THE STRUCTURE OF THE AMOLE ARKOSE NORTH OF KING CANYON, TUCSON MOUNTAINS, ARIZONA

by

Gerald Greenstein

A Thesis Submitted to the Faculty of the

DEPARTMENT OF GEOLOGY

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

1961

STATEMENT BY AUTHOR

This thesis has been submitted in partial fulfillment of requirements for an advanced degree at The University of Arizona and is deposited in The University Library to be made available to borrowers under rules of the Library.

Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in their judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: Gerald Greenstein

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

Evans B. Mayo
E. B. MAYO
Professor of Geology

Sept. 11, 1961
Date

THE STRUCTURE OF THE AMOLE ARKOSE NORTH OF KING CANYON, TUCSON MOUNTAINS, ARIZONA

by

Gerald Greenstein

ABSTRACT

The Amole Arkose in the area studied is probably Upper Cretaceous in age and possibly equivalent to Kinnison's Echo Valley Formation. The bedding in the Amole Arkose is arced and this arc may be roughly visualized as a northeast-plunging nose, concave to the southwest and convex to the northeast.

The Amole Arkose has been brecciated and mildly metamorphosed by the emplacement of Tertiary intrusions. These intrusions are from oldest to youngest, the Amole Latite, the Amole Granite and Quartz Monzonite, and the Silver Lily dikes. The Amole Latite, which was forcefully intruded, carried or pushed upwards limestone blocks into the arkose sequence and by doing so created local folds in the arkose. The latite intrusions occurred in an east-west structural belt that crosses the Tucson Mountains and was accompanied by an east-west uplift. This uplift is thought to be responsible for the arcuation in bedding.

The collapse of the east-west uplift was accompanied by the emplacement of the Amole Granite and Quartz Monzonite. This collapse pulled open east-west joints that were then filled by the Silver Lily dikes.

The limestone blocks in the area studied were brought into position by the latite and not by thrusting.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF PLATES

INTRODUCTION

Location and Access

The area studied is located some 20 miles west of the city of Tucson, Arizona, on the western slope of the Tucson Mountains. The Arizona-Sonora Desert Museum is located just west of the southwest boundary of the area investigated (Fig. 1.1). This area, in the Tucson Mountain Park, is situated in parts of secs. 1 and 6, T. 14 S., R. 11 E., and secs. 25, 31, and 36, T. 13 S., R. 11 E.; on U.S. Geological Survey, San Xavier Mission, and Cortaro, Quadrangle Maps. The area mapped is approximately 2-1/2 square miles.

The Arizona-Sonora Desert Museum may be reached from Tucson in all weather on paved roads. The Gates Pass road comes directly over the Tucson Mountains and the Ajo and Kinney roads permit a more southerly approach. From the museum the interior of the area studied may be reached via the King Canyon road.

Objectives

On Brown's (1939) geologic map a few structural symbols indicate a northwesterly trend of bedding in the Amole Arkose on the western slope of the central part of the Tucson Mountains. For several years

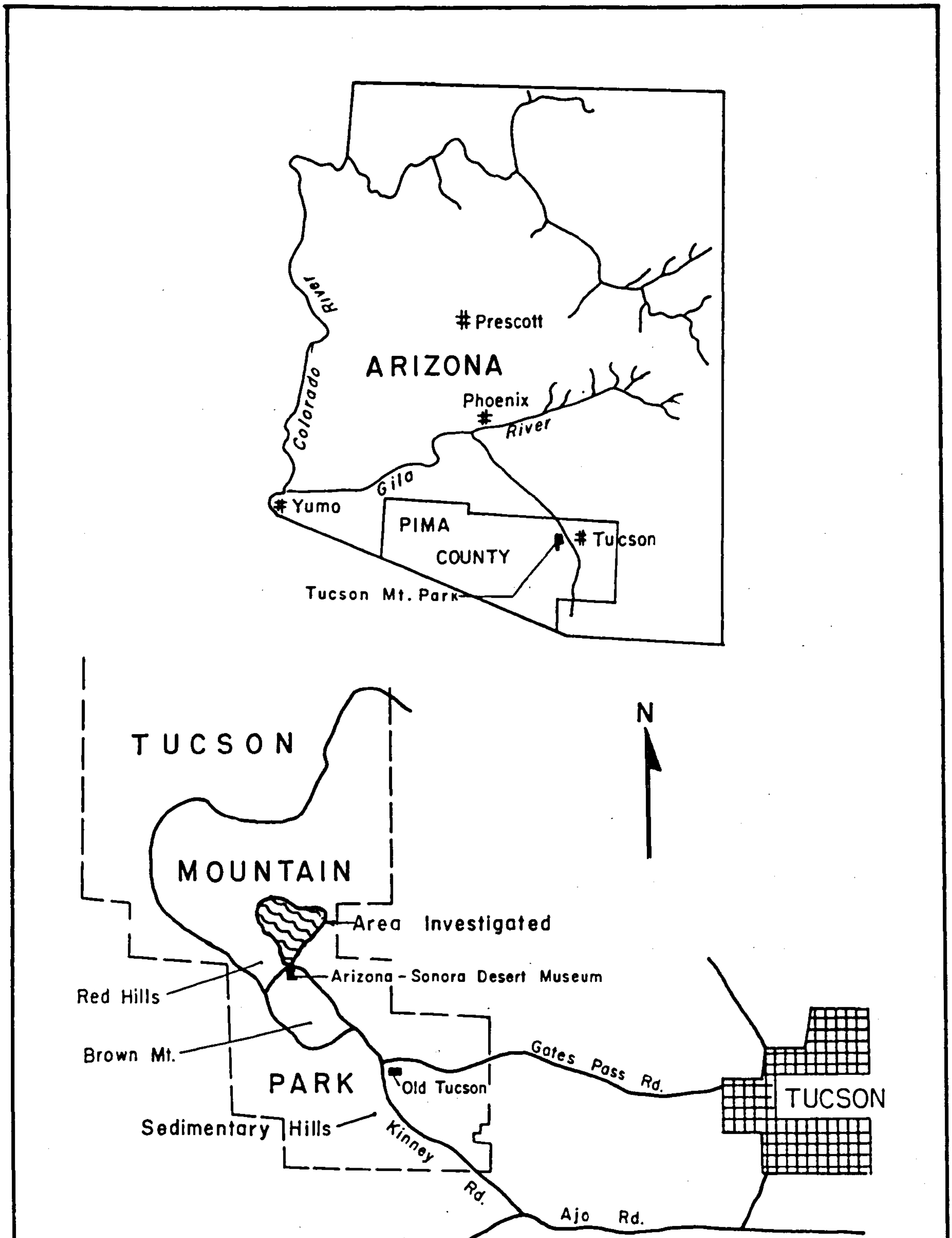


Figure I.I - Map showing location of area investigated it has been known that nearly east-west and even northeasterly bedding trends exist in the northern part of this thesis area. These "cross" trends lie near the southern margin of the large granite and quartz monzonite intrusion mapped by Brown.

The present study was undertaken, first to obtain additional structural data to determine the relation of the northwest to the "cross" trends. It was hoped that from this relation might emerge some suggestion as to the manner of emplacement of the large intrusion. Because the studied area includes part of the large overthrust fault mapped by Brown, it was also hoped that some contribution could be made to the problem of overthrusting in the Tucson Mountains.

With these goals in mind fieldwork was begun in the fall of 1960 and completed in the spring of 1961. Mapping was done on aerial photographs and on previously enlarged U. S. Geological Survey, San Xavier Mission and Cortaro, Quadrangle Maps. The quadrangle maps were enlarged to the scale of one inch equals one thousand feet.

Climate

The climate of the Tucson Mountains is typical of the Basin and Range province of southern Arizona. The winters are dry with temperatures seldom below freezing. The summers are hot with temperatures often exceeding 100°.

The flora and fauna of the Tucson Mountains are characteristic of the lower Sonoran life zone.

Acknowledgments

The writer wishes to express his gratitude to Dr. E. B. Mayo of the Geology Department of the University of Arizona who directed this thesis and gave considerable time and effort toward its completion. He also desires to thank Dr. S. Titley of the Department of Geology of the University of Arizona for his many kindnesses in reviewing this manuscript.

SUMMARY OF THE GEOLOGY OF THE TUCSON MOUNTAINS

Previous Work

The first study of the geology of the Tucson Mountains was made by Guild (1905) who described some of the rock types seen in the range. Tolman (1909) and Wilson and Jenkins (1920) added additional information.

In 1939 W. H. Brown made the first comprehensive study of the geology of the Tucson Mountains. His report contained details of stratigraphy and a structural interpretation of the range. This work has served as a basis for all subsequent studies in the Tucson Mountains.

Feth (1948) and Bryant (1955) reviewed the stratigraphy of the Permian System at Snyder Hill; Bryant (1952) presented a resume of the stratigraphy of the range. Britt (1955) reported on the stratigraphy of the Twin Peaks area and Bennett (1957) studied the geology of the Sedimentary Hills.

In 1957 Whitney studied the geology of an area in the east-central part of the range. Kinnison (1958) described the geology of the Tucson Mountains south of Ajo road, and Colby (1958) reported on the geology of the Red Hills and Brown Mountain. In 1959 Imswiler reported on the geology of the Safford Peak area (Fig. 2.1).

The Rocks

The age of the rocks in the Tucson Mountains ranges from Precambrian to Quaternary. The Precambrian is represented by the Pinal Schist (Brown, 1939, p. 711) which is exposed in the Picacho de Calera Hills. In the Picacho de Calera Hills the Paleozoic rocks represent parts of the Cambrian, Devonian, Mississippian, Pennsylvanian, and Permian Systems. The rocks are mostly limestones except for the basal Bolsa Quartzite which is middle Cambrian in age.

The Cretaceous sediments which crop out along the western slope of the Tucson Mountains and along the northeastern slope of the range are the most abundant sedimentary rocks in the Tucson Mountains. The basal Cretaceous(?) appears to be represented by the clastic sediments of the Recreation Redbeds Formation. These sediments are in part older than and in part equivalent to a volcanic sequence exposed on Brown Mountain (Colby, 1958, p. 6). The youngest Cretaceous sedimentary rock in the range is the Amole Arkose Formation (Brown, 1939; Kinnison, 1958; and Colby, 1958).

The Cretaceous System is in part metamorphosed by and in part deformed by Laramide(?) intrusions (Brown, 1939). In the vicinity of Amole Peak (Fig. 2.1) the Amole Granite and Quartz Monzonite intrudes the surrounding Cretaceous sediments as do latite sills and dikes.

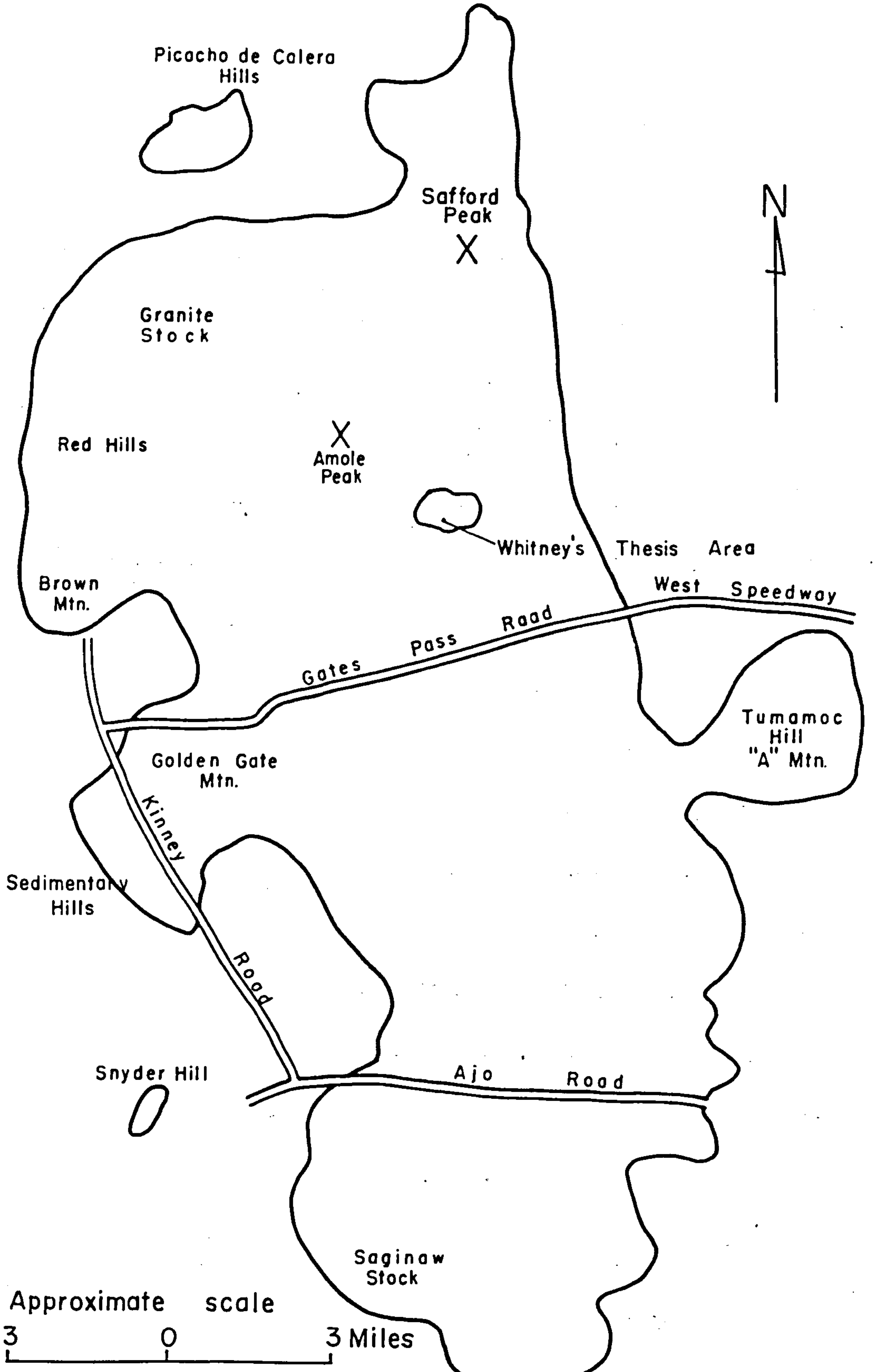


Figure 2.1 – Sketch map of the Tucson Mountains showing locations mentioned in the text

Farther south in the range is the Saginaw Stock (Fig. 2.1), which is a latite porphyry.

The Tertiary rocks are dominantly lavas and tuffs such as the Cat Mountain Rhyolite (Brown, 1939; Kinnison, 1958). These lavas and tuffs can be observed along the eastern slope of the range. Basalt flows dated as Tertiary-Quaternary occur in the southern part of the Tucson Mountains.

Structure

Brown (1939, p. 748) divided the Tucson Mountains into three structural units: a basement block of Cretaceous and older rocks that were folded and thrust in the Laramide(?) orogeny; a series of tilted lavas and tuffs of Tertiary age; and a series of flat-lying basalts of Tertiary-Quaternary age.

The major structure of the Cretaceous basement block is a northwest-trending syncline. This fold is located on the western slope of the range, southeast of the Arizona-Sonora Desert Museum. Brown (1939) believed that the basement structure was complicated by a great thrust fault. The thrust, according to Brown, resulted in the Paleozoic sediments being transported from the west onto Cretaceous sediments.

The Tertiary volcanic series rests with marked angular unconformity on the erosion surface of the basement complex (Brown, 1939, p. 751). The lavas and tuffs are tilted eastward at an angle of 10° to

15°. This tilted lava cap emphasizes the tilted block character of the range. Two sets of high-angle faults are found in the Tertiary volcanic sequence. One set strikes north-northeast and the other set strikes west-northwest (Brown, 1939, p. 752).

In the southern part of the range, flat-lying basalt flows are present at "A" Mountain and at Tumamoc Hill. The basalt flows overlie the Tertiary volcanic sequence with marked angular unconformity.

FORMATIONS IN THE INVESTIGATED AREA

General Statement

The lithologic units exposed in the area studied are from oldest to youngest, the Recreation Redbeds, the Amole Arkose, the Amole Latite sills and dikes, the Amole Granite and Quartz Monzonite, the Silver Lily dikes, and the Quaternary alluvium.

The Recreation Redbeds and the Amole Arkose have been assigned a Cretaceous age by Brown (1939), Colby (1958), and Kinnison (1958).

The Cretaceous rocks in the area studied have been brecciated near their respective contacts with granite and quartz monzonite by the emplacement of the Amole intrusions. The Amole Arkose has been metamorphosed near its contact with the Amole Granite and Quartz Monzonite.

The Amole Latite sills and dikes, the Amole Granite and Quartz Monzonite, and the Silver Lily dikes have been assigned a Tertiary age by Brown (1939).

Exposures of limestone that do not appear to be part of the Amole Arkose sequence were observed in the arkose in the northern part of the area investigated.

Sedimentary Rocks

Recreation Redbeds

The Recreation Redbeds were named by Brown (1939) and studied in detail by Colby (1958). This formation is observed to crop out on Brown Mountain and in the Red Hills (Fig. 2.1). Brown (1939) and Whitney (1957) have reported the presence of redbeds on the eastern slope of the Tucson Mountains.

Colby (1958) who studied the redbeds in the Brown Mountain and Red Hills area, divided the redbeds into three members. They are from oldest to youngest, the sandstone-siltstone member, the volcanic conglomerate member, and the tuff member. The volcanic conglomerate and tuff members which are believed by Colby to be younger than the sandstone-siltstone member, were originally mapped by Brown (1939) as Cretaceous volcanics and according to Brown, the volcanics were older than the sandstone-siltstone member.

The sandstone-siltstone member is exposed in the Red Hills and is in contact with the Amole Arkose in the area studied. The two younger members are exposed on Brown Mountain and are in contact with the Amole Arkose south of the area studied.

The sandstone-siltstone member is estimated to be 2,290 feet thick (Colby, 1958, p. 8), and is composed primarily of a brick-red, fine-grained sandstone. Beds of purple- and gray-colored sandstone are observed locally.

No fossils were found in the Recreation Redbeds by Brown or Colby. The age of the redbeds is believed by both workers to be Lower Cretaceous because the redbeds underlie the Amole Arkose. The Amole Arkose has been assigned a Cretaceous age by Brown (1939) and by Kinnison (1958) on the basis of fossils. Because no evidence of Triassic or Jurassic sedimentation is found in southeastern Arizona, the possibility that the Recreation Redbeds are Triassic or Jurassic in age is considered unlikely.

In Windmill Canyon, 200 yards west of the well (Pl. 1), the redbeds were observed in fault contact with the Amole Granite. At the contact there is no alteration or discoloration of the redbeds, although at points over 200 yards from the contact there is some alteration where jointing is well developed. At these places epidote and sometimes chlorite are found.

Amole Arkose

The Amole Arkose Formation crops out along the western slope of the Tucson Mountains and is the principal rock in the area studied. The formation was named by Brown (1939) who described it as being composed primarily of arkosic sandstones. Kinnison (1958, p. 14) studied the Amole Arkose in detail in the area south of the Ajo road (Fig. 2.1). As a result of his investigation Kinnison (1958, p. 15) proposed that the Amole Arkose be renamed the Amole Group. He points out that the arkosic sandstones are only one of the many rock types that are present in the formation and that the Amole Arkose can be subdivided into four units.

Kinnison divided the Amole Arkose into four units; they are from oldest to youngest, the Braun Formation, the Dead Cow Formation, the Mouse House Formation, and the Echo Valley Formation. He (1958, p. 13) also describes a 10-foot thick limestone conglomerate which underlies the Braun Formation. Kinnison believes that this conglomerate may be equivalent to the basal Cretaceous conglomerate (Glance) that is found throughout southeastern Arizona. The total thickness of the Amole Group is considered to be approximately 6,000 feet.

In King Canyon and elsewhere in the area studied, siltstones, shaly sandstones, and gray sandstones were observed to be the dominant lithologic types (Pl. 3). Arkose beds (Pl. 4) make up less than 10 percent of the sequence and quartzite and limestone beds are even less common. This assemblage compares best with Kinnison's Echo Valley Formation, to which he assigned an Upper Cretaceous age on the basis of Upper Cretaceous pollen grains found in the underlying Mouse House Formation.

Near the contact between the Amole Arkose and the Amole Granite and Quartz Monzonite, the arkose has been metamorphosed by the emplacement of the granite and quartz monzonite. Where metamorphic

PLATE 3

TYPICAL LITHOLOGIC TYPES OBSERVED IN THE AMOLE ARKOSE SEQUENCE

Figure 1. Shaly sandstone and gray sandstone.

Figure 2. Siltstone.

PLATE 4

Arkose beds in King Canyon.

processes have affected the Amole Arkose, it appears that the arkose has been indurated and possibly silicified. Recrystallization due to metamorphism is imperfect and in some areas it appears to be lacking. Where recrystallization does occur its presence is indicated by the occurrence of epidote, micas, and chlorite. The epidote, mica, and chlorite association is considered by Turner and Verhoogen (1960) to be typical of the albite-epidote-hornfels facies of contact metamorphism. This suggests that the temperature of metamorphism was very low and also that the intrusion was emplaced at a low temperature.

Limestone blocks

In the northern part of the area studied there are two localities where limestone blocks or masses are exposed. One of these localities is located north and the other is located south of Windmill Canyon (Pl. 1). At both localities the Amole Arkose appears to overlie the limestone. At the northern locality the contact between the Amole Arkose and the limestone was observed (Fig. 4.1).

In both exposures the limestone is pale gray, highly brecciated, and crystalline. No fossils were found at either locality. At both places mineralization of part of the limestone has occurred. Where the limestone is mineralized it is black in color and contains garnet, sphalerite, and pyrite.

The lower contact between the limestone blocks and the Amole

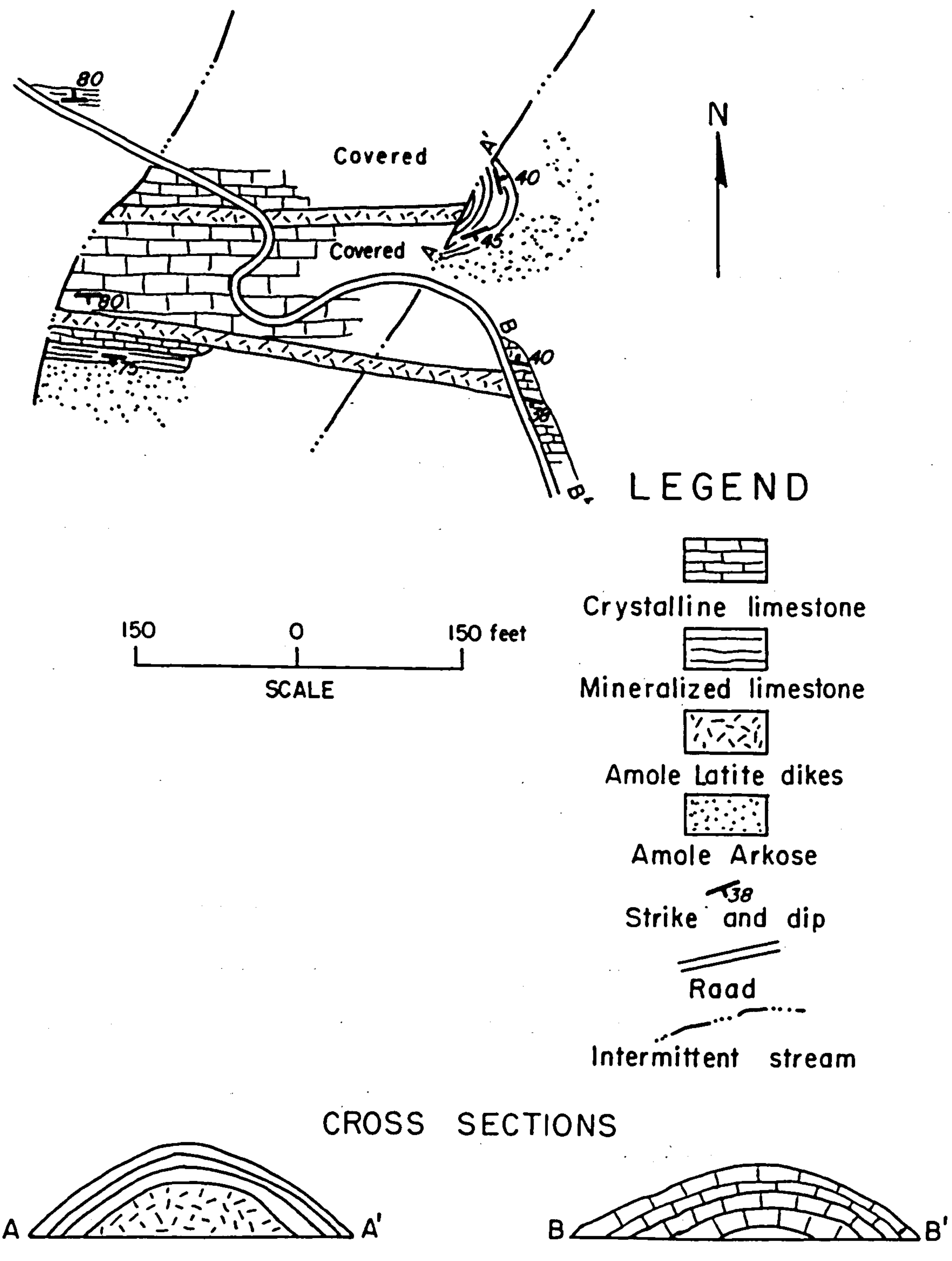


Figure 4.1

Map and section of limestone exposure north of Windmill Canyon

Arkose was not observed in the area studied. The structure of the limestones suggests that these masses have been forced upward into the Amole Arkose and in this case no lower contact with the arkose is to be expected.

Brown (1939) described similar limestone masses that contain Permian fossils in an area to the east of the southern part of the area investigated by the writer. A comparison of hand specimens between the limestones exposed in the writer's area and those exposed in Brown's area reveals that the limestones from both areas are similar in lithologic character.

The limestone exposures are of particular significance in the interpretation of the structural geology of the Tucson Mountains and will be discussed further under "Structure."

Quaternary alluvium

The Quaternary alluvium is exposed in all parts of the Tucson Mountains. In the area studied it forms a thin cover on most ridges and is usually exposed along the walls of the washes (Pl. 5).

The alluvium appears to be a heterogeneous collection of fragments from all earlier rocks. Usually the alluvium is light brown in color.

PLATE 5

QUATERNARY ALLUVIUM IN KING CANYON

Figure 1. Cut and fill relation in King Canyon.

Figure 2. Typical exposures of alluvium in King Canyon.

Igneous Rocks

Amole Latite

Brown (1939) describes two dike sets in the Tucson Mountains that he believes are Tertiary in age. One of these, the Amole Latite, was related in origin to but older than the major Amole intrusion. The Amole Latite dikes and sills are exposed in the area immediately adjacent to this intrusion.

Both dikes and sills of the Amole Latite are filled with latite porphyry. The phenocrysts are quartz and feldspar.

Amole Granite and Quartz Monzonite

The Amole Granite and Quartz Monzonite is exposed to the north and to the northwest of the area studied. The unit was mapped in a general way by Brown (1939) and has not been studied in detail. This is the major intrusion in the Tucson Mountains.

The rock in most places is coarse grained, yellowish white, and composed of quartz, feldspar, and biotite. The age of the intrusion is probably Tertiary. The rocks are definitely younger than the Cretaceous sediments into which they intrude.

Silver Lily dikes

The Silver Lily dikes according to Brown (1939) are younger than the Amole Latite dikes and sills and also younger than the major Amole intrusion. This dike set is exposed in nearly east-west joints or fissures at a distance from the Amole Granite and Quartz Monzonite.

The composition of the Silver Lily dikes is identical to that of the Amole Latite dikes and sills. The only difference that the writer could find between the two sets was texture. In general the Silver Lily dikes are coarser grained than the Amole Latite dikes and sills.

STRUCTURE

General Statement

The dominant directions of structure in the area studied are northwest and nearly east-west. In King Canyon (Pl. 1) the strike of bedding in the Amole Arkose is N. 40 W. Traversing the area from south to north the northwest structure is observed to turn westward. In the canyons north of Windmill Canyon (Pl. 1), in the northern part of the area studied, the strike of the beds in the Amole Arkose averages N. 85 W. Thus the beds define an arc, concave toward the southwest and convex northeastward.

Where the Amole Arkose strikes northwestward it usually dips to the northeast at an angle of 5^{o} to 50^{o}. Where the Amole Arkose strikes east-west the dips are usually toward the north. The magnitude of the dip varies from 10^{o} to 80^{o}. Dips of 80^{o} or even steeper are found on the south limb of the syncline in the northern part of the area studied (Pl. 1). The arc of bedding, then, may be visualized roughly as a northeastward plunging nose. Local details complicate this simple structure. The same nose appears to exist in the Recreation Redbeds, and the arc is reflected in the course of the Windmill Canyon fault.

There appears to be a major syncline or basin-like structure, as revealed by measurements of the attitudes of bedding in the southeastern part of the area studied (Pl. 1). This large fold appears to die out northwestward where it should cross the northeast-plunging nose. The small folds shown southwest of this syncline seem to represent an associated, somewhat crumpled anticline and a similar anticline appears on the northeast flank of the syncline (Pl. 2, structure section A-A').

With the exception of these larger structures, the folds in the area studied appear to be minor, and closely localized. Some of the small folds seem to be related to emplacement of the Amole Latite, the Amole Granite and Quartz Monzonite, and the limestone blocks. Others still may record adjustments of the sedimentary beds in response to movements along the Windmill Canyon fault.

Faults, closely spaced joints, and breccia characterize the contact between the Recreation Redbeds and the Amole Arkose, the Recreation Redbeds and the Amole Granite and Quartz Monzonite, and parts of the contact between the Amole Arkose and the Amole Granite and Quartz Monzonite. As previously mentioned, the limestone blocks are intensely shattered.

Contacts of Sedimentary Rocks with Major Amole Intrusion

Both the Amole Arkose and the Recreation Redbeds are in contact with the large intrusion of Amole Granite and Quartz Monzonite north and northwest of the area studied. The contact between granitic rock and the redbeds trends nearly east-west and is remarkably straight (Pl. 1). These observations, plus the virtual absence of alteration of the redbeds along the separating surface, suggests that the granitic and sedimentary rocks are in fault contact. This impression is supported by local observations. At a point 200 yards west of the well in Windmill Canyon (Pl. 1) the granitic rocks were observed in fault contact with the Recreation Redbeds. The fault strikes N. 87 E. and dips 75° south. Flow layers in the intrusion, north of the contact strike parallel to this boundary and dip steeply toward it; bedding in the redbeds south of the contact also strikes parallel to this boundary, and dips gently toward it.

In striking contrast to the above, the granite-Amole Arkose contact is sinuous. Nearer the redbeds is a north-northwest projection of Amole Arkose into granite, followed on the east by a corresponding reentrant of granite into arkose. The dip of the contact is shown (Pl. 1) wherever it was measured. At the tip of the projection, and in the reentrant, bedding in the Amole Arkose strikes approximately parallel to the contact, but on the western side of the projection the contact transects bedding. Even in the reentrant, the contact is not concordant, for the beds dip northward into the south-dipping contact (Pl. 2, structure section C-C'). The southward-dipping beds in the tip of the projection as well as the associated synclinal crease, are possibly the result of a local, forceful upwelling of the crystalline granite.

Amole Latite and Limestone Blocks

Some reason has been given under the description of the limestone blocks for supposing that these masses were forced upward into the Amole Arkose. Additional support for this conclusion and a possible cause of the upthrusting is found in the fact that, in the area studied the blocks seem always to be directly associated with dikes or irregular bodies of Amole Latite. In some cases the latite forms the cores of folds in the limestone; in other cases the limestone is present as large separated pieces embedded in the latite.

North of Windmill Canyon (Pl. 1) a block of limestone 500 feet long is exposed. The limestone appears to be deformed into an anticlinal fold with east-west axis, plunging eastward. At the eastern end of the fold the limestone underlies, and is in contact with the Amole Arkose (Fig. 4.1). Along the contact the outer shell of limestone is black and mineralized. Underlying the mineralized shell, the core of the anticline is pale-gray, highly brecciated, crystalline limestone intimately associated with latite.

Directly across the little canyon south of the above mentioned exposure several small limestone folds may be seen. Here, also, several limestone blocks may be seen apparently embedded in the latite (Fig. 4.2).

These phenomena, together with the fact that rocks resembling

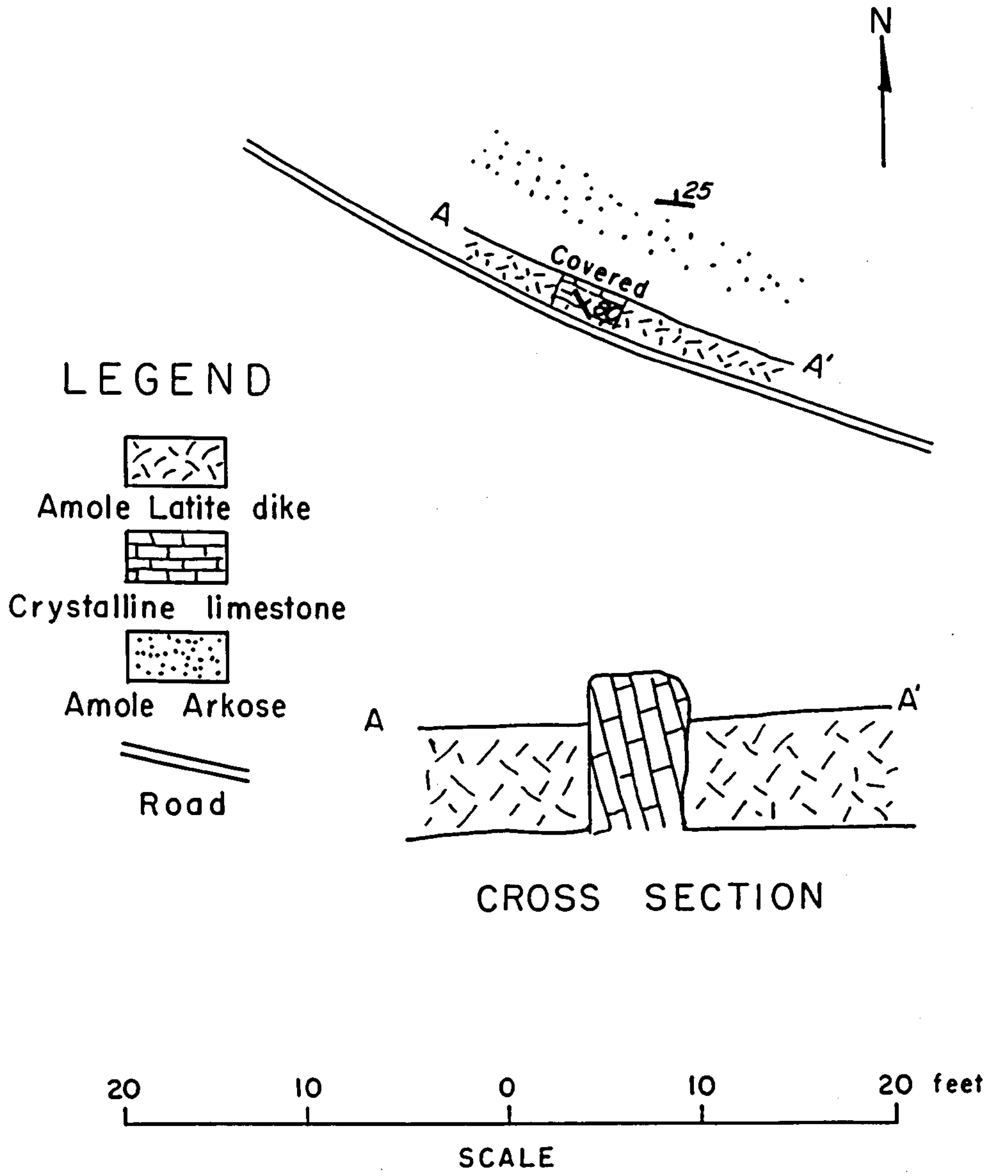


Figure 4.2. Plan view—cross section of a limestone block in Amole Latite

these limestones are known only from strata older than the Amole Arkose, lead to the conclusion that the limestone has been carried upward in the latite, or has been pushed upward ahead of the latite. Accordingly, the latite was emplaced forcefully, and if the limestone is Paleozoic in age, blocks of it appear to have been pushed or carried upward several thousands of feet.

The Silver Lily Latite Dikes

As previously noted the material of these dikes is the same in composition as the Amole Latite, but the dike rock is somewhat more coarsely crystalline. The difference in grain size would seem to follow from the fact that the Amole Latite is much the more contaminated by the sedimentary wall rocks, therefore probably more quickly chilled.

The Amole Latite is exposed as many irregular intrusive bodies as well as dikes and sills. The Silver Lily dikes, on the contrary, have much more formal shapes, and are oriented to a nearly east-west belt of fractures that is prominent in the area (Fig. 4.3). The latite porphyry of the Silver Lily Dikes possibly represents a final expulsion of the Amole Latite magma into nearly east-west fractures as these were opened by tension.

The Windmill Canyon Fault

This fault separates the Recreation Redbeds from the Amole

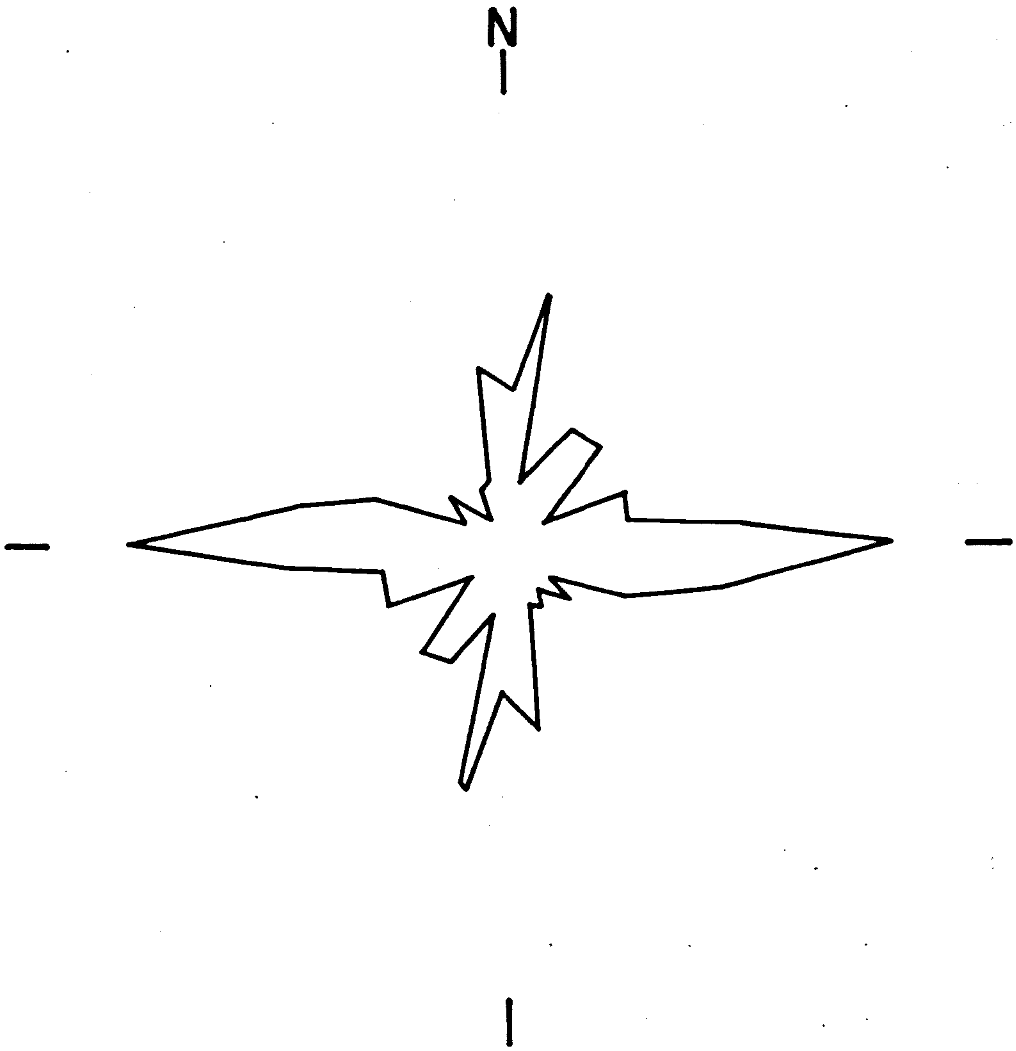
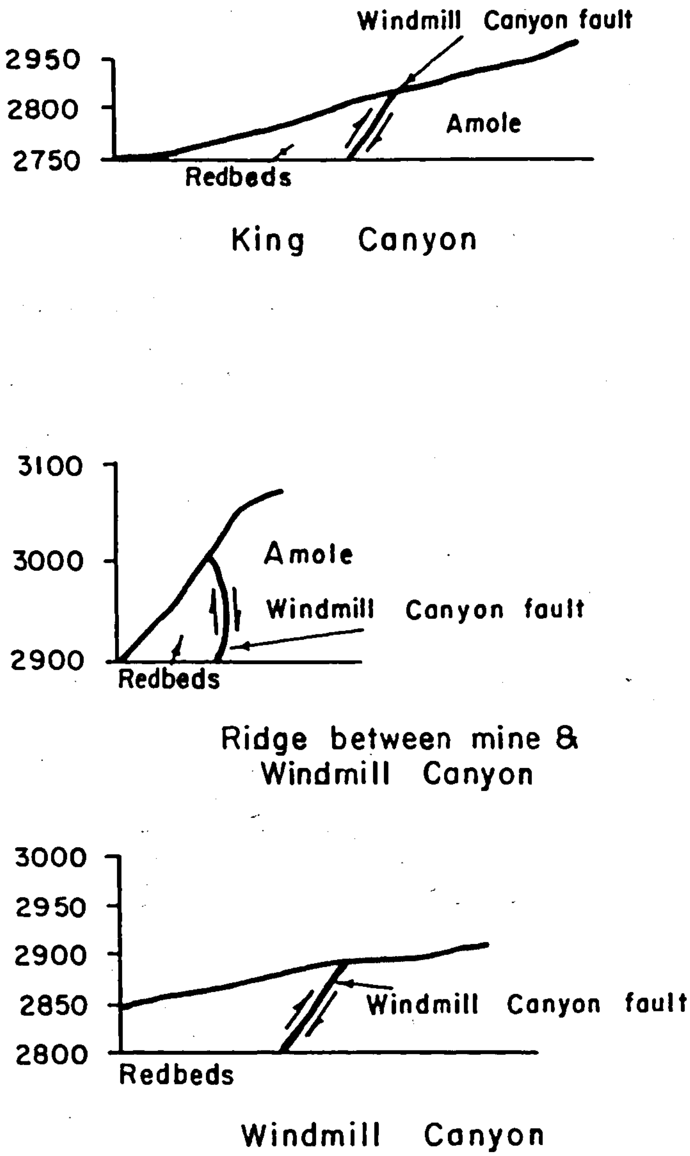


Figure 4.3--Rose diagram showing the orientation of joints in the area studied based on 250 measurments of strike

Arkose and the major Amole intrusion. Its surface trace, reflecting the arc of bedding in both the Recreation Redbeds and the Amole Arkose has been mentioned. In King and Windmill Canyons the fault dips approximately 70^{o} to the west. Between Mine and Windmill Canyons the topographic elevation along the fault trace increases abruptly, and the trace is revealed as the contact between red soil derived from the redbeds and gray soil derived from the arkose. This contact between the soils is observed to migrate westward as elevation increases, indicating that the Windmill Canyon fault dips to the east at the higher elevations (Fig. 4. 4). Thus it appears that the surface of the Windmill Canyon fault is curved in a vertical as well as a horizontal plane (Pl. 1). The fault dips westward at low elevations and eastward at high elevations.

The relative stratigraphic position of Recreation Redbeds and Amole Arkose along the trace of the fault together with observations on crossbedding which prove that the sequence is normal, indicate that the Amole Arkose moved relatively downward. The top of the redbed sequence shows interbedded Amole Arkose and the bottom of the arkose sequence shows interbeds of Recreation Redbeds. Brown (1939) believed that the sedimentary contact between the Amole Arkose and the Recreation Redbeds was gradational through a zone of 75 feet. If this figure is correct then the vertical displacement on the Windmill Canyon fault is less than 75 feet, and the redbeds are relatively upthrown.

A rather extensive shattering of the Amole Arkose near the



Horizontal scale: $\frac{1''}{2}$ inch= 100 feet
Vertical scale: Exagerated(5) times

Figure 4.4
Relationship between elevation of topograpy and the direction of dip of the Windmill Canyon Fault

fault suggests normal faulting and tension rather than compression and upthrust.

Movement on the Windmill Canyon fault appears to have been complicated by some left lateral strike slip. This is indicated by offsets where the fault traverses two of the Silver Lily dikes, and perhaps by the little, westward-projecting prong of Amole Arkose just north of Windmill Canyon (Pl. 1).

The two displaced dikes are nearly vertical, and their offsets measured by pacing, amount to 125 feet. This exceeds the estimated vertical component and can hardly result from the vertical faulting of near vertical dikes.

Some closely associated folds may have formed as adjustments in response to movement on the fault. One of these folds is the curved syncline in the Amole Arkose that crosses Windmill Canyon about 1,000 feet east of the well (Pl. 1). Another possible example is the complication in the Amole Arkose in and near King Canyon just east of the fault trace (Pl. 1). In the southern part of this complication arkose beds bend to the fault as though dragged by the strike slip. The northern part of this complication is less easily explained. Perhaps this northern part records the gliding off of little consolidated Amole Arkose from the uplifted block, or perhaps a local sagging of the relatively downthrown block is indicated. It seems unlikely that the fault and local complication are unrelated.

Joints

A joint rose based on 250 measurements of strike (Fig. 4.3) furnishes a summary of the joint directions and their relative importance. A nearly east-west direction predominates, and a few examples are shown on the map. There are two nearly north-south maxima, a northeast maximum, and a very subdued northwest maximum.

The predominant east-west maximum is of particular interest. The component fractures are distributed throughout the area studied, and are closely spaced near the Recreation Redbed-Amole Granite and Quartz Monzonite contact, and in a broad belt where bedding swings from northwest to nearly due west. The genetic, or mechanical, relation of the turned beds to the east-west joints is not clear, but the spatial relation is obvious. As already mentioned, some of the east-west joints appear to have been pulled open to receive the latite porphyry of the Silver Lily dikes. As shown by the offset dikes the east-west joint set is older than at least the latest movement on the Windmill Canyon fault.

DISCUSSION OF THE STRUCTURAL FEATURES

Arcuate Pattern of Bedding

The first objective of this study was to bring out the relation between northwest and east-west trends of beds in the sedimentary rocks. This relation was established by the structural measurements. Does the arcuate pattern so revealed mean that the sedimentary rocks have been turned aside and perhaps dragged upward to provide space for forceful emplacement of the Amole Granite and Quartz Monzonite? Somewhat similar structural relations have been used as evidence of forceful emplacement.

In this example however, the gentle, intrusionward dips of Amole Arkose in the eastern reentrant (Pl. 1) make the forceful squeezing aside of the sediments seem highly questionable. So, also, do the gentle northward dips of the Recreation Redbeds along the granite-redbed contact. In view of this evidence it seems reasonable to conclude that the arcuation of the sedimentary bedding was not caused by forceful intrusion.

A second possibility is that beds with northwest strike have been turned by left lateral strike slip along an east-west zone of adjustment. Perhaps this suggestion merits careful consideration, but it is open to objections. Excepting the Windmill Canyon fault, no feature with east-west trend has been observed to have accommodated strike slip. Moreover, the many east-west fractures seem to be mostly joints, not faults, and they are younger than the arced beds, which they traverse. Perhaps the observed arcuation represents the adjustment of near-surface materials to strike slip on a very deep-seated shift zone.

A third suggestion is that beds with northwest strike are crossed by a broad anticlinal uplift with northeast plunge, and that strike slip is not important. This would explain the northeast strikes in the northeastern part of the area studied, and it would account for the arcuation. The uniformly due westward strikes of bedding in the Amole Arkose at the northwestern border of the arkose's exposures, and a similar strike of layered structures in the Amole Granite west of the contact, do not appear to fit naturally into this explanation.

A fourth possibility is that in the northern part of the area studied, and beyond, an east-west welt once rose across the northwest strike of the sedimentary beds. If this swell plunged westward, it would account for most structural observations in this and adjacent areas. Some combination of the last three possibilities may yield the closest approach to the truth.

The East-West Structural Trend

On Brown's (1939) geologic map an east-west structural belt is shown in a general way that includes more than the entire north-south extent of the major Amole intrusion. This belt is accented by east-west fingers of Amole Latite, by cross faults, and by an east-west arrangement of limestone blocks.

In the area studied the following east-west structures were observed: a joint set, a dike set, bedding, and a segment of the Windmill Canyon fault. West of the area studied, in the Red Hills, Colby (1958) reports a joint and a dike set that strike east-west. To the east of the area studied, on the eastern slope of the Tucson Mountains, Whitney (1957) reports the transverse arrangement of limestone blocks.

The above observations appear to warrant the conclusion that an east-west structural belt crosses the Tucson Mountains and that this cross belt may reflect the presence of a strand of the Texas Lineament which crosses southeastern Arizona (Mayo, 1958).

Emplacement of the Intrusive Rocks

According to Brown (1939), the Amole Latite is cut off at its contact with the Amole Granite and Quartz Monzonite. The latite, therefore, is the older. Moreover the latite appears to be restricted to the broad, nearly east-west structural belt discussed above. As stated before, the field observations suggest that the Amole Latite was intruded forcefully. Accordingly, at the time of latite intrusion there may have been some tendency for the east-west belt to rise as an elongated swell.

At some time after the latite was emplaced the main intrusion of Amole Granite and Quartz Monzonite took place. The main intrusion took place in the east-west structural belt and on the northwest-trending axis of the Tucson Mountain exposure. It has been mentioned that evidence in the mapped area seems to preclude forceful thrusting or squeezing of sedimentary wall rocks to provide space for the intrusion. None of the evidence at hand seems to preclude shattering of the walls and the lifting of blocks to levels where they would have been removed by erosion. Indeed, some active upwelling must have been required to bring the granitic material to the present level of exposure. Except by a very detailed study of the entire intrusion and its exposed walls, no answer to the problem of emplacement is to be hoped for, but the gentle intrusionward dips of the sedimentary rocks along the intrusive contacts clearly suggest collapse and downward stoping as an active process. Therefore, there may have been a time when the postulated east-west swell began to collapse. This collapse could have caused the opening of already existing east-west fractures to receive the Silver Lily dikes.

It is beyond the scope of this thesis to carry the above discussion further, but it should be pointed out that the Silver Lily dikes traverse the Cat Mountain Rhyolite which, according to Brown (1939) is younger than the Amole Latite!

The Problem of Overthrusting in the Tucson Mountains

Brown (1939) proposed that the many limestone blocks that appear to rest on Cretaceous rocks in the Tucson Mountains are remnants of a once extensive overthrust sheet. That is, the Paleozoic rocks had been thrust over the Cretaceous ones.

In the area studied, all observed limestone blocks appear to have been pushed or carried upward by the Amole Latite. As shown on Brown's map, most of the limestone blocks are located in or near the supposedly uplifted east-west structural belt, where the Amole Latite is known, and off which some of the blocks, undermined by erosion, might have possibly rolled or glided. This mechanism could cause some of the blocks to rest on the Amole Arkose. It is perhaps too early to apply observations made in a restricted area to explain the distribution of limestone blocks in a much larger area. It is obvious, however, that the observations do cast doubt on the reality of the postulated thrust.

CONCLUSIONS

As a result of the study in the mapped area, and of the available geologic literature on the Tucson Mountains, the conclusions listed below appear to follow.

1. The Amole Arkose of the mapped area seems to correlate with the Echo Valley Formation of Kinnison. If this correlation is correct the Amole Arkose of the mapped area is Upper Cretaceous in age.

2. The arcuation of beds in the mapped area is no indication of forceful intrusion, and it probably is no indication of left lateral strike slip along an east-west structure belt. Uplift along the east-west belt, or along this belt and a northeast-trending nose, could account for the arcuation.

3. The Amole Latite, somewhat older than the major Amole intrusion, was emplaced forcefully and pushed and carried limestone blocks several thousand feet upward to their present position.

4. The major Amole intrusion may have risen actively, but local evidence suggests collapse and downward stoping as an important process. The collapse may have pulled open east-west joints to receive the Silver Lily dikes.

5. The Windmill Canyon fault, which is curved in both a

horizontal and a vertical plane, shows both a vertical and a horizontal (strike slip) component of movement. The horizontal displacement at least is younger than the Silver Lily dikes.

SUGGESTIONS FOR FURTHER STUDY

During the course of the present investigation several interesting problems arose which merit additional study. One of these is the mechanism of emplacement of the major Amole intrusion. This question will only be answered after a detailed study of the intrusion has been made. Another problem that merits attention is the extent and influence of the east-west structure in the Tucson Mountains. Lastly the writer suggests that a study be made of the limestone blocks southeast of this thesis area.

BIBLIOGRAPHY

Bennet, P. J., 1957, The geology and mineralization of the Sedimentary Hills area, Pima County, Arizona: Univ. Arizona, unpublished master's thesis.

Britt, T. L., 1955, Geology of the Twin Peaks area, Pima County, Arizona: Univ. Arizona, unpublished master's thesis.

Brown, W. H., 1939, Tucson Mountains, an Arizona basin-range type: Geol. Soc. Am. Bull., v. 50, p. 697-760.

Bryant, D. L., 1952, Paleozoic and Cretaceous stratigraphy of the Tucson Mountains: Arizona Geol. Soc. Guidebook, no. 1, p. 33-42.

Colby, R. E., 1958, The stratigraphy and structure of the Recreation Redbeds, Tucson Mountain Park, Arizona: Univ. Arizona, unpublished master's thesis.

Guild, F. N., 1905, Petrography of the Tucson Mountains, Arizona: Am. Jour. Sci., v. 20, p. 313-318.

Imswiler, J. B., 1959, Structural geology of the Safford Peak area, Tucson Mountains, Pima County, Arizona: Univ. Arizona, unpublished master's thesis.

Jenkins, O. F., and Wilson, E. D., 1920, A geologic reconnaissance of the Tucson Mountains: Ariz. Bur. Mines, Bull. 106, p. 5-18.

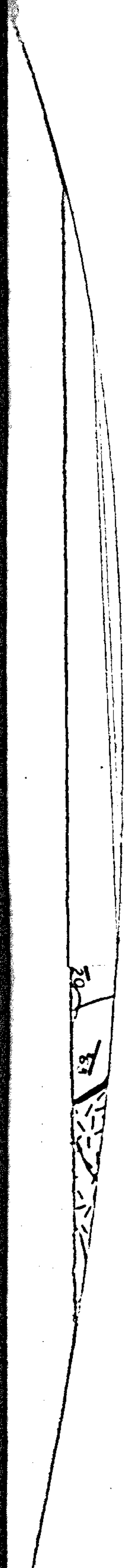
Kinnison, J. E., 1958, Geology and ore deposits of the southern section of the Amole Mining District, Tucson Mountains, Pima County, Arizona: Univ. Arizona, unpublished master's thesis.

Mayo, E. B., 1958, Lineament tectonics and some ore districts of the Southwest: Min. Eng., v. 10, p. 1169-1175.

Tolman, C. F., 1909, The geology in the vicinity of the Tumamoc Hills, Arizona: Carnegie Inst. Wash., pub. 113, p. 67-82.

Whitney, R. L., 1957, Stratigraphy and structure of the northeastern part of the Tucson Mountains: Univ. Arizona, unpublished master's thesis.

2 Plates



Geologic Map of the Amole Arkose near King Canyon

By
Gerald Greenstein

E9791
1962
192
PL. I

LEGEND

SEDIMENTARY ROCKS

Recent — Qal — Alluvium

Tertiary

Cretaceous — Ka — Amole Arkose

Cretaceous — Kr — Recreation Redbeds

Age uncertain — Limestone

IGNEOUS ROCKS

Silver Lily dikes

Tkg — Amole Granite

Amole Latite dikes and sills

STRUCTURE

Strike and dip

General direction of strike and dip

Generalized strike and dip of beds

Anticline

Syncline

Dashed where approximately located

FLOW STRUCTURE

Strike and dip of flow structure in dikes and sills

Strike and dip of flow structure in granite

FAULTS

Accurately located, showing relative vertical movement

Showing relative strike movement

Concealed

Inferred

JOINTS

Strike and dip where joints are very strongly developed

CONTACTS

Closely located

Concealed

Inferred

CULTURE

Mine

House

Well

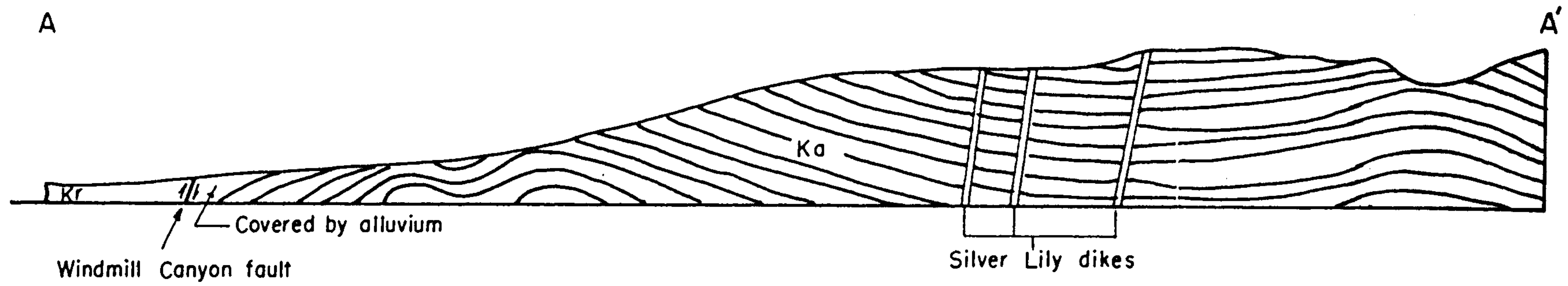
Scale: 1" = 1,000 feet

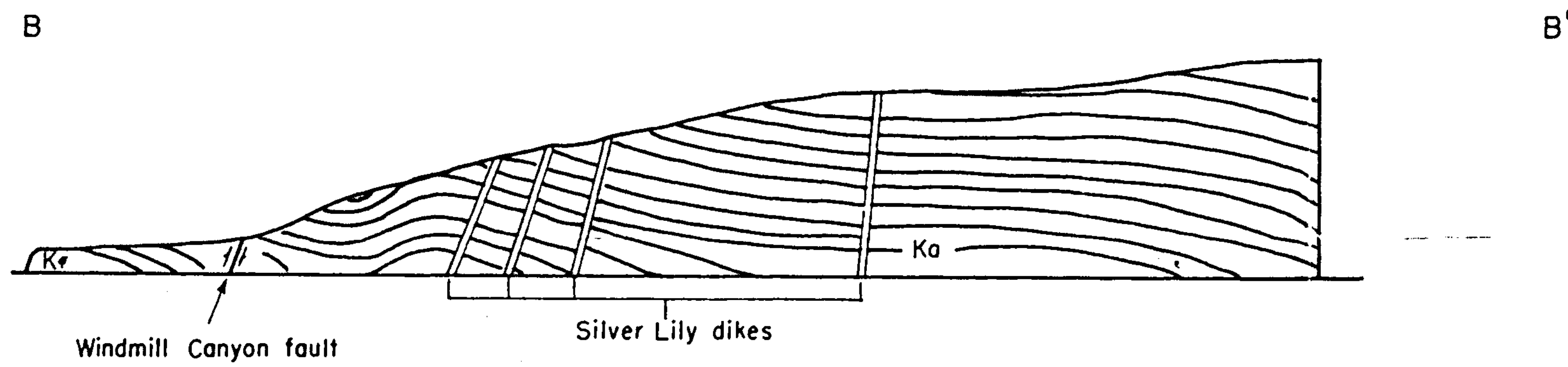
2,000 1,000 0 1,000 2,000

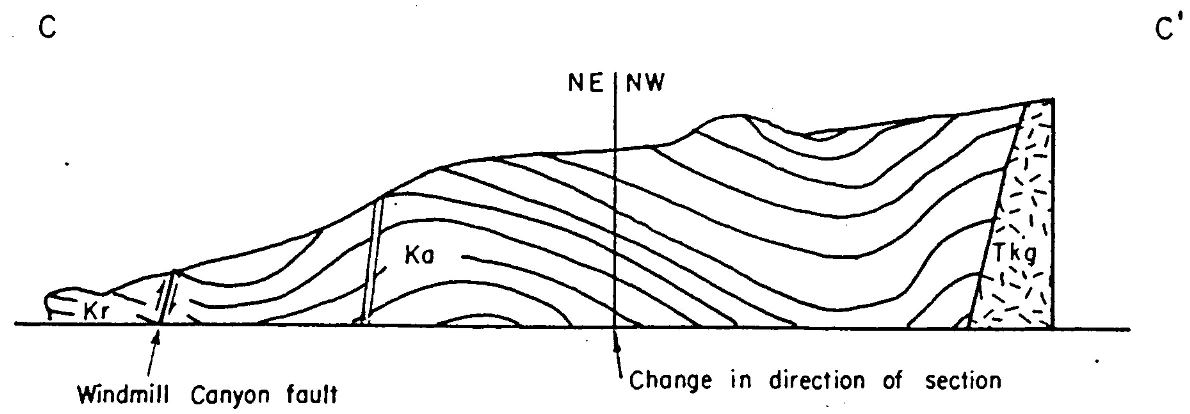
E979I
1961
.92
Pt. II

CROSS — SECTIONS THROUGH THE AMOLE ARKOSE

By
Gerald Greenstein







Scale: 1" = 1,000 feet