces together with the hornfels adhered to them on the granitic boulder described by Franks (1965) and shown in Figures 4 and 6 suggest that post-Cretaceous weathering and erosion released that boulder from a larger mass of Rose "granite" that not only was partly enclosed by Weston hornfels, but that also may have had a dikelike or sill-like form.

Partial melting and brecciation of Rose "granite" probably affected the Rb-Sr isotope ratios in that there was ample opportunity for interchange of Rb and Sr ions with the alkaline ultramafic magma. The enrichment of Weston hornfels in potassium (Table 1) points up the opportunity for exchange, and the scatter of isotope ratios in Figures 12, 13, and 14 strongly implies that Rose "granite" and its potash feldspar were not a closed system during emplacement. The clustering of isotope ratios of those samples containing appreciable late-stage quartzofeldspathic matrix or showing obvious brecciation below the inferred "isochron" of Figure 12 indicates that the feldspathic components of the samples may have become enriched in young rubidium or depleted in radiogenic strontium by reaction with the potassium-rich peridotite magma. Consequently, those whole-rock samples have younger apparent ages than other phases of Rose "granite," but neither the extent of melting nor the rate of cooling was sufficient to allow complete re-equilibration.

SUMMARY AND CONCLUSIONS

The boulders of granitic rock on Rose Dome, Woodson County, Kansas, are fragments of Precambrian basement that were rafted to their present stratigraphic position during mid- to late-Cretaceous time as inclusions in an alkaline mica peridotite magma. Rb-Sr isotope ratios show that the age of the Precambrian parent rocks was in the range from 1100 to 3000 m.y.. Some of the spread of the isotopic data may stem from the "sampling" of different levels of granitic crust by the ultramafic magma, or from the thermal effects of and chemical exchanges with the mica peridotite magma. The less dense granitic basement materials seem to have been concentrated in the upper parts of the phlogopite-bearing peridotite intrusive, which was emplaced in the Pennsylvanian section of Rose Dome about 90 m.y. years ago (Zartman and others, 1967).

The temperatures of the peridotite magma were unusually high during emplacement, probably more than but not much more than 800°C. The high-temperature low-pressure environment led to the development of extensive contact metamorphism of Pennsylvanian country rock and to partial melting of Rose "granite." Contact metamorphic effects include the development of sanidine-magnesian biotite hornfels from Weston Shale and recrystallization of Stanton Limestone with local formation of brucite in the recrystallized limestone. The hornfels is much enriched in K_2O compared to unmetamorphosed Weston Shale and the source of the additional potassium probably was the K-rich mica peridotite, which contains from 5 to 6 percent K_2O.

Partial melting of Rose "granite" is indicated by the abundant volcanic textures and structures in the sanidine-rich quartzofeldspathic matrix that binds together fragments of thermally metamorphosed Precambrian leucogranite and fragments of quartz and feldspar derived from that granite to form the wide variety of textures and structures shown by Rose "granite." The volcanic textures and structures include spherulitic growths of sanidine and the entrapment of resorbed quartz and feldspar in the late-stage quartzofeldspathic matrix. Much of the original feldspar in the granitic inclusions has been converted to high-temperature sanidine and albite although intermediate microcline and low albite still remain in the inclusions.

A variety of other features also indicate high-temperature emplacement of the mica peridotite and granitic xenoliths on Rose Dome. They include the growth of andalusite in vuglike aggregates of quartz in both Rose "granite" and the mica peridotite as well as the short, stumpy habit of quartz in the vugs in the granitic rocks. That habit is suggestive of derivation from an original high-quartz polymorph. Both the vugs and the andalusite are in accord with the low pressures suggested by sanidinite facies metamorphism of the country rock. Load and fluid pressures during intrusion and metamorphism are thought to have been in the range from 200 to 300 bars. The pressure estimate derives from estimations of the thickness of overburden removed by post-Cretaceous erosion and from the ample evidence that the igneous-metamorphic system was saturated with water. Evidence that the system was "wet" is provided by the presence of hydrous phases in both the peridotite and the hornfels as well as by the evidence for easy migration of potassium to the argillaceous country rock during metamorphism. Abundant water doubtless facilitated partial melting of Rose "granite."

Patial melting of the granitic inclusions accounts for most of the enigmatic features shown by Rose "granite." Partial melting doubtless aided cataclasis in Rose "granite" and thus facilitated the development of the wide variety of textural and structural phases in the granitic material. Partial melting probably led to emplacement of the granitic material as a mush of crystal and rock fragments that may have been shoved into the Weston Shale with consequent development of flow structures in the granitic rocks and development of apparently intrusive relationships between the "granite" and Weston hornfels like those described by Twenhofel (1926) and Franks (1965). Emplacement of Rose "granite" as a mush driven by the upwelling mica peridotite magma also accounts for the entrapment of inclusions of hornfels in the "granite." The source of the chertlike aggregates of quartz in the granitic rocks is problematic, but they too are thought to be xenoliths and perhaps are related to the boulders of chert that locally are found on Rose Dome. Partial melting of the "granite" probably contributed to the disruption of whole-rock and mineral-separate Rb-Sr isotope ratios in some phases of the granitic material by favoring interchange of ions with the peridotite magma. Cooling rates were too rapid and melting was insufficient to permit complete re-equilibration of Rb and Sr isotopes in Rose "granite."

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Table 1. Representative chemical analyses of selected samples of igneous, metamorphic, and sedimentary rocks from Rose Dome, Woodson County, Kansas, and vicinity, (1) coarse-grained "granite," surface boulder; (2) fine-grained "granite" showing flow structure, surface boulder; (3) calcareous mica peridotite containing limestone xenoliths, drill hole 3, 53.0 ft; (4) non-calcareous mica peridotite, Silver City Dome, drill hole no. 2M, 59.3 ft; (5) Weston hornfels, grader ditch, U.S. Highway 75; (6) unmetamorphosed Weston Shale, cen., N line, sec. 13, T. 26 S., R. 15 E., Woodson Co.. Analyst, George Shimer, State Geological Survey of Kansas.

	1	2	3	4	5	6
SiO_2	73.08	74.09	35.91	45.76	52.19	66.72
Al_2O_3 (including MnO_2 if present)	12.78	10.83	5.24	6.31	21.51	16.19
Total iron oxide (as Fe_2O_3)	1.97	2.25	9.42	8.32	8.37	6.20
TiO_2	0.48	0.93	2.45	2.45	1.21	0.97
CaO	0.75	0.90	8.19	1.56	0.93	0.30
MgO	0.42	0.93	20.29	22.31	1.99	1.18
P_2O_5	0.11	0.39	0.62	0.28	0.18	0.08
SO_3	0.05	0.03	0.27	Trace	0.07	0.01
K_2O	7.64	7.58	5.72	6.30	9.01	2.46
Na_2O	1.97	0.74	0.08	1.52	0.31	0.85
Sulfide Sulfur	0.01	0.01	0.15	0.04	0.04	0.01
Loss on ignition (1000°C)	0.92	0.96	11.57	4.38	3.89	5.16
Totals	100.18	99.64	99.81	99.23	99.70	100.13

Figure 1. Map of Kansas showing the locations of outcropping igneous rocks. The rocks in Woodson County include alkaline mica peridotite and altered "granite;" those in Riley County are kimberlite. Data for Riley County are from Byrne and others (1956) and Brookins (1970).

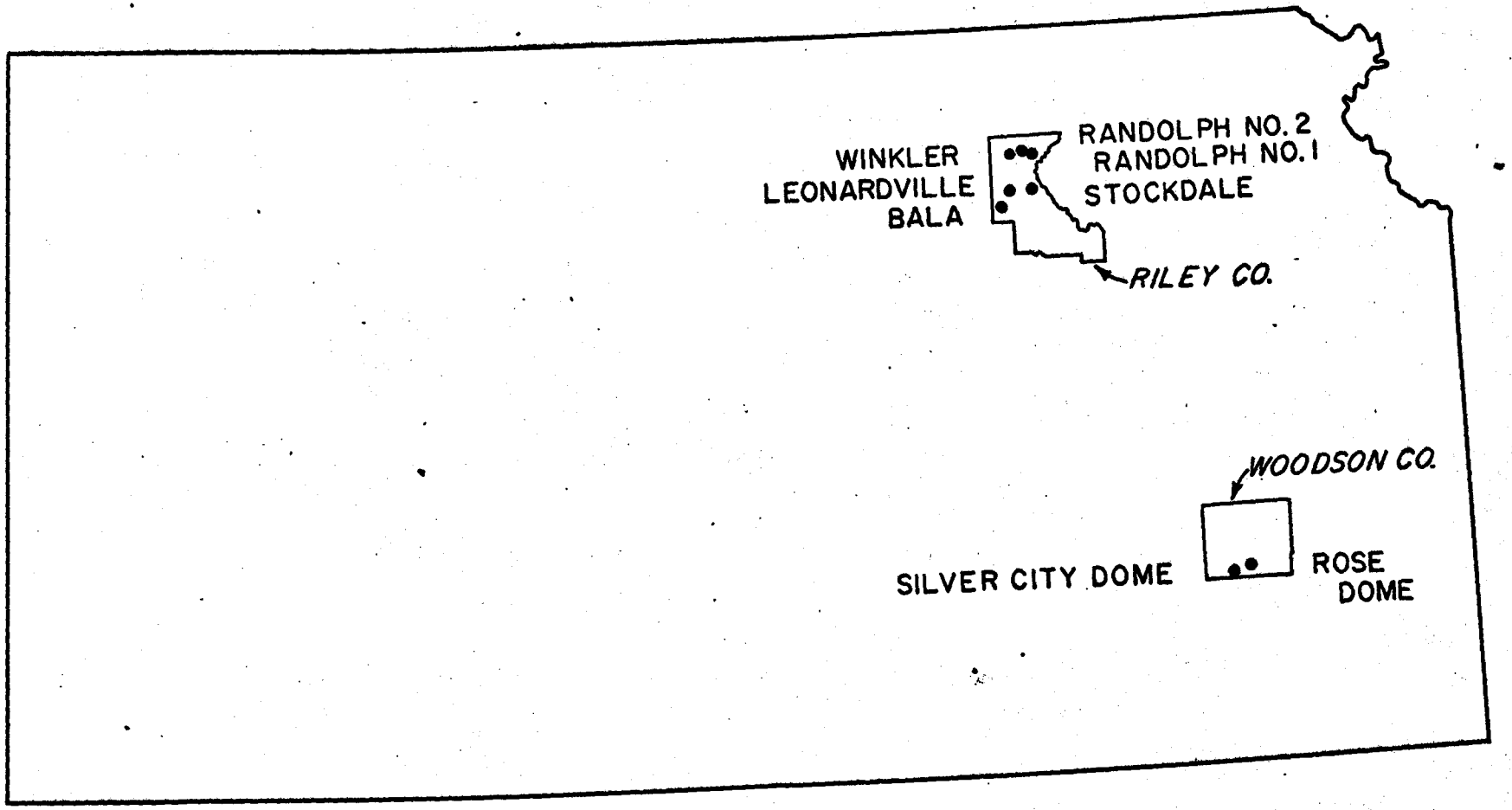

WINKLER
LEONARDVILLE
BALA
RANDOLPH NO. 2
RANDOLPH NO. 1
STOCKDALE
RILEY CO.
WOODSON CO.
SILVER CITY DOME
ROSE
DOME

Figure 2. Simplified geologic map of sec. 13, T. 26 S., R. 15 E., Woodson Co., Kansas, showing location of diamond-drill holes and line of cross-section W-E shown in Figure 3. Rock units in order of increasing age are: Kmp, Cretaceous mica peridotite (checked pattern); Pd, Douglas Group, Pennsylvanian (ruled lines); Psw, Weston Shale Member, Stranger Formation, Douglas Group, Pennsylvanian (unpatterned or stippled where hornfels); Pst, Stanton Limestone, Pennsylvanian (cross-hatched); pCrg, chiefly Rose "granite" and granitic rubble, Precambrian (unpatterned). Contacts dashed where approximately located, short dashes where inferred. Geology by H. C. Wagner and P. C. Franks, 1951, 1964.

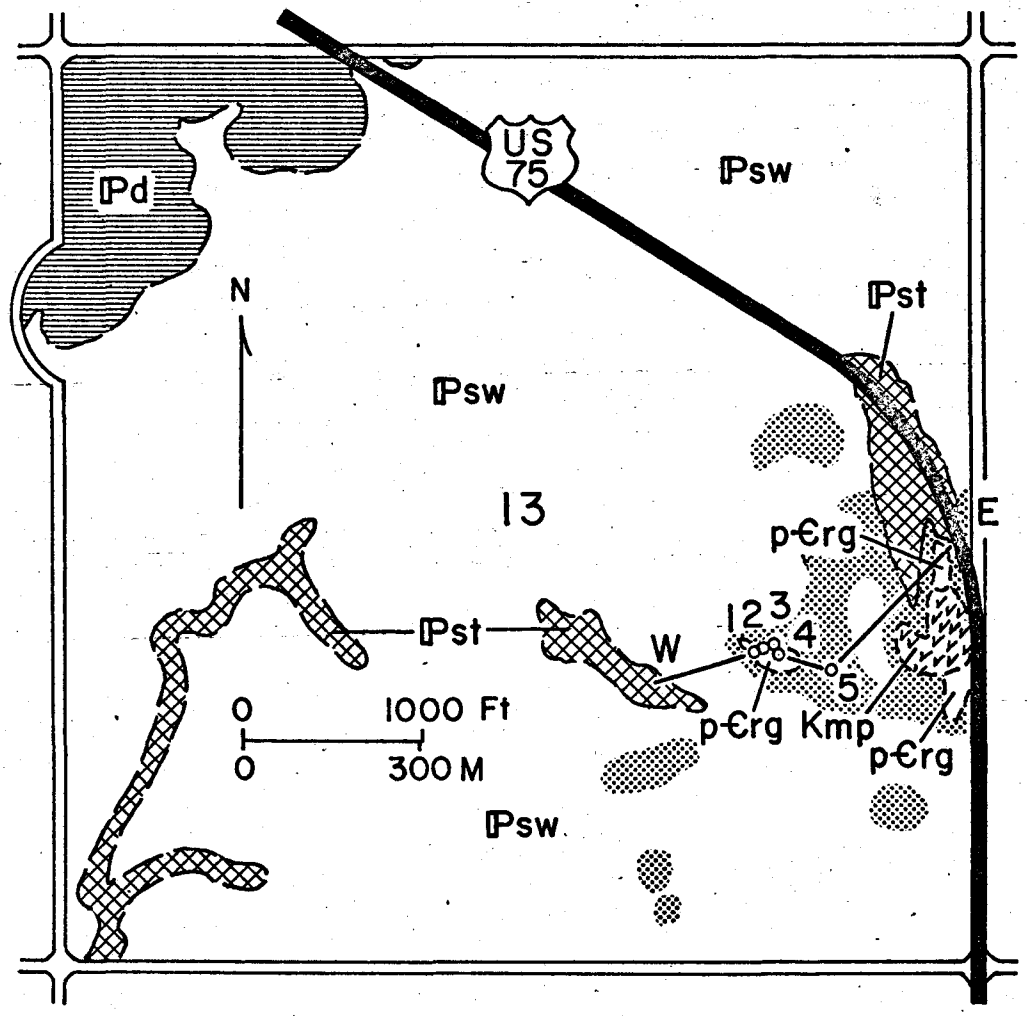

US 75
Psw
Pd
N
Pst
Psw
13
E
p-Crg
Pst
W
1 2 3 4
5
0 1000 Ft
0 300 M
p-Crg
Kmp
p-Crg
Psw

Figure 3. Cross-section W-E of igneous, metamorphic, and sedimentary rocks on Rose Dome based on drilling by State Geological Survey of Kansas. Short dashes indicate inferred geologic contacts and correlations. Dashed portions of drill holes indicate those parts of logs based on cuttings rather than core. Rock units in order of increasing age are: Kmp, Cretaceous mica peridotite; Psw, Weston Shale Member, Stranger Formation, Pennsylvanian; Pst, Stanton Limestone, Pennsylvanian; Psv(?), Vilas (?) Shale, Pennsylvanian; pЄrg, chiefly Precambrian Rose "granite" and granitic rubble but also includes admixed, weathered mica peridotite. Vertical exaggeration, X 10.

Figure 4. Boulder of Rose "granite" near cen. E 1/2 E 1/2 sec. 13, T. 26 S., R. 15 E.. Note fragment of hornels (H) adhering to relatively flat surface on the boulder. Scale, which is about 15 cm (6 in) long, lies along the same surface. Opposite side of boulder not visible in photograph also is a relatively flat surface to which hornfels adheres. The two opposed flat surfaces are suggestive of an original dikelike or sill-like form for the "granite." Small inclusions of hornfels (HI) are partly enclosed by "granite" in right-hand part of photograph.

Fig 4

Figure 5. Sawed face of sample from cen. E line sec. 13, T. 26 S., R. 15 E., showing textural extremes of Rose "granite." Rock in lower right part of sample is hypidiomorphic granular and very coarse grained. Fine-grained apparently porphyrytic rock in upper left part of sample shows flow structure. Arrow indicates weathered inclusion of hornfels entrapped by the fine-grained "granite."

Fig. 5

Figure 6. Close-up of sawed interior of boulder shown in Figure 4. Note flow structure imparted by large cleavage fragments of feldspar and rounded mass showing normal granitic textures.

Fig 6

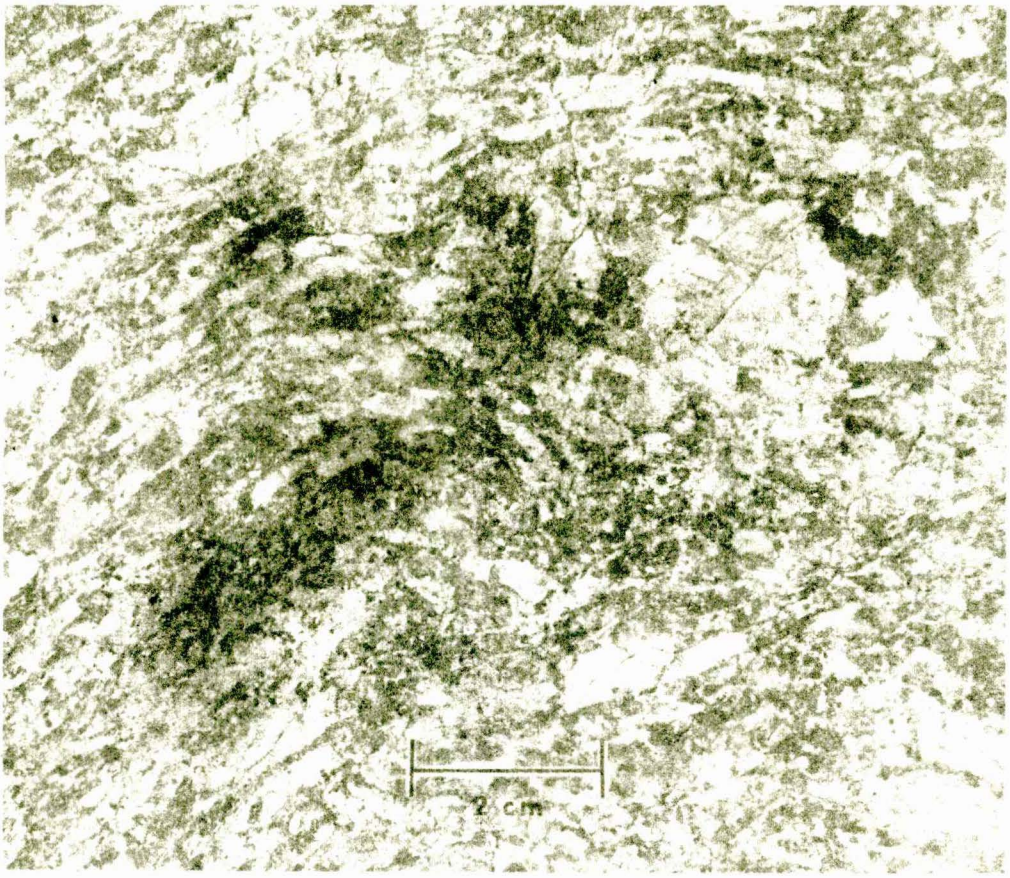


Figure 7. Photomicrographs of Rose "granite" showing volcanic textures in the quartzofeldspathic matrix. A. Sanidine spherulites in matrix of surface boulder near cen. E line sec. 13, T. 26 S., R. 15 E. Dark gray to black areas enclosing spherulites are chiefly sanidine. Q_1, fragment of original or first generation quartz enclosed by matrix; Q_2, second generation quartz forming part of the matrix; F_1, fragment of primary feldspar entrapped in matrix. B. Resorbed first generation quartz grain embedded in microgranular quartzofeldspathic matrix, surface boulder near cen. S 1/2 SW 1/4 sec. 16, T. 26 S., R. 16 E.. Crossed polarizers.

Fig 7

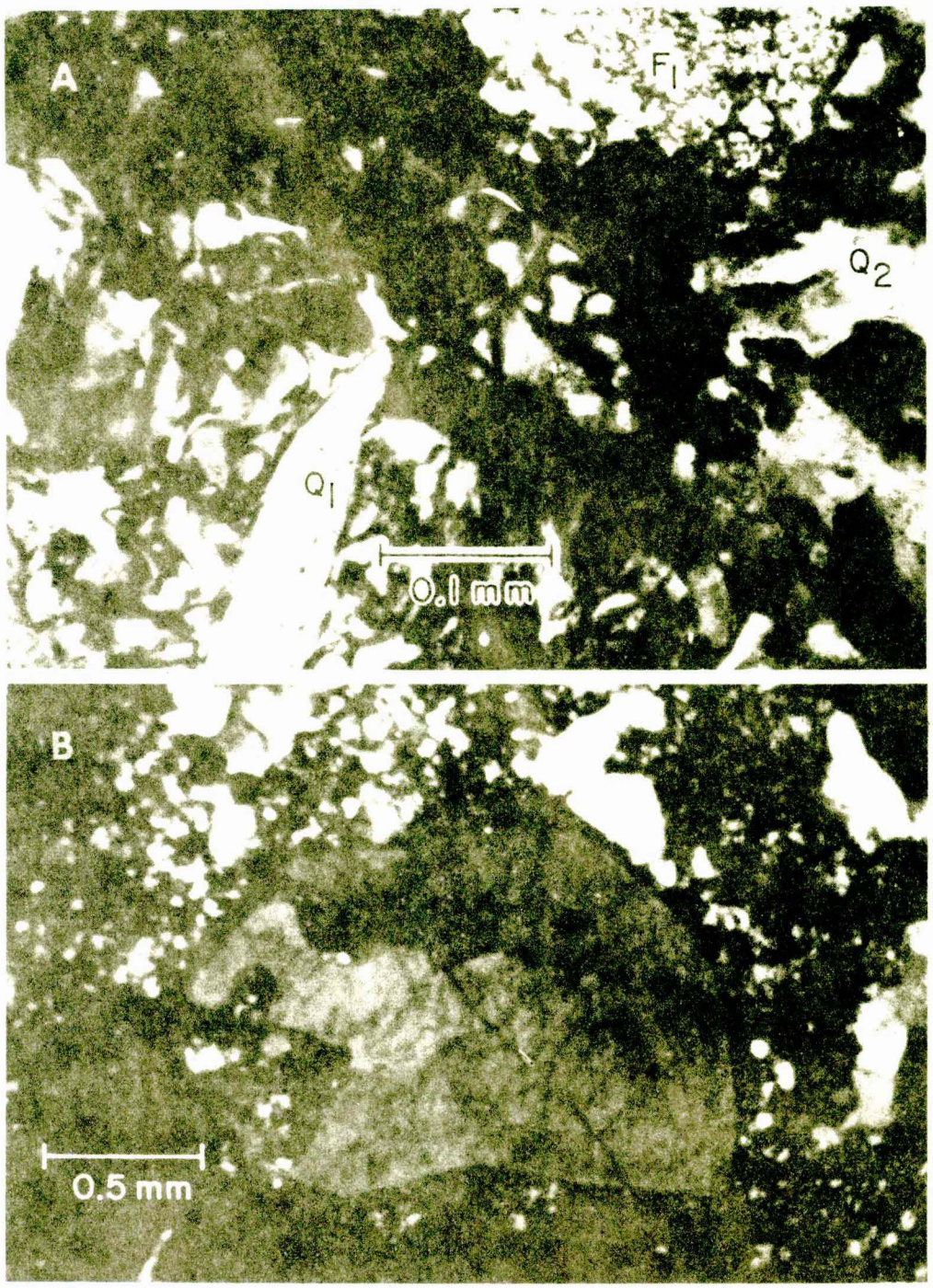


Figure 8. X-ray diffraction traces of packed samples of high-temperature feldspar in Rose "granite," nickel-filtered copper radiation, scan rate of 0.5°2θ per minute. A, potash feldspar picked from coarse-grained boulder near cen. N 1/2 SE 1/4 sec. 13, T. 26 S., R. 15 E.; $2V_x$ about 35° parallel to (010). B, plagioclase from same boulder; $2V_z$ about 180°.

Figure 9. Photomicrograph of chertlike inclusion in fine- to medium-grained sample of granitic rock from SE 1/4 sec. 13, T. 26 S., R. 15 E.. Note variations in grain size of the quartz in the inclusion. The "granite" shows some sign of cataclasis and contains some finely crystalline quartzofeldspathic matrix. Crossed polarizers.

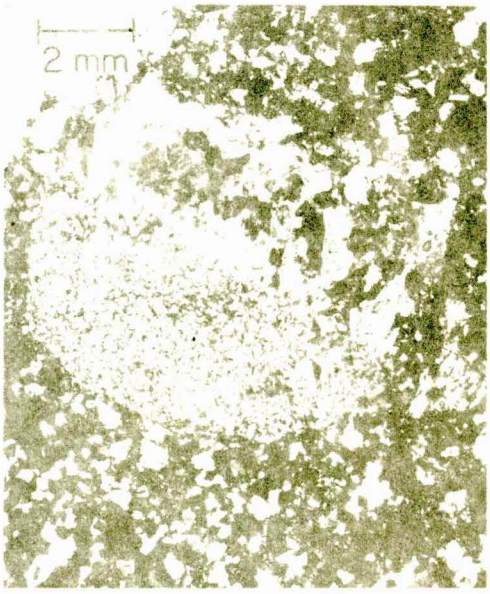

2 mm

Figure 10. Core sample of mica peridotite containing inclusion of granitic rock, diamond drill hole 3, depth 9.3 m (30.5 ft). Note zonation of inclusion produced by reaction with the mica peridotite. Small inclusions are fragments of recrystallized limestone (white) and of shale (medium gray).

Fig. 10

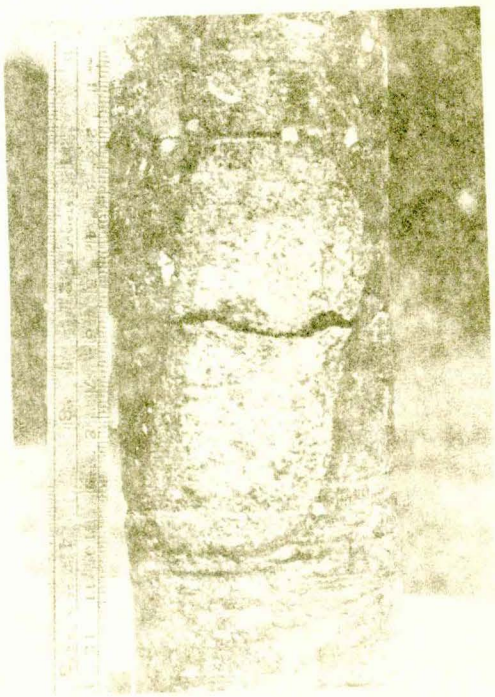


Figure 11. X-ray diffractograms of selected samples of Weston Shale and hornfels, nickel-filtered copper radiation, scan rate 1°2θ per minute. A. Oriented mount, fraction finer than 2 μ, Weston Shale near cen. N line sec. 13, T. 26 S., R. 15 E.. C, chlorite; I, illite; K, kaolinite; M-L, mixed-layer clay; Q, quartz; underlining indicates major component contributing to diffractions. B. Packed sample of unfractionated Weston Shale, same locality as A. F, feldspar; M, mica; other symbols as for A. C. Packed sample of buchitelike hornfels from grader ditch near cen. E line sec. 13, T. 26 S., R. 15 E. M indicates mica diffractions; other diffractions from sanidine. D. Hornfels from surface of "granite" boulder shown in Figure 4. E. Hornfels inclusion from same boulder.

Figure 12. Rb^{87}/Sr^{86} and Sr^{87}/Sr^{86} diagram for 16 whole-rock samples of Rose "granite." Size of boxes indicates errors of measurement. Solid boxes, samples showing granitic textures; closed boxes, samples containing abundant quartzofeldspathic matrix or showing obvious brecciation.

Fig 12.

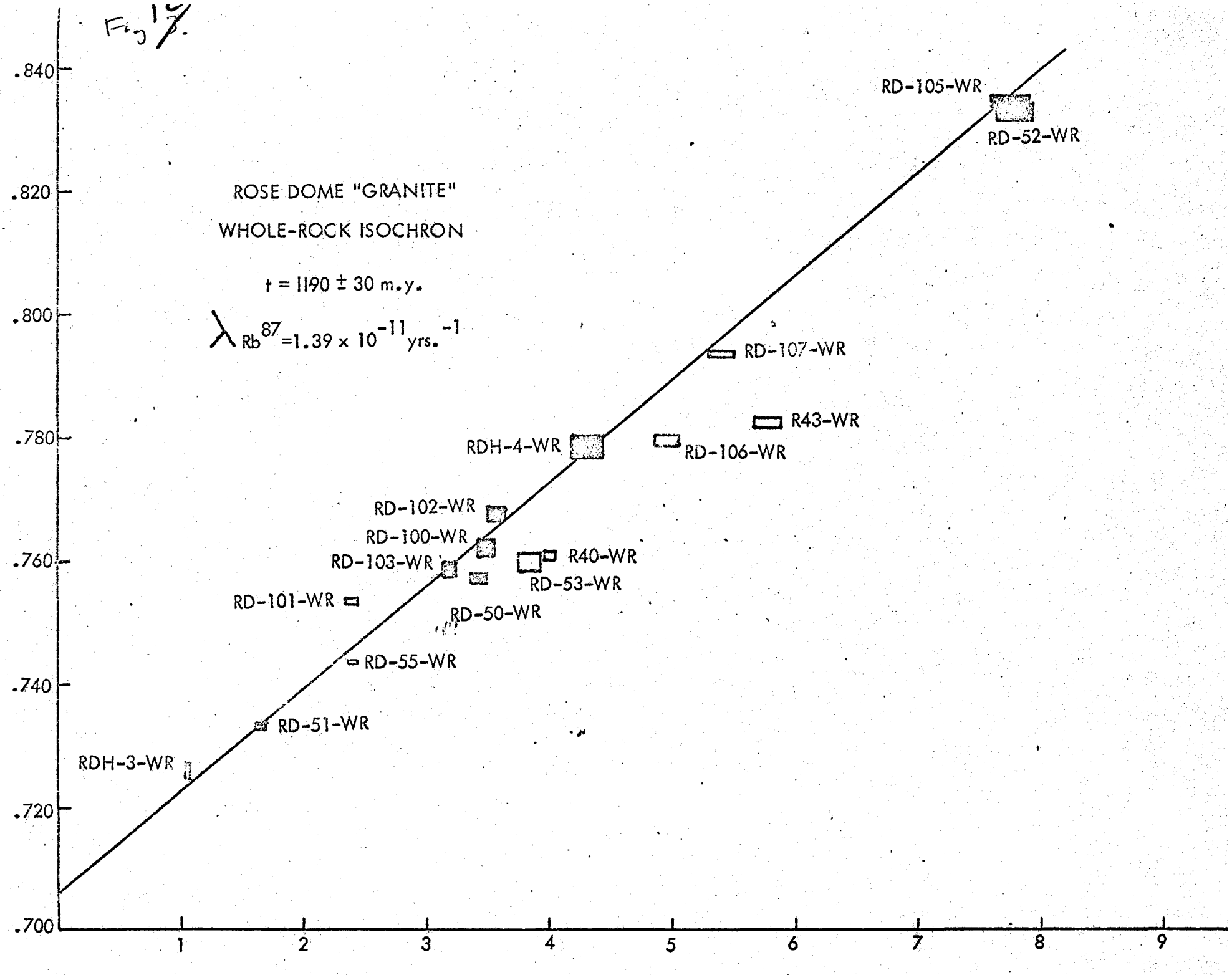

ROSE DOME "GRANITE"
WHOLE-ROCK ISOCHRON
t = 1190 ± 30 m.y.
λ Rb87 = 1.39 x 10-11 yrs.-1
RD-105-WR
RD-52-WR
RD-107-WR
R43-WR
RDH-4-WR
RD-106-WR
RD-102-WR
RD-100-WR
RD-103-WR
R40-WR
RD-53-WR
RD-101-WR
RD-50-WR
RD-55-WR
RD-51-WR
RDH-3-WR
.840
.820
.800
.780
.760
.740
.720
.700
1
2
3
4
5
6
7
8
9

Figure 13. Rb^{87}/Sr^{86} and Sr^{87}/Sr^{86} diagram for whole rock and mineral separates from "granite" sample RDH-3, drill hole 3, depth 6.7 m (22 ft).

Fig 12

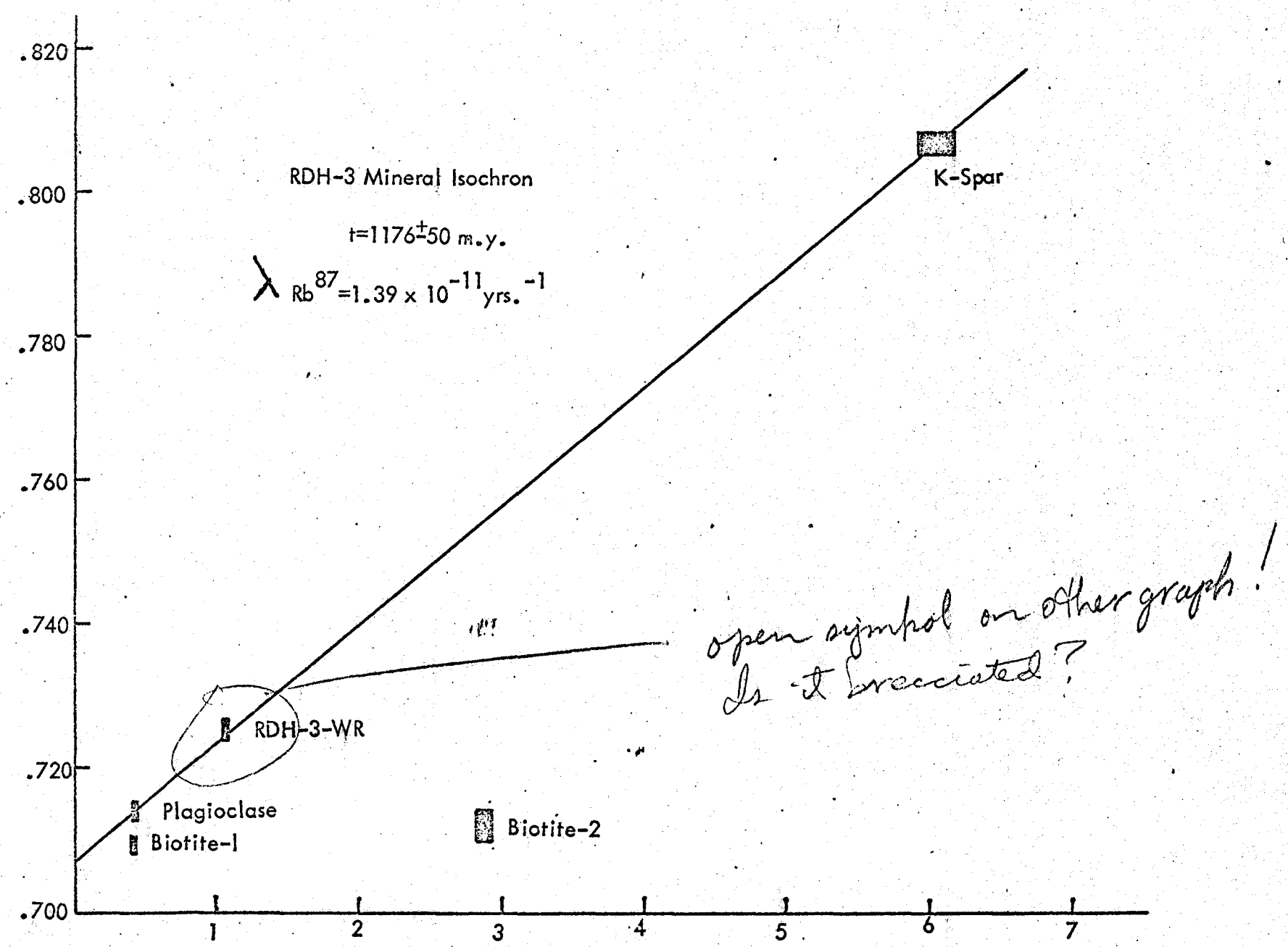

.820
.800
.780
.760
.740
.720
.700
1
2
3
4
5
6
7
RDH-3 Mineral Isochron
t=1176±50 m.y.
Rb87=1.39 x 10-11 yrs.-1
K-Spar
RDH-3-WR
Plagioclase
Biotite-1
Biotite-2
open symbol on other graph!
Is it brecciated?

Figure 14. Rb^{87}/Sr^{86} and Sr^{87}/Sr^{86} diagram for whole rock and mineral separates from "granite" sample RDH-4, drill hole 4, depth 4.9 m (16 ft).

Fig 14

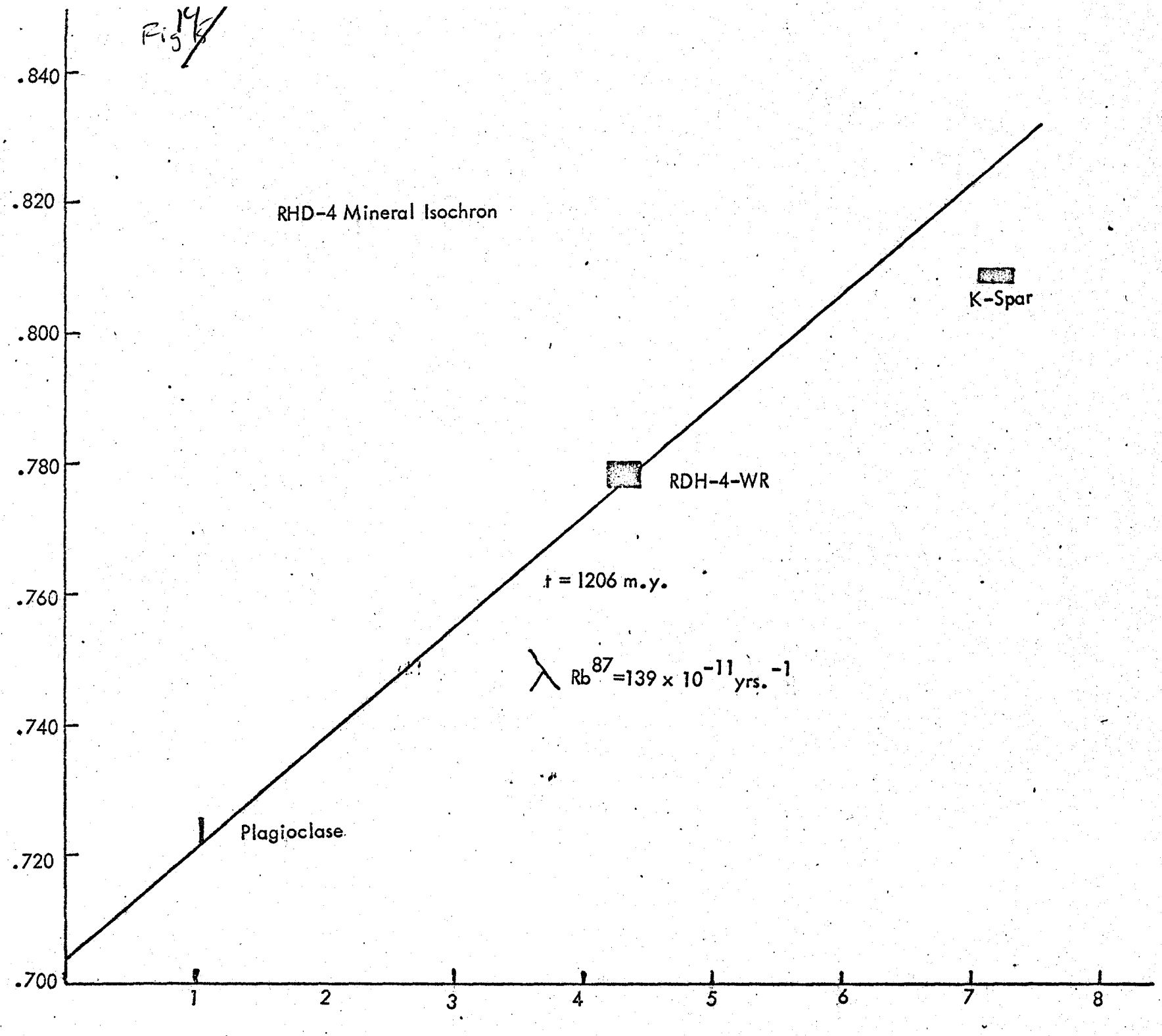
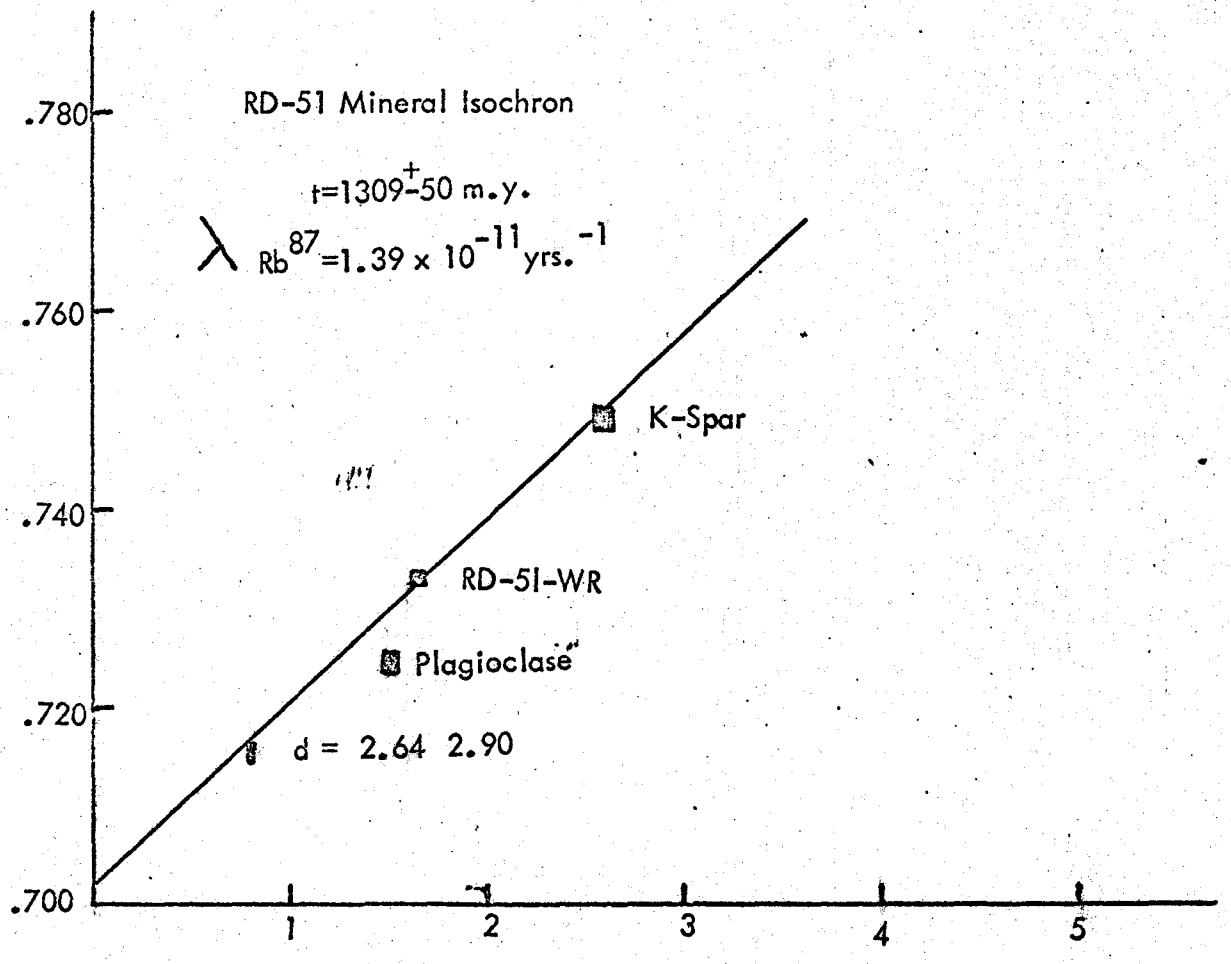

RHD-4 Mineral Isochron
.840
.820
.800
.780
.760
.740
.720
.700
1
2
3
4
5
6
7
8
K-Spar
RDH-4-WR
t = 1206 m.y.
λ Rb87=139 x 10-11 yrs.-1
Plagioclase

Figure 15. Rb^{87}/Sr^{86} and Sr^{87}/Sr^{86} diagram for whole rock and mineral separates from "granite" sample RD-51, surface boulder near cen. N 1/2 NE 1/4 sec. 13, T. 26 S., R. 15 E..

Figure 16. Temperature-pressure diagram showing equilibrium curves for various minerals that are present in the igneous and metamorphic rocks on Rose Dome. Circle indicates inferred realm of temperature and pressure that obtained during intrusion and metamorphism. Data from Eugster and Wones (1962), Evans (1965), Luth and others (1964), Richardson and others (1969), Tuttle and Bowen (1958), Velde (1966), Winkler (1967), Wones (1967), Yoder and Kushiro (1969).

Fig 15


RD-51 Mineral Isochron
t=1309±50 m.y.
λ Rb87=1.39 x 10-11 yrs.-1
.780
.760
.740
.720
.700
K-Spar
RD-51-WR
Plagioclase
d = 2.64 2.90
1
2
3
4
5