FUSION OF ARKOSIC SAND BY INTRUSIVE ANDESITE,

VALLES MOUNTAINS, NEW MEXICO

By

Roy Alden Bailey

U. S. Geological Survey
Open-file release
54-14

CONTENTS

ILLUSTRATIONS

ABSTRACT

An andesite dike in the Valles Mountains of northern New Mexico has intruded and partly fused arkosic sediments for a distance of 50 feet from its contacts. The dike is semi-circular in form, has a maximum width of about 100 feet, and is about 500 feet long. Small associated arcuate dikes are arranged in spiral fashion around the main dike, suggesting that they were intruded along shear fractures similar to those described by Burbank (1941). The fused rocks surrounding the andesite dike are of three general types: 1) partly fused arkosic sand, 2) fused clay, and 3) hybrid rocks. The fused arkosic sand consists of relict detrital grains of quartz, orthoclose, and plagioclase, imbedded in colorless glass containing microlites of tridymite, cordierite, and magnetite. The relict quartz grains are corroded and embayed by glass; the orthoclase is sanidinized and partly fused; and the plagioclase is inverted to the high temperature form and is partly fused. The fused clay, which was originally a mixture of montmorillonite.and hydromica, consists primarily of cordierite but also contains needle-like crystals of sillimanite (?) or mullite (?). The hybrid rocks originated in part by intermixing of fused arkosic sediments and andesitic liquid and in part by diffusion of mafic constituents through the fused sediments. They are rich in cordierite and magnetite and also contain hypersthene, augite, and plagioclase. The composition of pigeonite in the andesite indicates that the temperature of the andesite at the time of intrusion probably did not exceed 1200°C. Samples of arkosic sand were fused in the presence of water in a Morey bomb at 1050°C. Stability relations of certain minerals in the fused sand suggest that fusion may have taken place at a lower temperature, however, and the fluxing action of volatiles from the andesite are thought to have made this possible.

INTRODUCTION

Several basaltic and andesitic dikes and plugs with aureoles of partly fused wall rock were discovered during geologic mapping of the Valles Mountains in north central New Mexico by the U. S. Geological Survey in 1951. In this paper, one of these, a small semi-circular dike that has intruded and partly fused arkosic sand, is described in detail. It is of particular interest because of its relatively wide aureole of fusion glass and the unusual assemblage of minerals contained therein.

The dike is about 10 miles west-northwest of Espanola, New Mexico, in the southwest corner of the Chili quadrangle (Fig. 1). It forms a resistant knob (Fig. 2) just north of the Santa Clara Peak Lookout road, which joins U. S. Highway 85 twelve miles east of the dike and one mile north of Espanola (Pl. 1).

During June, July, and August, 1952, the author spent a total of 25 days mapping the dike by plane table methods on a scale of 30 feet to an inch (Pl. 3). A reconnaissance geologic map of the surrounding area was also made on aerial photographs and later was transferred to a newly published topographic map, which was not available at the time of the field work (Pl. 1). Laboratory studies included petrographic examination of thin sections and a series of hydrothermal experiments that were undertaken in an attempt to determine the temperature of fusion of arkosic sand.

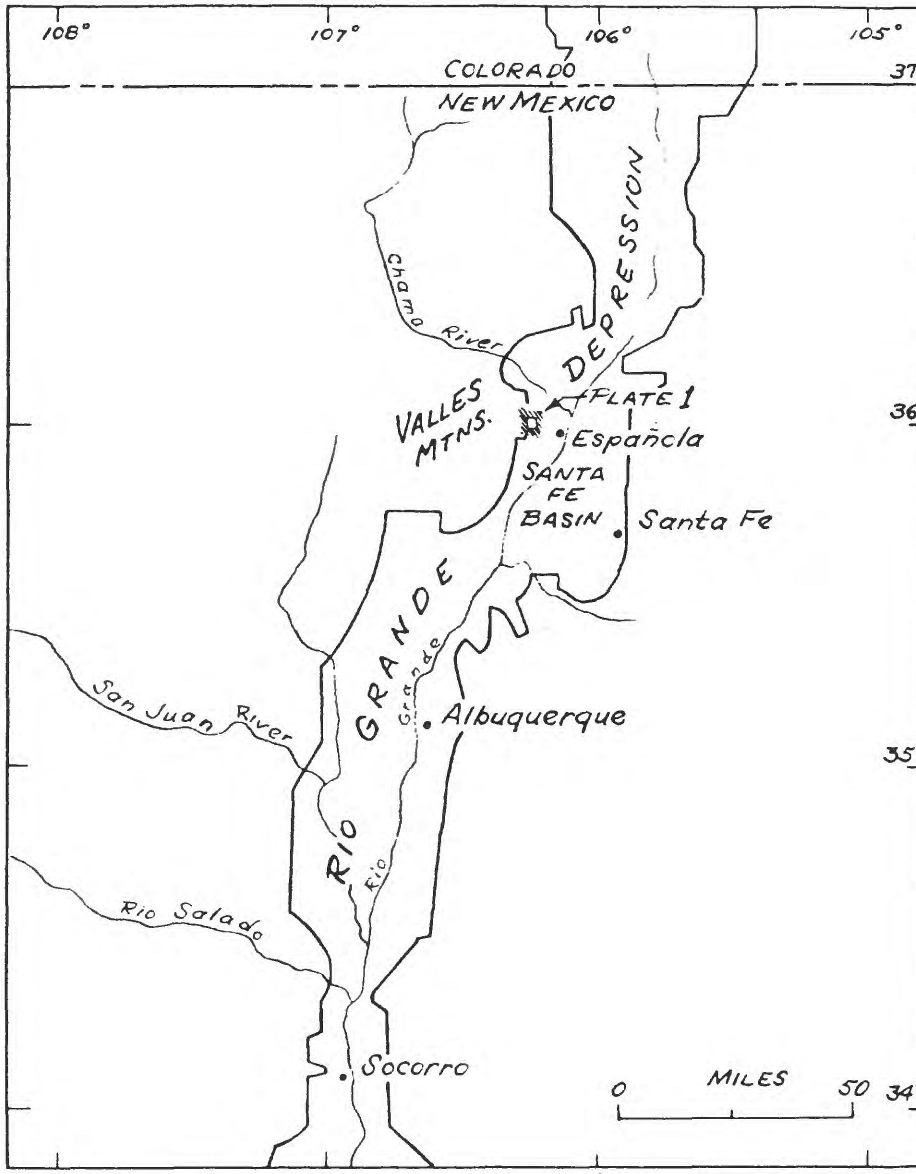


Figure 1. Index map of northern New Mexico

Fig. 2. View looking north toward the andesite dike. (Dike outlined in black.)

This problem was undertaken with the approval of Dr. Clarence S. Ross and Robert L. Smith of the U. S. Geological Survey. They have in preparation a report on the volcanic history of the region, and with their permission some of the data to be included in it have been used here. I am indebted to them for this and for many favors and helpful suggestions offered during the course of the field work and final preparation of the paper. My thanks are due also to Paul L. Cloke, of Massachusetts Institute of Technology, who assisted with the plane table mapping. Dr. William T. Holser was a constant source of inspiration during the course of the laboratory work. Dr. Charles M. Nevin offered many helpful suggestions on structural aspects of the problem. Twenty-five thin sections and 4 chemical analyses were furnished by the U. S. Geological Survey. I am grateful to Mrs. Robert L. Smith for typing the manuscript.

GEOLOGIC SETTING

GENERAL STATEMENT

The andesite dike, with its aureole of fused arkosic sand, is near the structural and topographic boundary between the Valles Mountains, a large complex field of Pliocene and Pleistocene volcanic rocks (Ross and Smith, unpublished), and the Santa Fe Basin, one of several interconnecting, alluvium-filled grabens that make up the Rio Grande Depression (Bryan, 1938). (See fig. 1.)

The dike intrudes arkosic sands which underlie the basalt cap of Santa Clara Peak (Pl. 1 and Fig. 3). The formations exposed in the area are, from oldest to youngest, 1) arkosic sands of the Santa Fe group, 2) basalt flows related to the Valles Mountains volcanic field, and 3) the Puye conglomerate and associated pediment gravels. In the following paragraphs these formations are described briefly in order to give a clearer picture of the geologic setting of the dike.

ARKOSIC SANDS OF THE SANTA FE GROUP

The arkosic sands, which are intruded by the andesite dike, constitute a part of the Santa Fe group, a thick deposit of alluvium that accumulated in the Santa Fe Basin from early Miocene to Pleistocene time (H. T. U. Smith, 1938; Bryan, 1938; Denny, 1940; Stearns, 1953). The particular sands exposed around the andesite dike are believed to be Pliocene age, but their exact position in the group has not been established.

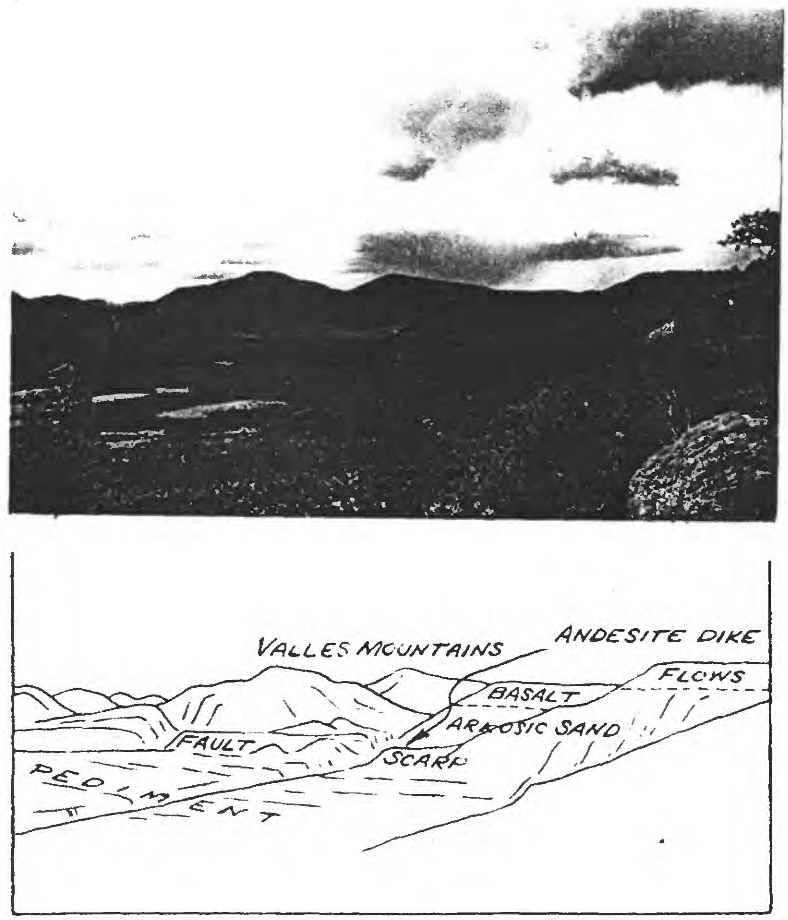


Figure 3. View looking west across the area in the vicinity of the andesite dike. The dike intrudes the arkosic sand at the foot of the basalt-capped scarp on the right and is overlain by gravels capping the pediment in the foreground. (See Pl. 1.)

The sediments consist largely of unconsolidated pale yellowish-brown arkosic sands intercalated with beds and lenses of reddish-brown and green bentonitic clay and lenses of volcanic pebbles. Bedding in the sands is difficult to recognize, but near the andesite dike silicification related to the intrusion of the dike has accentuated differences in grain size and clay content in various layers of the sand, and bedding is distinct. Cross-bedding is present locally and occurs in large lenses consisting of a mixture of poorly sorted sand, irregular lumps of clay, and volcanic pebbles.

Throughout the entire area, the beds dip about 20° north-northwest. This dip was imposed on the sediments during an episode of normal faulting that affected the Santa Fe Basin in Pliocene(?) time.

BASALT FLOWS

Basalt flows with a total thickness of 600 feet rest unconformably on the arkosic sands north of the andesite dike. These flows represent a stage of volcanism thought to be late Pliocene in age (Ross and Smith, unpublished). In most places the flows are gently dipping or horizontal. No detailed study of the rock types was made, but in general they appear to differ minerallogically and texturally from the andesite dike. By analogy with similar andesites associated with basalts elsewhere in the region, however, it seems likely that the andesite dike is about the same age as the basalts.

PUYE CONGLOMERATE AND PEDIMENT GRAVELS

The Puye conglomerate constitutes a thick Pleistocene fan deposit of basalt, andesite, dacite, and quartz-latite cobbles and boulders, which underlie most of the area immediately south of the andesite dike (H. T. U. Smith, 1935). It was deposited against the south-facing erosion scarp of Santa Clara Peak by eastward flowing streams. The surface of the fan has been truncated by a pediment and is capped by pediment gravels 10 to 20 feet thick. These pediment gravels at one time covered the top of the eroded andesite dike, but recent erosion has removed all but a thin veneer of them.

FAULTS

Four normal faults displace the formations in the area of the andesite dike. The youngest and most prominent of these is the Pajarito fault which strikes northeastward and displaces the pediment cut on the Puye conglomerate about 300 feet downward to the southeast (Fig. 3). Three older faults striking northwest displace the basalt flows and arkosic sands north of the andesite dike. They are buried beneath the Puye conglomerate south of the dike.

SPACIAL AND STRUCTURAL RELATIONS OF THE ANDESITE DIKE AND FUSED SANDS

GENERAL STATEMENT

The rocks in the immediate vicinity of the andesite dike may be separated conveniently into three structural and lithologic units: 1) a core, the semi-circular andesite dike; 2) an inner zone of fused arkosic sand; and 3) an outer zone of silicified and indurated arkosic sand (Pl. 2). The sediments beyond the silicified zone are unconsolidated and unaffected by the andesite dike.

FORM AND STRUCTURE OF THE SILICIFIED ZONE

The arkosic sands on the east, south, and west sides of the andesite dike are silicified. Presumably they are silicified on the north side also, but outcrops are absent there. These silicified sands form an irregular zone several hundred feet wide on the east and west sides of the dike and about a thousand feet wide on the south side of the dike (Pl. 1). The radius of the zone varies both horizontally and vertically and seems to be related to local differences in grain size and clay content of the sands. This is especially evident south of the dike, where beds of coarse sand are silicified several hundred feet farther away from the dike than are underlying beds of fine-grained argillaceous sand. The silicification is thought to have been caused by the solution and redeposition of silica by juvenile water emanating

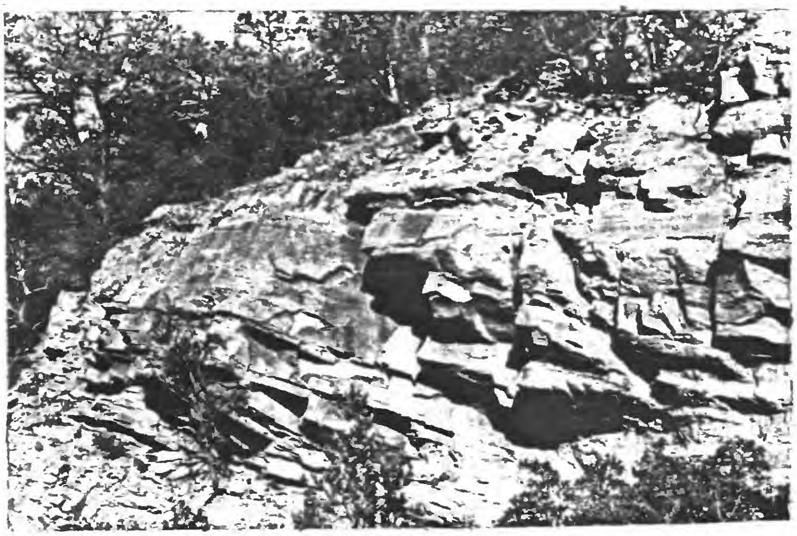


Figure 4. A typical outcrop of silicified arkosic sand showing the jointed nature of the rocks in the silicified zone. These joints are related to faults in the area.

from the andesite dike or possibly a combination of juvenile water and heated ground water.

Outcrops in the silicified zone have a characteristically blocky, angular appearance that is determined by three intersecting sets of joints (Fig. 4). The most prominent set strikes N.40°E., dips about 60°SE., and is characterized by smooth straight surfaces with occasional slickenslides. The other two sets of joints appear in the field to be a single set nearly at right angles to the more prominent set, i.e. striking generally northwest. The joint surfaces are vertical and commonly broadly undulating. Plotted statistically this single set resolves into two sets striking N.40°W. and N.60°W. (Fig. 5, B_1 and B_2).

These three sets of joints are not related in any way to the intrusion of the andesite dike, because they postdate silicification of the sands. They are related to the faults in the area. The most prominent set of joints is approximately parallel to the Pajarito fault (p. 9), and certain fractures in this set have slickenslided surfaces which indicate the same direction of movement as the fault. The relation of the two less prominent sets of joints to the major set suggests that they also are related to the fault. Figure 5 shows that the poles of all three sets lie on the same great circle, and that the angle between the planes of the two minor sets (B_1 and B_2) is bisected by the plane of the major set (A). The major set, which is parallel to the fault, is probably related to the tensional stress that caused the faulting. The two minor

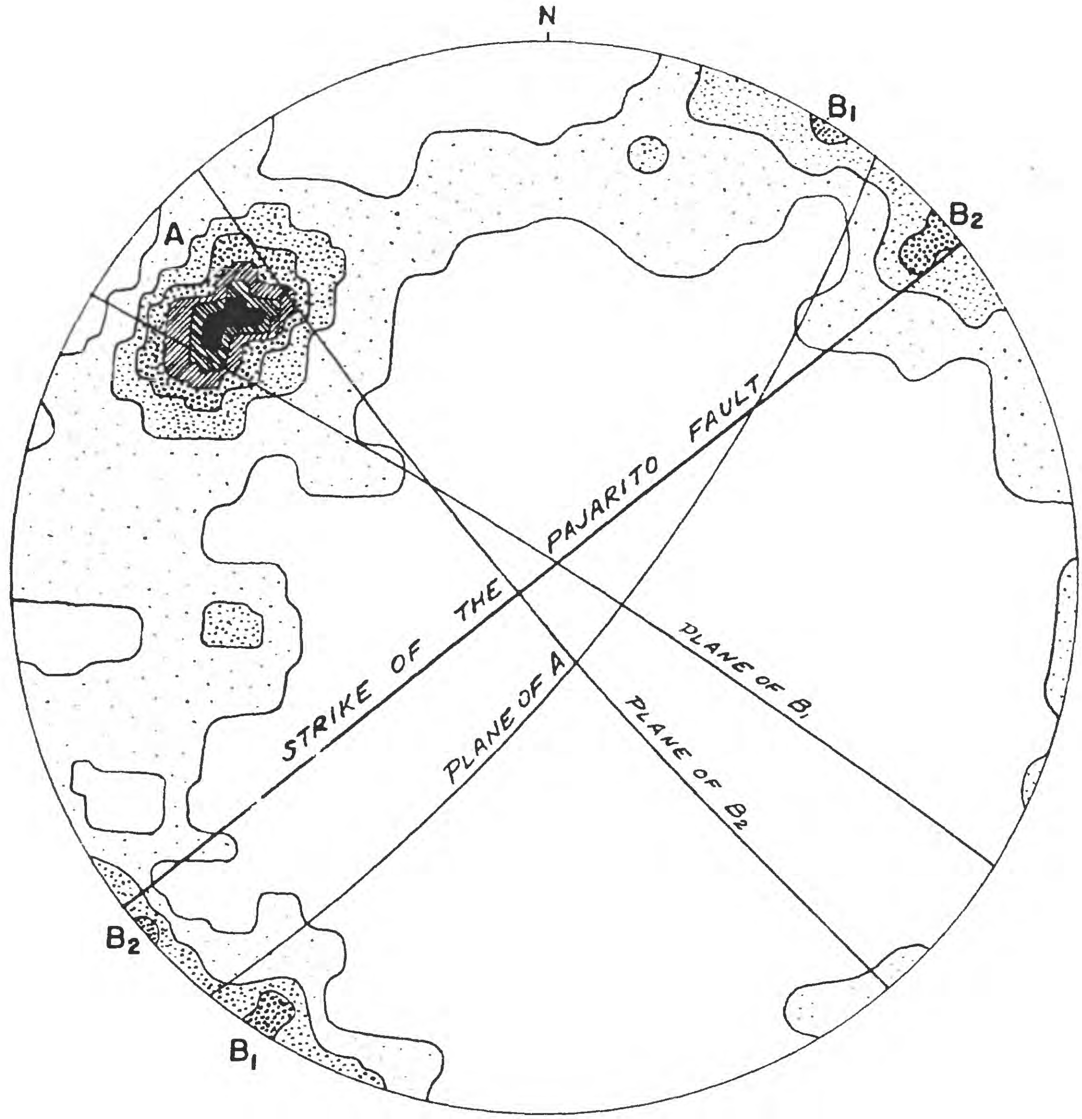


Figure 5. Orientation diagram of joints in the silicified zone, showing their relation to the Pajarito fault. A = pole of joints approximately parallel to the fault. B_1 and B_2 = poles of joints nearly at right angles to the fault. The latter joints are thought to be related to torsional stresses caused by differential vertical movement on the fault. Based on 100 joints; contours = 1%, 3%, 6%, 9%, 12%, and 15%.

Figure 6. Flow-banded fused sand in contact with andesite (contact dashed). The dark elongate spots in the fused sand are blebs of fused clay. The columnar joints in the andesite are at right angles to the contact and are continuous into the fused sand.

sets appear to constitute a conjugate pair, which may be related to torsional stresses which accompanied the faulting.

FORM AND STRUCTURE OF THE FUSED ZONE

Gray vitreous fused sand crops out on all sides of the dike and forms a continuous zone around it. The maximum width of the zone is not known, but in places partly vitrified rock is exposed as far as 50 feet away from the nearest exposed andesite contact.

Bedding in the outer part of the fused zone has essentially the same attitude as in the silicified zone, but near andesite contacts it is deformed. Beds overlying dike- and dome-like apophyses of andesite are commonly gently arched or warped. Bedding in a zone one to six feet from intrusive contacts is commonly dragged upward, or it may be intricately contorted or completely obliterated by flowage. Flowage is particularly noticeable in the more argillaceous sediments, where lenses of fused clay have commonly been disrupted and drawn into elongate blebs parallel to flow planes in the adjacent andesite (Fig. 6).

Columnar jointing is present in most of the fused sand adjacent to the andesite dike. It is most prominent on the west side of the dike, where three- to five-sided (rarely six-sided) columns about six inches in diameter have formed. They are more or less perpendicular to the intrusive contacts and are continuous with similar columns in the basalt. Undoubtedly they are the result of contraction during cooling of the fused sand.

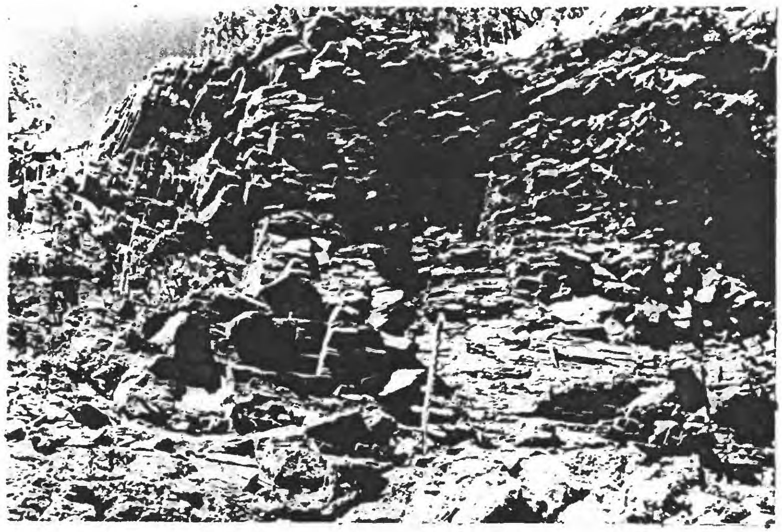


Figure 7. Sheet-like jointing in fused arkosic sand on the east side of the dike. Four different sets of joints are visible: a vertical set, a curved set dipping left, a curved set dipping toward the observer, and a curved set dipping away from the observer.

Figure 8. Sheet-like jointing in fused arkosic sand on the east side of the dike. The trace of bedding on the joint surfaces may be seen parallel to the edge of the compass.

The dominant structure in the fused zone is a complex system of very closely-spaced intersecting joints that give outcrops a sheeted or platy appearance (Figs. 7 and 8). These joints are from one to three inches apart, and have very smooth surfaces, which are usually gently curved. They are very similar to the curved sheet-like joints that occur in very viscous lava flows, and here they are interpreted as representing shear fractures which formed as a result of incipient flowage in the fused sandstone. The exact relationship of these joints to the intrusive contacts is difficult to determine because of their complexity and variability. The different intersecting sets probably formed at slightly different times and may have been governed by stresses exerted from several different directions as the configuration of the dike and its apophyses changed during growth.

Super-imposed on these complex platy joints are widely-spaced vertical planar joints, which tend to form a radial pattern around the semi-circular dike. These are radial tension fractures, which formed as a result of tangential stresses around the dike. These fractures formed after the solidification of the andesite, for some of them cut the andesite as well as the fused sand.

Very few joints related to the Pajarito fault are within the fused zone. Probably much of the strain of faulting was relieved along previously formed joints related to the intrusion of the andesite.

FORM AND STRUCTURE OF THE ANDESITE DIKE

The main body of andesite is a semi-circular dike with several associated smaller dikes and sills (Pl. 3). The main dike is about 500 feet long and has a maximum width of about 100 feet. The average radius of the semi-circular form is about 150 feet. On the concave side of the dike the contacts are vertical, and on the convex side they dip outward 80° to 85°. The contacts are generally very irregular, and many apophyses of andesite embay the fused sand. In places the fused sand and andesite are so intimately mixed that the contacts are gradational. Planar flow structure is visible throughout the dike and is approximately parallel to the contacts. Lineation also commonly is present, especially near the contacts, and is in the form of grooves in the flow planes and elongated vesicles and inclusions. Well-formed horizontal and gently inclined joint columns occur near the margins of the dike, but in the center they are crude and indistinct.

At the northwest end of the dike, along the southern contact, an interesting group of andesite columns forms a horizontal fan-like pattern, in which the attitude of the columns changes from nearly perpendicular to nearly parallel to the contact. Where the columns are parallel to the contact, the isothermal planes during cooling must have crossed the contact at right angles. Thus, the fused sand and the andesite were at about the same temperature during their cooling history.

The southern end of the dike terminates in a small cupola about 30 feet in diameter, in which flow planes dip outward in a complete circle. A sill dipping 25°N. extends westward from this cupola and forms a continuation of the main dike at the surface. Another sill, with about the same attitude, is 30 feet above and to the northeast of this one. The attitude and direction of lineation in these two sills indicate that the andesite in them migrated up the dip of the sediments from a source below the fused sand that is bounded by the concave side of the main dike. This suggests that a short distance below the surface the main dike widens and assumes a more pipe-like form.

In the central segment of the dike, a large irregular mass of fused sand about 60 feet in diameter interrupts the continuity of the western contact (Pl. 3). This mass is either a roof pendant or an enormous inclusion which was mobilized and partly torn from the western contact of the dike. The mass contains the most intensely fused rock in the area and also various rock types produced by mixing of fused sand and andesite. It is transected by flow banding that is continuous with flow planes in the surrounding andesite, and bedding in it is completely obliterated. The entire mass appears to have been mobilized and to have flowed upward with the andesite.

On the north side of the dike, a large apophysis of basalt forms an embayment about 90 feet wide in the fused sand. A similar

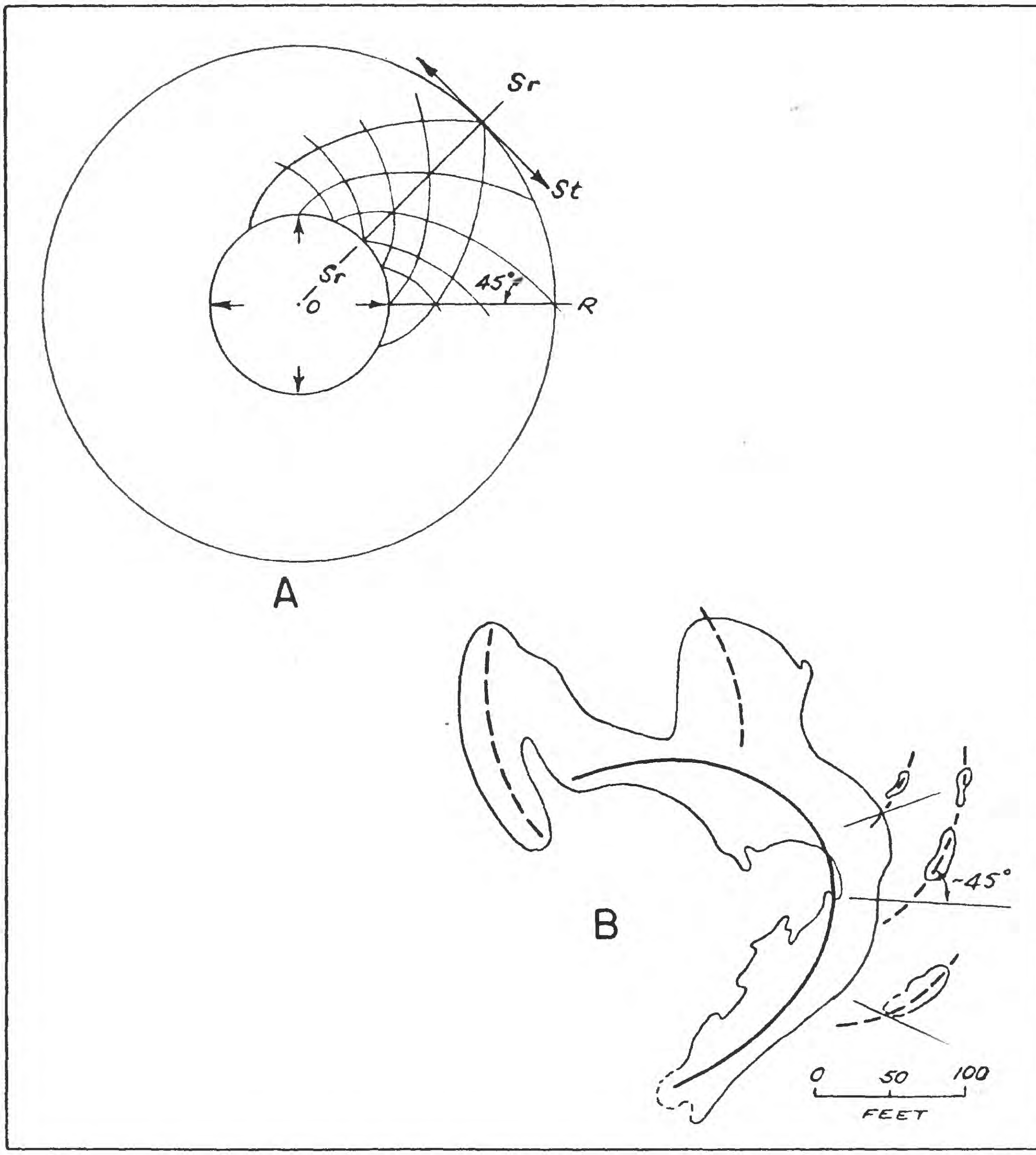


Figure 9. "Spiral" fractures and their relations to centers of radial stress.

Part A represents ideal stresses about a circular center. Sr, radial stress; St, tangential stress; the curved lines intersecting the radial directions of principal stress, OR, at 45° are directions of maximum shearing stress. Such lines are logarithmic spirals. (After Burbank, 1941)

Part B shows the relation of the small dikes to the main semi-circular dike. They may be localized on spiral fractures.

but less symmetrical embayment terminates the northwest end of the dike. These embayments probably originated as small dikes that extended at angles from the main dike and gradually widened to their present form.

On the east side of the main dike four, short, curved dikes intrude the fused sand. They vary in length from 30 to 60 feet and in width from 5 to 15 feet and are approximately parallel to one another. These four curved dikes and the two embayments on the north side of the main dike appear to be geometrically related to the semicircular trend of the main dike. Their medial lines make angles of about 45° with radial lines drawn from the convex wall of the main dike. (See fig. 9-B.) Burbank (1941, p. 170-178) has described similar dikes and also fractures, which have the same relationship to volcanic pipes in the San Juan Mountains of Colorado. He calls them "spiral" fractures and compares them to the shear fractures commonly observed in flat metal plates pierced by a hole and subjected to internal radial stress. These fractures constitute two orthogonal systems of spirals, as discussed by Nadai (1931, p. 227-228). (See fig. 9-A.) The mechanism of failure of internally stressed metal plates is described by Burbank (1941, p. 175) as follows:

> "Centrifugal forces sufficient to reduce the metals to a plastic state of flow produce an internal ring or cylinder of plastic material that widens to include the entire volume of the plate or cylinder when the stress exceeds certain critical values. The most nearly comparable but theoretical case is that of

yielding around a cylindrical cavity in an infinite elastic body (Nadai, 1931, p. 186-214). Under internal pressure the highest tangential stress exists along the boundary between an inner plastic zone and an outer elastic body. The radial stress is at a maximum at the edge of the cavity, but falls to about the value of the tangential stress at the boundary between the plastic core and the surrounding body."

Burbank pictures a similar mechanism operating during the formation of spiral fractures in the country rock around volcanic pipes in the San Juan Mountains. The character and structure of the brecciated country rock around the pipes suggest that it was reduced to a plastic mass by heated emanations (mainly water) in a manner which may be directly comparable to the experiments and theoretical deductions of Griggs (1940) and Goranson (1940). Simultaneous pressure of magma on the plastic wall rock resulted in failure by shearing along "spiral" fractures. That a similar mechanism has been operative in the formation of the curved dikes in the fused sand may be inferred from their "spiral" relationship to the semi-circular main dike and the undoubtedly plastic nature of the fused sand when they were intruded.

The formation of spiral fractures and dikes in plastic wall rocks may be contrasted with formation of radial fractures and dikes around plugs and pipes, which, because of insufficient volatiles and heat, were incapable of reducing their wall rocks to a plastic state. Although some radial tension fractures are associated with this particular dike, these were shown earlier to have formed after the andesite and fused sand solidified. Thus at the time of their formation, the wall rock was not plastic.

The semi-circular form and the steepness of the main dike suggest that it represents an incomplete ring-dike, but no structural or stratigraphic evidence could be found in the field to prove this. The semi-circular form may be strictly fortuitous.

PETROGRAPHY

INTRODUCTION

The following petrographic descriptions are based on the study of 30 thin sections of rocks collected from the andesite dike, the zone of silicified arkosic sand, and the zone of fused arkosic sand. The minerals were identified by standard methods. Indices of refraction were determined with white light in oils with .002 intervals and are correct within ± .001, except where otherwise indicated. The composition of the pyroxenes was determined from indices of refraction and optic axial angles measured on a universal stage. The estimated error of the optic axial angle measurements is ± 1°, except where otherwise indicated. The pyroxene compositions were taken from the optical curves of Hess (1949) and Kuno (1954).

The minerals forming microlites in the glass of the fused rocks were identified by crystal form and optical orientation in thin sections, and whenever possible, indices of refraction were determined. Cordierite in the fused clays and the clays in the non-fused rocks were determined by x-ray powder diffraction.

ANDESITE

The andesite is a dense, gray, aphanitic rock. It is finer grained in the smaller dikes and sills than in the main dike, but in any one body the grain size does not vary appreciably, even near the sandstone contacts. The rock is completely crystalline, except on the south side of the north half of the main dike, where the groundmass consists largely of brown glass. Near the contacts the andesite contains many inclusions of fused sand.

In thin section the andesite has a marked fluxion texture and consists of microphenocrysts of labradorite, bronzite, pigeonite, and augite, in a groundmass of labradorite, bronzite, clinopyroxene, and magnetite, with variable amounts of tridymite, cristobalite, and alkalic feldspar.

Labradorite

Labradorite constitutes 30 to 40 percent of the andesite and occurs in grains ranging in size from microphenocrysts about 0.45 by 0.09 millimeters to groundmass microlites about 0.04 millimeters long. The largest microphenocrysts have a maximum anorthite content of about 58 percent, but all of them are zoned and many have thin but distinct rims of more sodic plagioclase. The smaller microphenocrysts and the groundmass microlites are also more sodic than the large microphenocrysts, but none are more sodic than An50. Most of the microphenocrysts have combined carlsbad-albite twinning, and some of the larger ones also have pericline twinning. The small microphenocrysts and the groundmass microlites are commonly carlsbad twins.

Bronzite

Microphenocrysts of bronzite, and bronzite with lamellar overgrowths of pigeonite, constitute about 4 percent of the andesite.

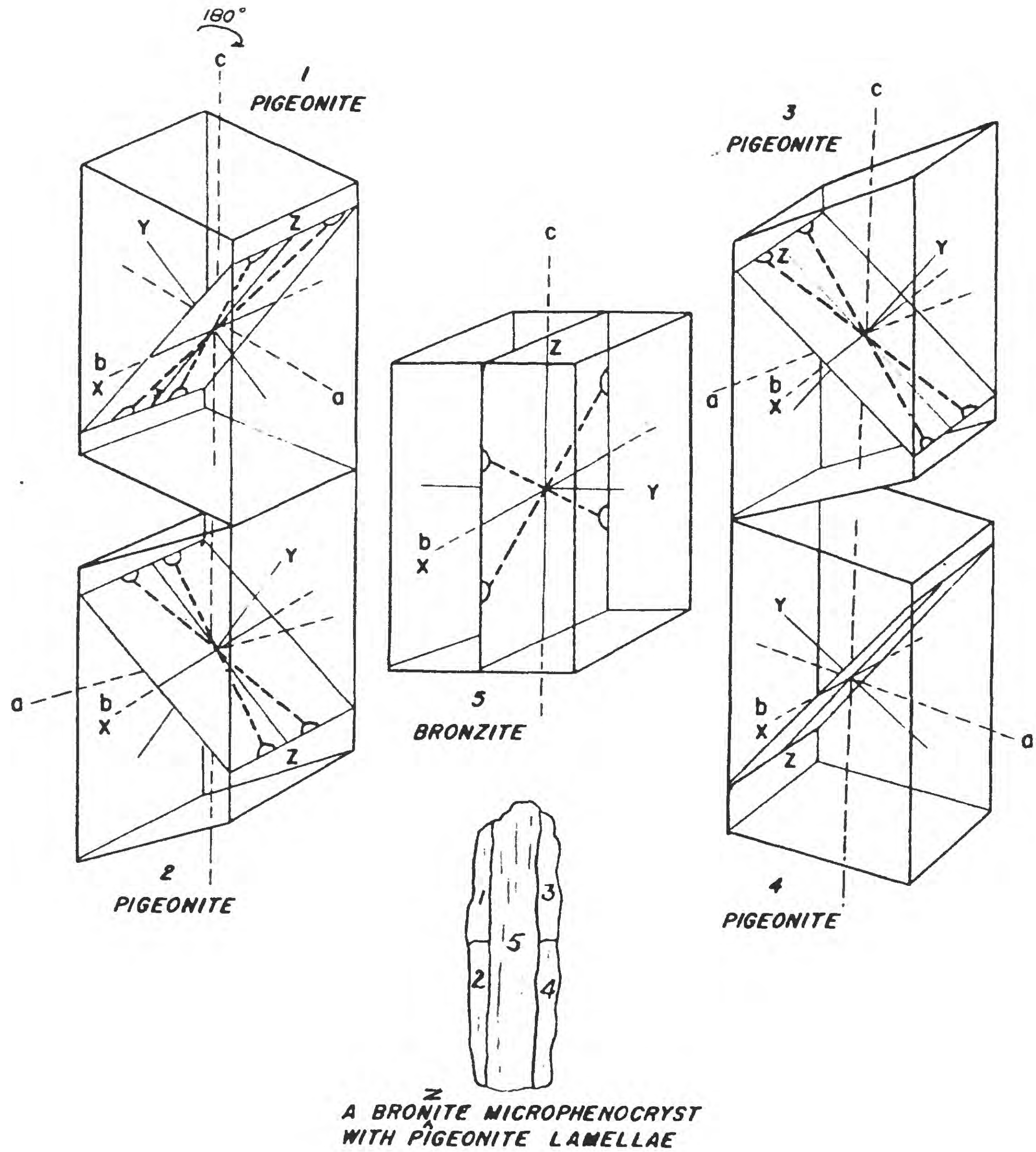


Figure 10. An isometric drawing showing the relations of the crystallographic and optical directions in a bronzite microphenocryst with twinned overgrowths of pigeonite. The five parts in the isometric drawing correspond to the five parts in the small sketch. Each pigeonite lamella consists of two parts which are related to one another by a rotation of 180° about the "c" axis. The twinning is a growth phenomenon, which preserves the orthorhombic symmetry of the bronzite core.

They form crystals about 0.35 millimeters long and 0.05 millimeters wide. A small amount of bronzite in the form of tiny crystals 0.03 to 0.04 millimeters long also occurs in the groundmass. The optical properties of the microphenocrysts ($n\alpha = 1.678$, $n\beta = 1.684$, $n\gamma = 1.689$, $2V_z = 79 \pm 1°$, pleochroism strong: X = pale yellow, Y = yellowish orange, Z = green) indicate a composition of about $En_{78}Fs_{22}$.

Pigeonite

The pigeonite overgrowths form two lamellae of variable width on the (100) and ($\bar{1}00$) faces of the bronzite microphenocrysts. Optic angles ranging from 16° to 20° (optic plane ⊥ (010)) were measured on several lamellae, and $n\gamma = 1.700 \pm .003$. The composition of the lamellae is therefore about $Wo_8En_{69}Fs_{23}$.

The pigeonite lamellae commonly have an unusual twinning relationship, which may be related in some way to the orthorhombic symmetry of the bronzite upon which the pigeonite grew. Each lamella consists of two parts that are separated by a medial plane approximately perpendicular to the "c" axis. (See fig. 10.) Structurally, the parts represent separate crystals that are related to each other by a rotation of 180° about the "c" axis. The optic plane and the Y and Z axes in one part appear to be rotated 90° about the X axis with respect to the optic plane and Y and Z axes in the other part. Thus the X axes are parallel and the Y and Z axes are interchanged. This relationship is a growth phenomenon which must have originated during the early stages of the crystallization of pigeonite. The structural change brought about in the transition between the growth of orthorhombic bronzite and monoclinic pigeonite involves a displacement of the silica chains in a direction parallel to the "c" axis. In the pigeonite lamellae, the silica chains are displaced in opposite directions on either side of a medial line. Thus, the two halves grew as separate crystals with opposing orientations. Most of the lamellae are twinned in this manner, and in every case the silica chains are displaced away from, not toward, the medial line separating the two parts. Geometrically this growth twinning preserves the orthorhombic symmetry of the original bronzite microphenocryst. Possibly it was caused by a preferred symmetrical distribution of calcium atoms on the orthorhombic pinacoid when the pigeonite began to form.

Salite

Clinopyroxene microphenocrysts constitute 2 to 3 percent of the andesite. Some of them are as large as the bronzite microphenocrysts, but most of them have average dimensions of about 0.20 millimeters by 0.05 millimeters. Many of them have multiple twinning on (100). The index of refraction of n β is 1.691 and $2V_z = 56 \pm 5^{\circ}$; thus, the composition is about $Wo_{47}En_{38}Fs_{15}$. According to the classification of Poldervaart and Hess (1951), this lies in the field of salite and is a little higher in calcium than clinopyroxenes in most mafic magmas.

Hornblende

Euhedral prismatic crystals of a mineral now completely altered to a dusty mass of magnetite and fine-grained pyroxene constitute about 3 percent of the andesite. They are the largest crystals in the andesite and are commonly a millimeter or more long. Their crystal habit suggest that they were probably hornblende phenocrysts that formed at depth and reacted with the melt near the surface.

Groundmass

The groundmass of the andesite contains microlites of andesine-labradorite (An_{60}), bronzite, and clinopyroxene but is composed largely of a very fine-grained mosaic of cristobalite and alkalic feldspar, and locally brown glass. Dust-like grains of magnetite and tiny rods of apatite are accessory minerals. The clinopyroxene microlites may be either pigeonite or augite, or both, but the grains are too small for optical determinations. The brown glass, which constitutes the groundmass in some places, has an index of refraction of 1.496. According to the optical curves of George (1924), a glass with this index has a silica content of about 73 percent. Presumably the cristobalite and alkalic feldspar crystallized from a residual liquid of about this composition.

Vesicles in the andesite are commonly studded with clustered hexagonal plates of tridymite and cubic crystals and "balls" of cristobalite, most of which has inverted to tridymite and shows in thin section the characteristic wedge-shaped twinning of tridymite. Some of the vesicles, especially those near inclusions of fused sand, are lined with opal and chalcedony.

Deuteric alteration

In the central part of the main dike and also in the center of some of the smaller associated dikes and sills, there is pronounced deuteric alteration of the ferromagnesian minerals. Most of the bronzite microphenocrysts are altered along cleavage planes and fractures to a fibrous, moderately high-birefringent mineral with nearly parallel extinction - possibly kupfferite. The salite microphenocrysts are partly altered to antigorite and the groundmass contains much fine-grained greenish-brown alteration products. Many of the plagioclase microphenocrysts have discontinuous fractures, approximately parallel to $(10\bar{1})$, in which sericite has crystallized.

Inclusions

The andesite contains a variety of xenoliths, many of which have recrystallized or reacted with the andesite and now have features similar to those so well described by Lacroix (1890).

Small angular fragments of tonalite, probably carried from depth, are distributed throughout the andesite. They consist largely of sodic andesine and hornblende and minor amounts of

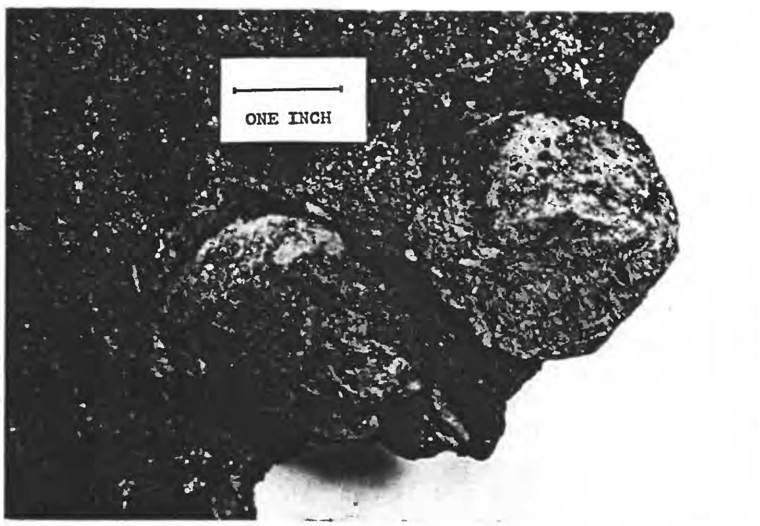


Figure 11. Corroded inclusions of fused sand in glassy andesite. They consist largely of fine-grained tridymite and relict detrital grains of quartz. Near their margins tiny augite crystals have formed as a result of reaction with the andesite. The large cavity to the left of each inclusion is lined with botryoidal protuberances of opal.

quartz and apatite. The andesine grains are clouded with minute opaque inclusions and commonly show a gradual increase in angle of extinction toward the margins, indicating a change in composition from sodic to calcic andesine. This reverse zoning is an example of the reaction of xenoliths with mafic magmas, whereby a member of a solid solution series (in this case, sodic andesine) is altered to a member of the series that is in equilibrium with the magma (in this case, calcic andesine). (See Bowen, 1922, p. 524.) The hornblende grains in the tonalite have completely recrystallized to a fine-grained aggregate of augite that is clouded with tiny grains of magnetite, much of which is concentrated along relict cleavage planes. The quartz grains have apparently passed through the inversion point between low- and high-quartz, for they are thoroughly fractured. The apatite grains are unaffected.

Rounded aggregates of sand up to 3 or 4 inches in diameter are abundant, especially near the contacts (Fig. 11). Most of them have been completely fused and have recrystallized as fine-grained masses of interlocking tridymite plates, but some still contain relict grains of quartz. Some have marginal zones several millimeters wide consisting of many tiny crystals of green augite, which formed as a result of reaction with the andesite. This reaction is in accordance with the principles set forth by Bowen (1922, p. 523-531), whereby silicic xenoliths in a mafic magma are assimilated or altered to a composition more nearly like that of the melt, the heat required for melting of the xenoliths being supplied by the crystallization of minerals in equilibrium with the melt.

Near the margins of the dike, the andesite contains many xenocrysts of quartz, orthoclase, and plagioclase derived from the sand. The quartz grains commonly are deeply embayed by brown glass and surrounded by reaction rims of augite crystals; the orthoclase grains are almost completely fused and consist largely of a turbid network of glass separating microscopic rectangular blocks of material with very low birefringence; the plagioclase grains, most of which are andesine, are clouded with minute inclusions and also are altered to a network of glass and tiny rectangular blocks. Some plagioclase xenocrysts have been partly resorbed and now have new overgrowths of plagioclase of the same composition as the microphenocrysts in the andesite.

Petrogenesis

The abundance of inclusions and the presence of a very silicic groundmass in a rock containing microphenocrysts of labradorite, salite, and bronzite suggest that the andesite was derived by contamination of a magma with basaltic affinities. However, with the data available, it is difficult to explain the composition of the andesite by local assimilation of the arkosic sand. Bowen (1922, p. 521) has reasoned that a magma cannot assimilate country rock amounting to more than 10 percent of its mass. Table 1 shows the changes in composition of the andesite when 10 percent and 20

Table 1. Theoretical compositions of andesites derived by subtracting various amounts of "assimilated" arkosic sand.

	1	2	3
SiO_2	62.76	60.84	58.45
Al_2O_3	16.20	17.01	18.01
Fe_2O_3	2.93	2.97	3.02
FeO	1.53	1.69	1.87
MgO	2.59	2.82	3.12
CaO	5.10	5.52	6.05
Na_2O	3.98	4.21	4.51
K_2O	2.48	2.52	2.56
H_2O -	.20	.13	.05
H_2O +	.97	.93	.88
TiO_2	.67	.70	.75
CO_2	.01	.01	.01
P_2O_5	.34	.38	.40
Cl	.02	.02	.02
F	.03	.03	.04
MnO	.07	.08	.09
BaO	.25	.27	.30
	100.13	100.13	100.13

1. Actual composition of andesite collected in the field.
2. Theoretical composition of andesite with 10 percent of composition of arkosic sand subtracted.
3. Theoretical composition of andesite with 20 percent of composition of arkosic sand subtracted.

percent of the chemical equivalent of the arkosic sand are removed from the andesite. (This was done by subtracting 10 percent and 20 percent of the composition of the sand from the composition of the andesite and then recalculating the analysis to 100 percent.) The resulting analyses do not approach the composition of a basaltic rock; in fact, the amount of alkalies increases and silica decreases only 2 percent for every 10 percent of the composition of the arkosic sand removed. At this rate, 40 to 50 percent of the composition of arkosic sand would have to be removed from the andesite before the silica content were reduced to that of a basaltic rock, yet at the same time the alkalies would be enriched far beyond the normal content for basaltic rocks. It therefore seems unlikely that the andesite changed much in composition by local assimilation of the arkosic sand. It must have been derived by fractionation or other processes at depth and been intruded as a differentiated magma.

Temperature of crystallization

Hess (1941, p. 582) has shown that the orthopyroxene-clinopyroxene inversion curve determined by Bowen and Schairer (1935) and the Mg:Fe ratio at which pigeonite begins to crystallize from melts may be used as a geologic thermometer. In a saturated mafic magma, orthopyroxene is generally the first ferromagnesian to crystallize, because the temperature of most magmas is below the clinopyroxene stability field (Fig. 12). As orthopyroxene continues

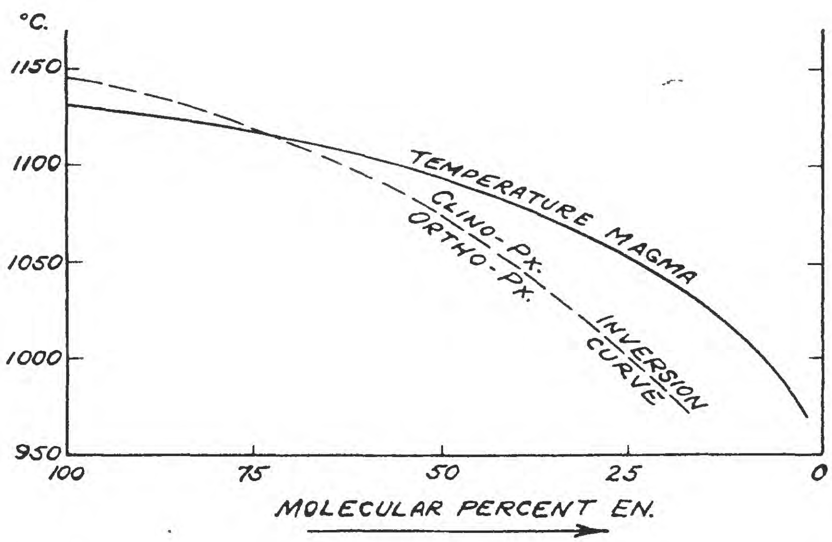


Figure 12. Cooling curve for mafic magma and pyroxene inversion curve. (After Hess, 1941)

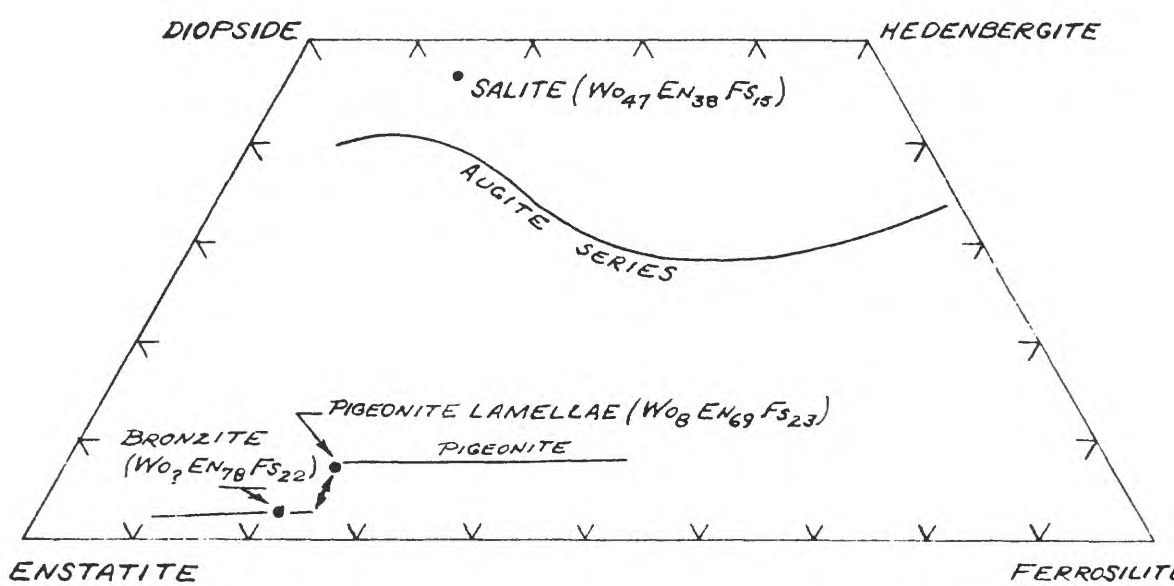


Figure 13. Pyroxene composition diagram showing the composition of pyroxenes in the andesite and the trend of crystallization in common mafic magmas. The composition of the pigeonite indicates that it began to crystallize when the MgO: FeO ratio of the magma reached 73:27.

to crystallize, the magma becomes enriched in iron and eventually the cooling curve intersects the orthopyroxene-clinopyroxene inversion curve, at which point pigeonite begins to crystallize. In a very great number of examples this happens at an Mg:Fe ratio of about 70:30, although examples with ratios between 85:15 and 60:40 are known. From this, Hess concludes that most mafic magmas crystallize between 1150°C and 1100°C. The compositions of bronzite and pigeonite plotted in figure 13 indicate that pigeonite began to crystallize in the andesite at an Mg:Fe ratio of 73:27. Thus the temperature of crystallization was about 1120°C (Fig. 12). Since it is doubtful that differentiated magmas can have appreciable amounts of superheat (Bowen, 1922, p. 522), the temperature of the magma at the time of intrusion could not have been a great deal higher than this.

UNALTERED SEDIMENTS

Arkosic sand

The arkosic sand beyond the fused zone and silicified zone is poorly consolidated. It consists primarily of grains of quartz, chert, and feldspar, sand-size rock fragments, and variable amounts of interstitial silt and clay. Heavy minerals constitute less than one percent of the sand. About 70 percent of the sediment by volume is sand grains; the remaining 30 percent is interstitial silt, clay, and pore space. The grains are rounded to sub-angular and vary in size from 0.05 millimeters to 0.3 millimeters. In general, the sand is poorly sorted, but locally there are lenses that are well sorted.

Quartz grains constitute 35 to 40 percent of the sand, and are generally sub-angular to rounded. Many of the grains contain inclusions, most of which are too small to identify. Fluid inclusions and small grains of epidote and amphibole were recognized in a few grains, however. Many of the grains have wavy extinction under crossed nicols. Grains of chert and extremely fine-grained aggregates of quartz constitute an additional 15 to 20 percent of the sand. The chert grains are brown and usually are well-rounded. The extremely fine-grained quartz aggregates have the texture of aplite, but contain no feldspar. They are commonly clouded with inclusions and have more or less rectangular outlines.

Orthoclase and microcline constitute 3 to 6 percent of the sand and occur as sub-rounded, rectangular cleavage fragments. Some of the grains are perthitic; some have carlsbad twinning. Like quartz, many of them have wavy extinction. No sanidine was found in the unaltered sand.

Plagioclase is about twice as abundant as alkalic feldspar and constitutes 6 to 8 percent of the sand. The grains are rectangular to sub-rectangular cleavage fragments and tend to be smaller than the quartz and alkalic feldspar grains. Many of the rectangular fragments are aligned more or less parallel to bedding planes. Carlsbad-albite twinning, albite twinning, and pericline twinning can be recognized in many of the grains. Zoning was noted in a few grains, but it is rare. Most of the plagioclase is andesine, but oligoclase and labradorite are present also. Much of the plagioclase is badly altered and sericitized.

Sand-size rock fragments of volcanic origin constitute 4 to 8 percent of the sand. Most of them are mafic and consist of microlites of plagioclase and granules of pyroxene and magnetite. Generally these grains are distributed evenly throughout the sand, but in places they are concentrated in lenses several millimeters to a centimeter thick.

Heavy minerals constitute less than one percent of the sand and are largely magnetite, ilmenite, muscovite, biotite, zircon, kyanite, and sphene. Magnetite and ilmenite are the most abundant heavies and are evenly distributed throughout the sand. The micas tend to be concentrated in certain zones and are rare elsewhere. Muscovite is more abundant than biotite. Zircon occurs as broken crystals and rarely as perfect doubly terminated crystals. Kyanite is in the form of rounded cleavage fragments. Sphene is in euhedral grains.

The amount of fine-grained interstitial material in the arkosic sand is variable; it may be as little as 5 percent or as much as 30 percent. It is an intimate mixture of montmorillonite and silt-size quartz grains and is commonly stained light reddish-brown by iron oxides.

Lenses and beds of clay

Thin beds and lenses of light green and reddish-brown clay occur at various horizons in the arkosic sand. They usually are not more than one or two inches thick, but they commonly form zones in the sand with a total thickness of two or three feet. Some of the beds are mud-cracked, and many of them have been slightly reworked, so that they now appear as discontinuous strings of irregular lumps and flat fragments of clay in the sand. The clay is a mixture of hydromica and montmorillonite and was probably derived from the alteration of volcanic ash, beds and lenses of which are common in the Santa Fe group.

Pebble lenses

Lenses of pebbles, varying in thickness from several inches to four feet, are at various horizons in the sand. They contain well-rounded volcanic pebbles 0.5 to 2 centimeters in diameter. Most of the pebbles are of basaltic, andesitic, or dacitic composition and have perphyritic texture. The mafic rocks contain phenocrysts of pyroxene and plagioclase, whereas the dacitic types contain phenocrysts of hornblende, biotite, and plagioclase. The groundmass textures vary from glassy to holocrystalline.

SILICIFIED SEDIMENTS

The sediments in the silicified zone are identical mineralogically and texturally with those beyond the silicified zone. The only noticeable difference is that the pore space in the silicified rocks is filled with opal. The clay lenses are also opalized.

FUSED SEDIMENTS

Introduction

The rocks within the zone of fusion consist primarily of partly fused detrital minerals in a matrix of siliceous glass containing microlites. Rocks of this type - mainly fused aluminous and siliceous sediments - have been called "buchites" by a number of previous writers (Flett, 1911, p. 94-95; Harker, 1932, p. 70; Thomas, 1922; Tomkeieff, 1940). However, in this paper the terms "fused sand" and "fused clay" will be used for the sake of clarity.

The sediments within the fused zone have melted and partially recrystallized with the formation of a variety of new mineral assemblages, each of which is determined by three factors: 1) the original composition of the sediment, 2) the degree of fusion, and 3) the amount of mafic material introduced from the andesite. The last two factors are related primarily to the proximity of the rock to the andesite contacts and probably also to the role played by volatiles. Field and textural relationships indicate that the rocks have passed through the following general sequence of events: 1) partial fusion of the sand, 2) introduction of mafic constituents from the andesite, 3) crystallization of new minerals from the liquified and contaminated sand, 4) chilling of the liquified sand and the formation of glass, and 5) devitrification of the glass. Not all of the fused sand has been contaminated with mafic constituents and not all of the glass has devitrified, but in general the above sequence is valid. In some of the rocks it is difficult to determine whether the introduction of mafic constituents preceded or succeeded fusion of the sand. Evidence for both sequences exists in different outcrops. In some outcrops andesitic liquid appears to have permeated and soaked the sand before the detrital grains became fused appreciably. Elsewhere contamination seems to have taken place by diffusion of mafic ions through previously formed fusion liquid.

In the following section, macroscopic features of some of the typical rocks will be described; a description of the partly fused detrital minerals will follow; and lastly the glass and the "new" minerals contained therein will be described.

Macroscopic features

The fused rocks may be grouped into three general types based on their composition and origin: 1) partly fused arkosic sand, 2) fused clay, and 3) fused sand - andesite hybrids derived either by mixing of mafic and siliceous liquids or by diffusion of certain mafic constituents through siliceous liquid. The three types have characteristic appearances and usually can be distinguished in the field if studied carefully.

Figure 14. A hand specimen of undisturbed lenses of fused clay (black) and fused arkosic sand (gray). The fused clay consists of cordierite, some sillimanite(?), and magnetite and glass. The fused sand consists of relict detrital quartz grains in a matrix of glass.

Figure 15. A hand specimen of fused arkosic sand spotted with numerous blebs and streaks of fused clay. The fused clay (black) consists of cordierite, sillimanite(?), and magnetite and glass. The fused sand (gray) is largely glass with scattered relicts of quartz and feldspar.

Partly fused arkosic sand

The most abundant rock in the zone of fusion consists of variable proportions of partly fused detrital grains and glass. It is light gray and has the general appearance of a fine mixture of pepper and salt. It is usually very hard and dense and breaks with conchoidal fracture. Some of the intensely fused rocks are permeated with very small vesicles and tend to disintegrate fairly easily. The partly fused detrital grains are usually too small to see with the naked eye, but they may be recognized with a hand lens. They are light gray to white. The glass surrounding them is usually gray. Tiny grains of iron oxide give the rock its "pepper and salt" texture.

Fused clay

The clay within the zone of fusion has melted and partly recrystallized to form an extremely fine-grained, dense, black or reddish brown rock resembling hornfels. It usually occurs as bands, lenses, and irregular blebs in the gray, fused arkosic sand (Figs. 14 and 15), but where bedding has been disturbed by flowage, it forms irregular swirls and streaks in the fused sand and the rock has the general appearance of marble cake (Fig. 16).

Fused sand - andesite hybrids

The appearance of the hybrid rocks is so variable that only a few of the most interesting types will be described. In general they vary in color from gray to black and always show signs of

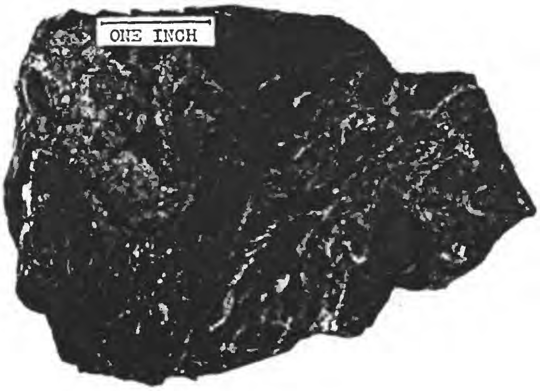


Figure 16. A hand specimen of fused sand and clay intimately mixed by flowage. The black areas are largely fine-grained cordierite; the gray areas are glass containing relict quartz and feldspar grains.

Figure 17. A hand specimen of flow-banded hybrid rock that formed by the intermixing of andesitic liquid and fused arkosic sand. The dark gray areas are dominantly andesitic and contain cordierite formed by the assimilation of silica from the fused sand. The light gray areas are dominantly fused sand and contain cordierite formed by the introduction of magnesia from the andesite.

flowage. In hand specimen, they are usually difficult to distinguish from the fused sand and clay. Some specimens may be recognized by the presence of black glass (brown in thin section).

Figure 17 shows a hybrid rock consisting of contorted bands of light and dark gray material. The light gray areas consist of colorless glass containing microlites of cordierite and partly fused grains of quartz and plagioclase. The darker streaks consist primarily of brown glass containing much dust-like magnetite, microlites of cordierite, a few plagioclase laths, and scattered relicts of detrital quartz and feldspar.

Some of the hybrid rocks consist of gray cordierite-rich glass cut by numerous tiny veinlets of vesicular black glass. In places, the contacts of the veinlets are sharp, but elsewhere they are gradational, and the rock as a whole is mottled light and dark gray and transected by black streaks of glass.

Much of the hybrid rock is black and extremely fine-grained. It resembles the contorted bands of fused clay, but in thin section is seen to be an intimate mixture of andesite and fused sand.

Microscopic features

Partly fused detrital minerals

Quartz

Practically all of the detrital quartz grains within the fused zone are fractured. This is probably the result of the strain caused by the inversion from low- to high-quartz. The partly fused quartz grains have very irregular or scalloped margins. Some of the grains have deep embayments of glass, which are guided by fractures or strings of inclusions. Near the contacts of the dike where the fused sand has flowed, the fractured quartz grains are disintegrated into small angular fragments, the corners of which are rounded by solution. Some of the quartz grains contain irregular patches of tridymite that appear to have inverted directly from the quartz. Other grains have thin plates of tridymite attached radially to their edges.

Orthoclase and microcline

One of the first noticeable effects of heat on orthoclase and microcline is reduction of the optic axial angle. This process, termed "sanidinization" by Spencer (1937), begins at a minimum temperature of 900°C and becomes more pronounced with increasing temperature and time. Optic axial angles measured on a number of orthoclase grains in the outer part of the fused zone had the following values: 6°, 10°, 16°, 22°, 26°, 29°, 31°, 31°, 34°, 40°, 44°, 46°, 58° (optic plane ⊥ 010). Since the minimum optic axial angle for orthoclase is about 30° and since no sanidine was found in the unaltered sediments, it seems evident that those grains with angles of less than 30° are sanidinized. The grains with angles of greater than 30° may or may not be sanidinized, because the optic axial angles for alkalic

Figure 18. Photomicrograph of a partly fused orthoclase grain, showing the vermicular texture of the partly fused rim and a non-fused core. The core is sanidinized; 2V = 16° (optic plane ⊥ (010)). (X 100).

feldspars vary between 70° and 80° depending on the soda content. Each of the above grains showed varying degrees of fusion. Others were clouded with minute unidentified inclusions which gave them a brownish color. This cloudiness is a thermal effect and has been described and discussed at length by MacGregor (1931) and Poldervaart and Gilkey (1954).

Throughout the fused zone, most of the orthoclase and microcline grains show signs of melting or solution. The edges of the grains are commonly rounded and corroded, and parts or all of most of the grains have acquired a peculiar reticulate or vermicular texture. The appearance of the texture varies depending on the orientation of the grain in thin section, but with a high power objective it is usually possible to see that it consists of small irregular or rectangular blocks of sanidine enclosed in a vermicular or rectangular network of thin films of glass. This texture has been observed by many others (Lacroix, 1890; Williams, 1936; Knopf, 1938; Larsen and Switzer, 1939; Watson and Mathews, 1948), but the details of its formation are not understood. It appears to form first at the margins of the grains and work inward toward the centers, for many grains have non-fused but sanidinized cores (Fig. 18). Possibly incipient fusion is localized along closely-spaced cleavage fractures, where volatiles or other fluxes may penetrate the grains and facilitate melting. Intensely fused orthoclase grains are mere "ghosts", consisting of glass with scattered relicts of crystal-

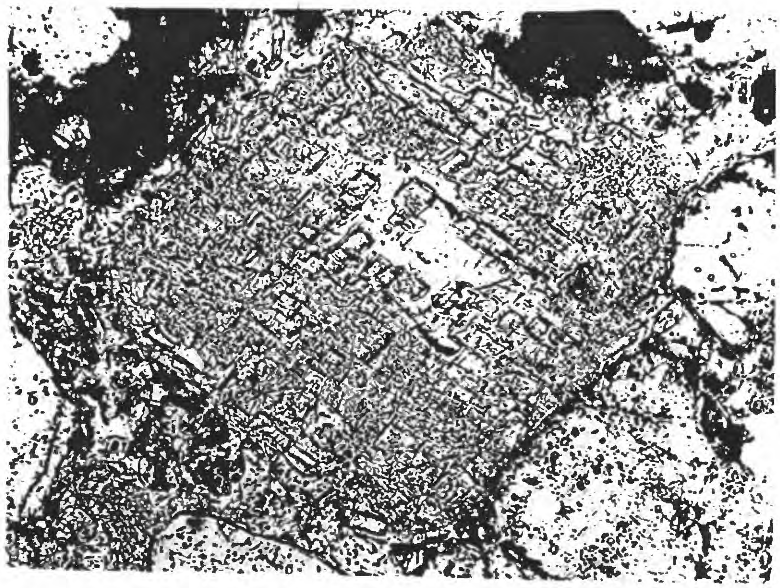


Figure 19. Photomicrograph of a partly fused plagioclase grain, with an irregular non-fused core. The partly fused areas consist of a network of thin glass films separating rectangular blocks of plagioclase about 0.0005 to 0.001 millimeters wide. (X 150)

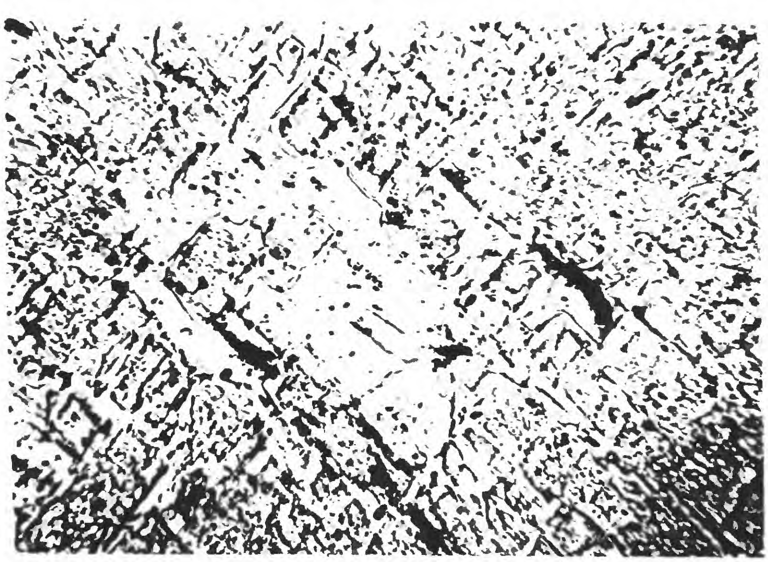


Figure 20. Photomicrograph of the same plagioclase grain shown in figure 19, showing the detail in the central part of the grain. Thin films of glass may be seen surrounding turbid blocks of plagioclase at the edge of the non-fused area. (X 450)

line material with low birefringence. In rocks that have flowed, these ghosts have disintegrated, and the crystalline relicts are scattered singly and in clusters throughout the glassy matrix of the fused sand.

Plagioclase

Plagioclase, when it fuses, acquires a reticulate texture very much like that formed in the orthoclase. Thin films of glass divide the feldspar into tiny rectangular blocks 0.0005 to 0.002 millimeters wide (Figs. 19 and 20). As in orthoclase, many of the grains have non-fused cores. In twinned grains, some twin lamellae are altered and others are not, indicating that certain lamellae - possibly because of slight differences in composition or structural imperfections - are more susceptible to fusion than others.

The parts of plagioclase grains that are partly fused (with reticulate texture) have a larger angle of extinction than parts that are not fused. Measurements on the universal stage by the Rittman zone method show that the extinction angle $x' \wedge (010)$ in sections $\perp [001]$ is 5 to $10°$ greater in the partly fused plagioclase. This might be interpretated as the result of a change in composition (a relative increase in lime and decrease in soda), or as the result of the inversion from a low- to a high-temperature form, since both mechanisms would cause a similar change in the angle of extinction. Consideration of the reaction principles of Bowen (1922, p. 524-525) indicates that the former interpretation

Figure 21. Photomicrograph of a partly fused twinned plagioclase, having a clear non-fused core. (X 100)

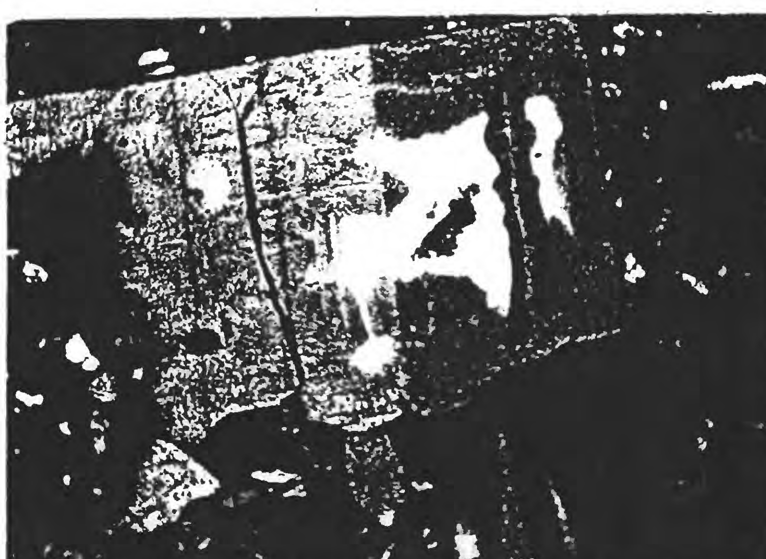


Figure 22. Photomicrograph of the same plagioclase grain as shown in figure 21 under crossed nicols. The grain is bounded on the right by (010) and on the upper side by (001) cleavage faces; the twin plane is (010). The non-fused core in the right hand twin has an angle of extinction X' $\wedge$ (010) in the section $\perp$ 001 of -1°. The turbid fused part of the twin has an angle of extinction of -7°. This is interpreted as the result of inversion of the turbid part of the grains to high-temperature plagioclase. (X 100)

probably is not correct, because a plagioclase crystal immersed in a silicic liquid would normally be expected to alter to a more sodic composition near the margins.

Work done by Kohler (1949), Van der Kaaden (1951), and others on the optics of high- and low-temperature plagioclases suggests that the latter interpretation is probably correct. If the extinction angles of partly fused and non-fused areas in the same plagioclase grain are plotted respectively on the high- and low-temperature optical curves determined by Van der Kaaden (1951), the compositions of the fused and non-fused parts of the grain are almost identical. For example, figures 21 and 22 show a plagioclase grain in plain light and under crossed nicols respectively. It is bounded by (010) and (001) cleavage faces and is twinned on (010). The clear area in the center of the grain is not fused; the turbid, reticulate area around it is partly fused. In the right-hand twin, the clear, non-fused area has an angle of extinction of $-1°$; the turbid, fused area has an extinction angle of $-7°$. Plotted respectively on the low- and high-temperature curves of Van der Kaaden (1951, p. 51, fig. 13), these angles give compositions of An_{21} and An_{22}. Within the limits of error of the determinations, this is very good agreement, and for practical purposes the compositions may be considered identical. The extinction angles of several partly fused plagioclase grains of different compositions, plotted in this manner, gave almost identical compositions for the fused and non-fused parts. For this reason, the difference in angles of extinction seems to be better explained by an inversion to a high-temperature form than by an actual change in composition.

Biotite and hornblende

Biotite and hornblende occur as detrital grains and as phenocrysts in volcanic pebbles in the fused sand. In both occurrences, they have decomposed to a fine-grained aggregate of magnetite and hypersthene, and rarely augite. The magnetite is commonly concentrated along relict cleavage planes but is also disseminated throughout the altered crystals. The hypersthene is oriented parallel to the relict cleavage and is in the extinction position when the relict cleavage is N-S under crossed nicols. Fine-grained augite commonly occurs in small patches in the central parts of the altered hornblende crystals, suggesting that they were originally zoned and had a more calcic core.

Sphene

A few detrital grains of sphene were recognized in thin sections of the fused sand. They are altered at the margins to leucoxene-like material and are surrounded by a very fine-grained, unidentified, colorless mineral with high relief and low birefringence.

Zircon and kyanite

Detrital grains of zircon and kyanite in the fused sand are unaltered.

Table 2. Modal analyses of fused arkosic sand.

⟶ increasing intensity of fusion

	Non-fused arkosic sand	Fused arkosic sand			
	1	2	3	4	5
Quartz, quartzite, and chert	52.9	34.8	30.1	22.8	13.9
Orthoclase and microcline	3.4	5.7	4.0	.0	.0
Plagioclase	6.8	7.5	7.5	4.7	4.2
Volcanic rock fragments	5.3	4.6	1.5	.1	.1
Silt and clay	31.6	---	---	---	---
Glass containing microlites	---	47.4	56.9	72.4	82.8

Order of fusion

Textural relations seen in thin section, and consideration of the four modal analyses of fused sand given in Table 2, enable one to make a few generalizations as to the order of fusion of the most abundant detrital minerals. A modal analysis of non-fused sand is included in Table 2 for comparison. It shows a lower percentage of feldspar than some specimens of fused sand, but this is to be expected since the composition of the sand varies slightly from place to place in the area. This fact would make one question the reliability of the absolute changes in the feldspar content shown in the four modes, but a consistent trend is shown in spite of it.

The first material to fuse is the interstitial silt and clay which constitutes about 30 percent of the sand. This is seen clearly in thin sections of slightly fused sand, in which all of the interstitial material has been converted to glass, whereas detrital grains of quartz and feldspar are altered only slightly.

In the fused sand represented by modes 2 and 3, both quartz and orthoclase appear equally affected by heat. The orthoclase contains much glass along cleavage planes, and quartz has irregularly scalloped margins and deep embayments of glass. In one thin section, however, orthoclase is almost completely fused whereas quartz is almost unaffected. On this basis, orthoclase is the first to fuse; quartz appears to dissolve in the glass thus formed. However, once quartz begins to dissolve, it disappears at about twice the rate of orthoclase, as is shown by the relative decrease of quartz and orthoclase between modes 2 and 3 and 3 and 4.

Plagioclase is the last of the major detrital minerals to fuse. This is to be expected because of its higher melting temperature. Although some of the plagioclase in rocks represented by modes 2 and 3 has a network of glass along cleavage planes, no significant change in the total percent of plagioclase takes place until nearly all of the orthoclase has dissolved.

Sand-sized volcanic rock fragments seem to disappear relatively early in the sequence, which is surprising in view of the fact that most of them appear to be of andesitic and basaltic composition.

Products of fusion and recrystallization

Glass

Glass derived from fusion of the detrital minerals constitutes from a few percent to as much as 80 percent of the fused sand and clay. It is generally colorless or straw-colored and has indices of refraction that range from 1.486 to 1.490. According to the curves of George (1924), glass with these indices contains 75 to 77 percent silica. Most of the glass is isotropic, but much of it, especially at a distance from the main dike, is devitrified. Most of the glass contains crystallites and microlites of tridymite,

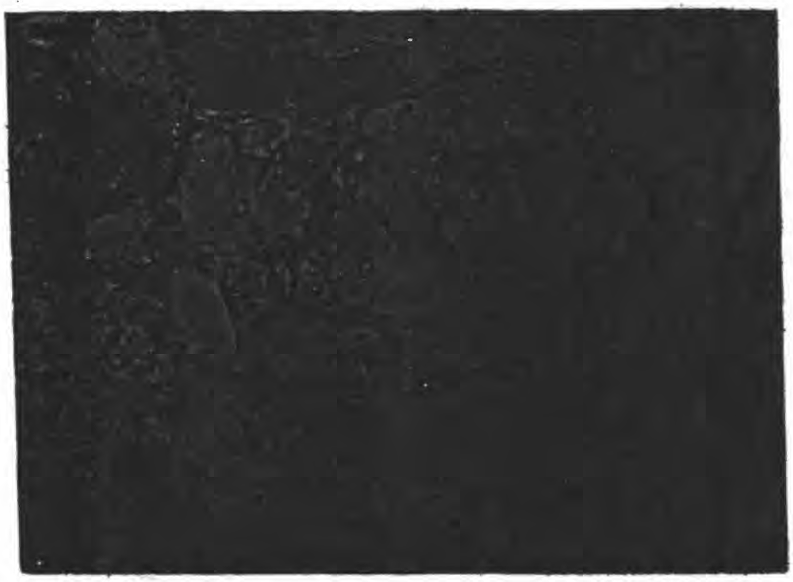


Figure 23. Photomicrograph of tridymite plates growing in glass that surrounds corroded quartz grains. T = tridymite, G = glass, Q = quartz. (X 100)

Figure 24. Photomicrograph of euhedral cordierite crystals. The largest crystal on the left is about 0.02 millimeters long. C = cordierite, G = glass, Q = quartz, M = magnetite. (X 450)

cordierite, magnetite and several other minerals. Vesicles are abundant, especially near the andesite contacts.

Tridymite

Tridymite is one of the most abundant minerals in the glass. It occurs most commonly as thin plates and wedge-shaped twins 0.05 to 0.08 millimeters long that appear to have crystallized directly from a liquid (Fig. 28). Other crystals form as a gas-phase mineral within the vesicles. Some tridymite has formed by direct inversion from detrital quartz, in which case it occurs as a fine-grained aggregate within the quartz grains. Thin plate-like crystals of tridymite also are attached at right angles to the edges of the quartz grains. The devitrified glass probably contains either tridymite or cristobalite, but it is too fine-grained to recognize optically.

Cordierite

Cordierite is the second most abundant mineral in the glass. It occurs in two distinctly different habits - subhedral and euhedral crystals containing relatively few inclusions and irregular crystals completely clouded with numerous dark inclusions.

The subhedral and euhedral crystals are rectangular prisms and twinned pseudo-hexagonal prisms, which vary in size from tiny crystallites to microlites 0.02 millimeters long and about 0.008 millimeters wide. The smaller crystals commonly have good hexagonal cross-sections, but the larger ones have square cross-sections or are poorly formed and have more or less round cross-sections. Some of the crystals are stubby, but most of them are two to three times as long as they are wide. The basal (001), the pinacoidal (010), and the prismatic (110) faces are commonly truncated by (111) faces. Many of the larger crystals have "blocky" outlines (Fig. 24). The crystals are usually colorless but those containing many inclusions have a pale blue or purplish color. The inclusions generally are clustered near the centers of the crystals. In some crystals viewed in cross-section, the inclusions form diagonal crosses similar to those observed in andalusite. The inclusions were not identified positively, but most of them appear to be octahedra and small specks of magnetite. These subhedral and euhedral crystals of cordierite usually occur in clear colorless glass, and are commonly associated with tridymite, and rarely with hypersthene.

The irregular crystals that are completely clouded with inclusions are larger than the subhedral and euhedral ones and have a maximum dimension of about 0.06 millimeters. They resemble in habit some of the cordierites in clays fused by burning coal seams described by Venkatesh (1952). They have very irregular general shapes, the edges of which consist of numerous small crystal faces at right angles to one another (Fig. 25). Except for a very thin rim at the margins, the crystals are almost opaque because of the abundance of inclusions of magnetite(?) or some other opaque mineral.

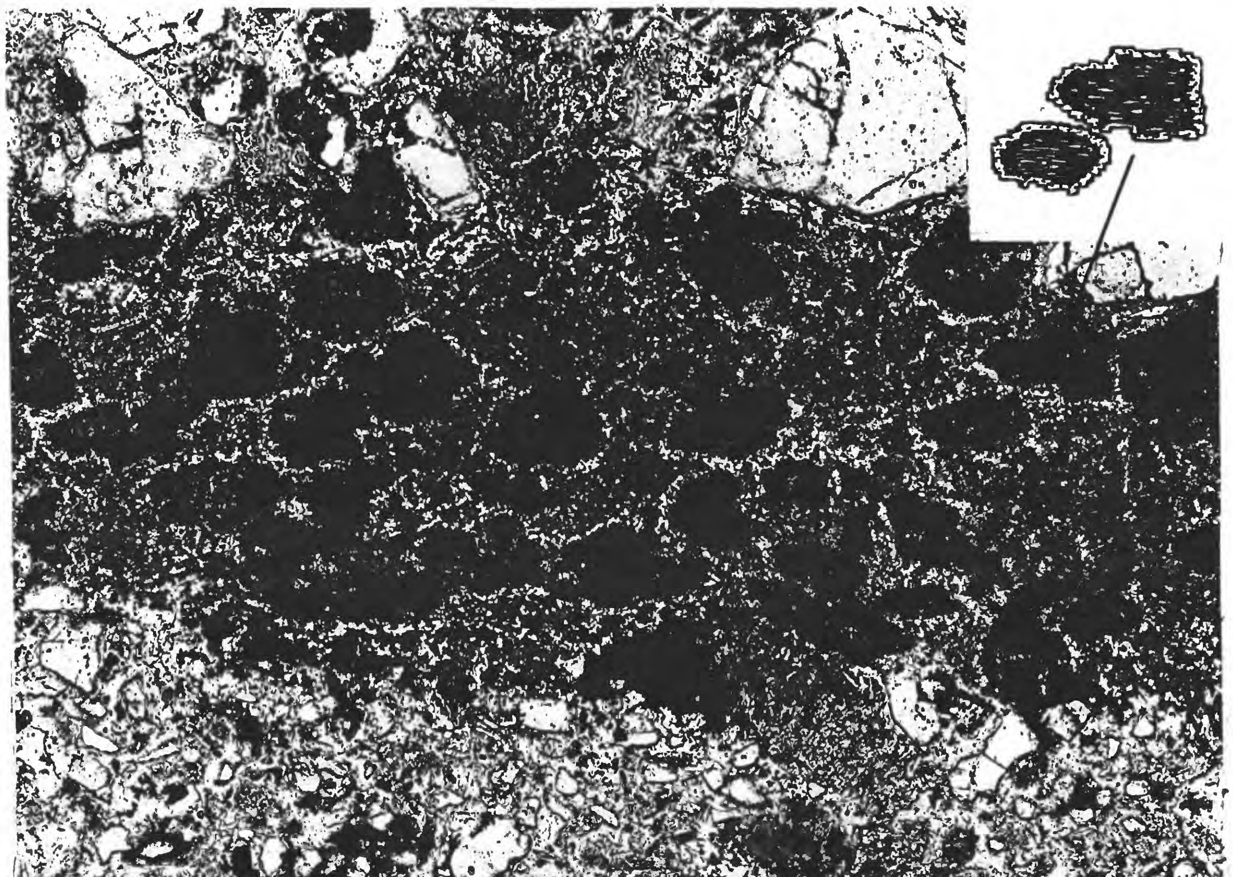


Figure 25. Photomicrograph of irregular crystals of cordierite in a lens of fused clay. Inset shows the detail of the small rectangular faces that bound the crystals. The cloudy matrix in which the crystals are imbedded consists of small cordierite crystals, glass, and opaque material. (X78).

The interiors of the crystals contain many irregular patches of glass. These crystals of cordierite are characteristic of the fused clay lenses, where they form dark spots in a glassy matrix clouded with much opaque material (Fig. 25). All of the cordierite has a large negative optic axial angle; $n\alpha = 1.540 \pm .005$.

<u>Sillimanite(?) or mullite(?)</u>

Aggregates of tiny criss-crossing needles of a mineral thought to be either sillimanite or mullite are associated with the ~~skeletal~~ irregular crystals of cordierite in the fused clay lenses. They have a maximum length of about 0.08 millimeters and are usually 10 to 15 times longer than they are wide. In thin section they are colorless, have high relief, low birefringence, and positive elongation. They occur in feathery clusters around quartz grains in and near the fused clay, and appear to have formed by reaction between the alumina in the clay and the silica of the quartz. They also occur as aggregates in patches of colorless glass in the fused clay. They could possibly be mistaken for hypersthene needles, but their association with quartz grains in clay lenses and their lack of pleochroism indicate that they are either sillimanite or mullite.

<u>Plagioclase</u>

A few microlites of plagioclase about 0.08 millimeters long and 0.05 millimeters wide were seen in one thin section of fused sand. They were twinned on (010) and had maximum angle of extinction of 20°, indicating a composition of at least 38 percent anorthite.

Hypersthene

Slender crystals of hypersthene that range in size and shape from tiny bobbin-like crystallites to prisms 0.08 millimeters long occur in the glass of the fused sand. Their indices of refraction could not be determined, but they are distinctly pleochroic - green to orange.

Augite

Pale green crystals of augite occur in light brown glass veinlets in some of the hybrid rocks. The crystals vary in size but are commonly about 0.03 millimeters long and 0.01 millimeters wide. Many of the crystals are arranged in glomeroporphyritic aggregates.

Magnetite

Tiny octahedral crystals of magnetite occur throughout the fused sandstone and are especially abundant in the fused clay and hybrid rocks. They commonly occur in groups or clusters.

"New" mineral assemblages

The rocks formed within the zone of fusion belong to the sanidinite facies (Eskola, 1939; Turner, 1949), which is characterized by conditions of high temperature and low pressure. In this environment chemical equilibrium is seldom attained and mineral assemblages do not generally represent stable end products, especially when glass is present. The following mineral assemblages, which occur in the glass within the zone of fusion, do not represent equilibrium products, but they may be used as a key to the amount of contamination that has taken place in the fused sand.

1) tridymite - magnetite - glass

2) tridymite - cordierite - magnetite - glass

3) cordierite - sillimanite(?) - magnetite - glass

4) cordierite - magnetite - glass

5) cordierite - hypersthene - plagioclase - magnetite - glass

6) augite - magnetite - glass

All of the rocks in which these assemblages occur contain variable amounts of relict detrital grains of quartz, orthoclase, and plagioclase.

Tridymite - magnetite - glass

The assemblage tridymite - magnetite - glass is usually found in the outer edge of the fused zone, in sediments relatively free of montmorillonite and where little or no contamination by andesite has occurred. The assemblage forms the matrix of fused sand containing a preponderance of quartz, orthoclase, and plagioclase grains. The tridymite has crystallized from a liquid derived largely from the fusion of interstitial silt and the magnetite has formed from iron oxides in the sediment.

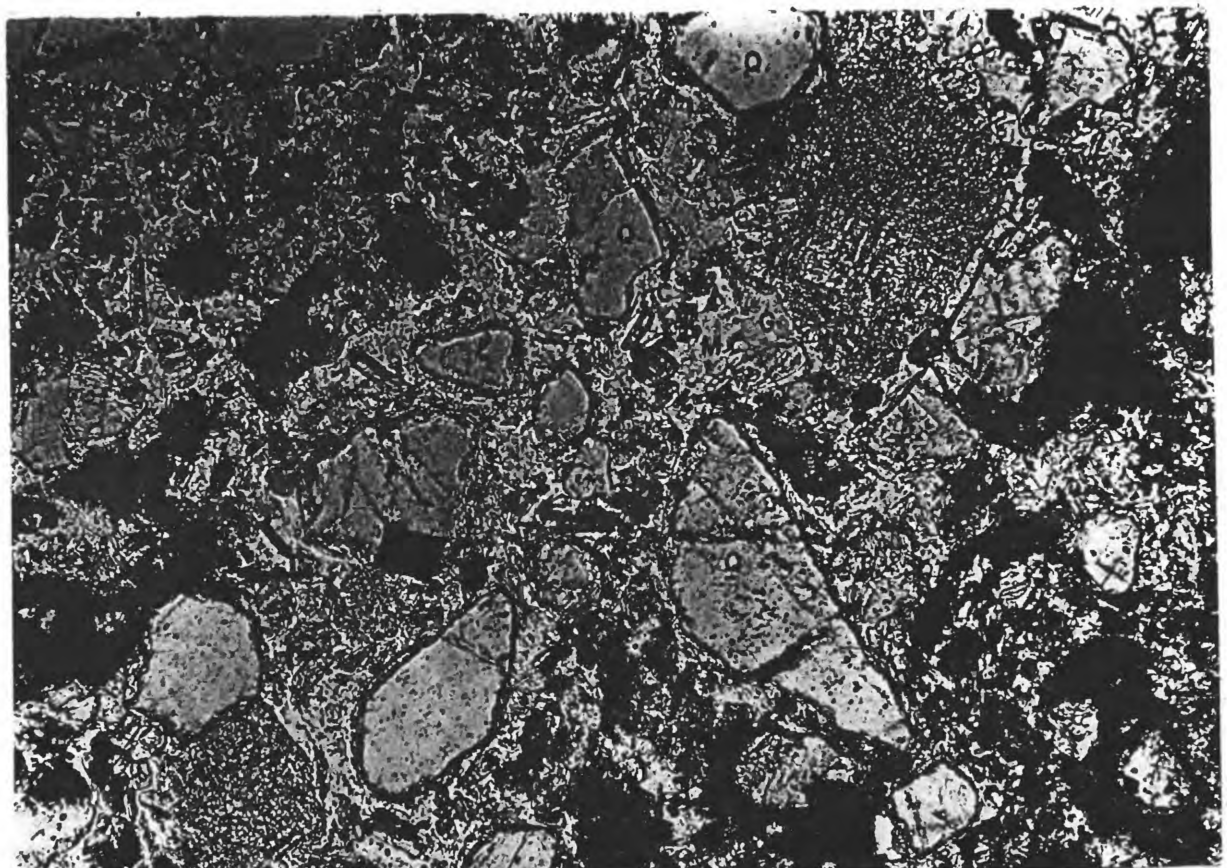


Figure 26. Photomicrograph of fused sand, showing tridymite - cordierite - magnetite - glass assemblage. T = tridymite, C = cordierite, M = magnetite, G = glass, Q = corroded detrital quartz grains, F = fused feldspar. (X150).

Tridymite - cordierite - magnetite - glass

Tridymite, cordierite, magnetite, and glass occur in rocks which, from their field relations, are thought to have been arkosic sands containing appreciable amounts of interstitial montmorillonite (Fig. 26). Most of the detrital quartz, orthoclase, and plagioclase grains are partly melted or dissolved. The cordierite crystals are subhedral or euhedral and are relatively free of inclusions. The magnesium for these cordierites probably came from interstitial montmorillonite. Tridymite forms thin twinned plates and is usually abundant. Magnetite is not very abundant. This relative abundance of tridymite and rarity of magnetite distinguishes this cordierite-bearing rock from cordierite rocks derived from contamination by andesite.

Cordierite - sillimanite(?) - magnetite - glass

This assemblage is characteristic of the fused clay lenses. The cordierite forms large, irregular crystals and is clouded with numerous inclusions. The magnesium for it was supplied by montmorillonite, which is one of the major constituents of the clay. The sillimanite(?) commonly forms around quartz grains and is probably a result of reaction between alumina in the day and the silica of the quartz.

Cordierite - magnetite - glass

Glass in fused sand near the andesite contacts commonly contains abundant cordierite and magnetite. The cordierite forms small

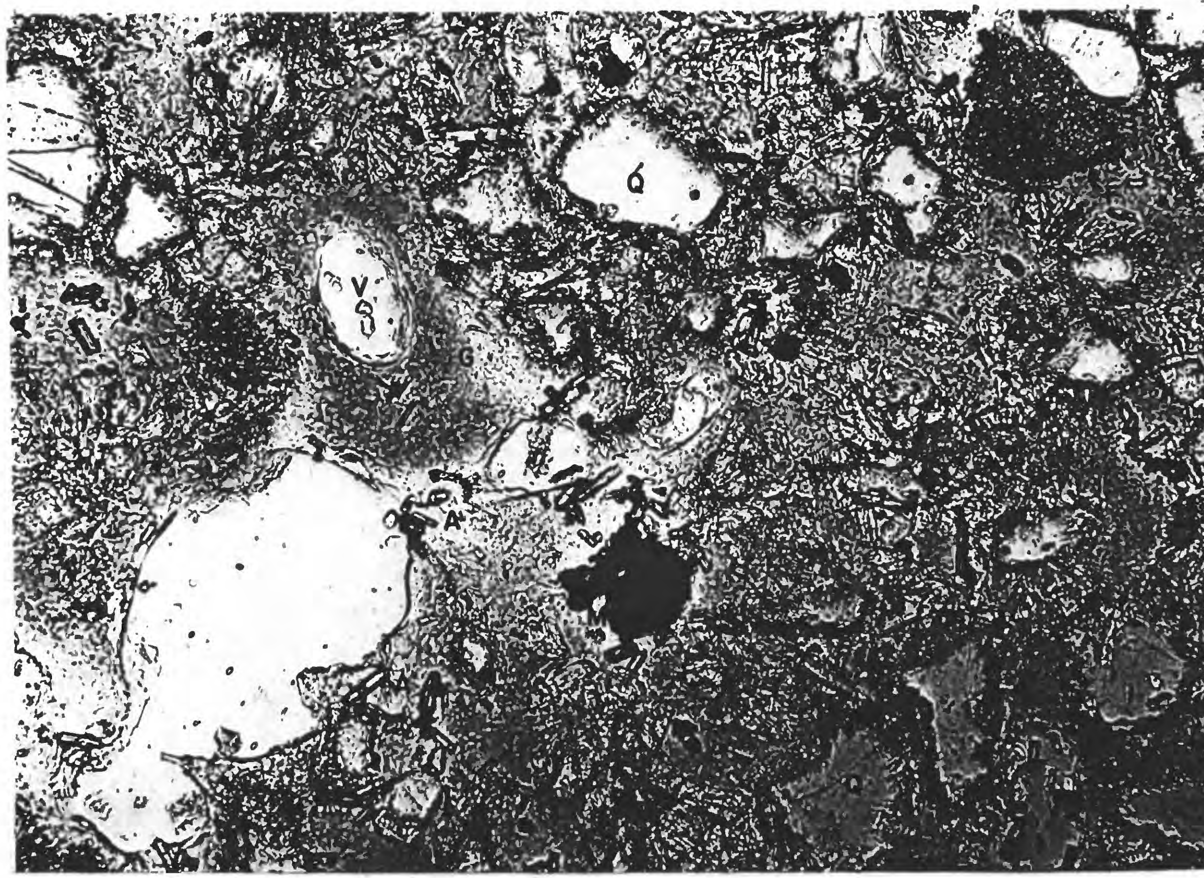


Figure 27. Photomicrograph of brown glass containing microlites of augite about 0.01 to 0.02 millimeters long. A = augite, M = magnetite, G = brown glass, Q = corroded quartz, F = feldspar "ghost", V = vesicle. (X150).

subhedral and euhedral crystals; the magnetite occurs as tiny octahedra. This cordierite-bearing glass represents fused sand that has been contaminated by the introduction of magnesium and iron from the andesite.

Cordierite - hypersthene - plagioclase - magnetite - glass

In more highly contaminated fused sand, hypersthene, and rarely plagioclase, is associated with cordierite and magnetite in the glass. These two minerals indicate the introduction of an amount of magnesium in excess of that required to form cordierite and a sufficient amount of calcium and sodium to form plagioclase. The plagioclase crystals are andesine and differ in habit from the plagioclase microlites in the andesite. Therefore they are probably a product of direct crystallization from the fused sand, and not inclusions from the andesite. The glass in which this assemblage is found has an index of refraction of 1.490, which is slightly higher than the glass in rocks known to be uncontaminated.

Augite - magnetite - glass

Thin veinlets of brown glass, which grade at their margins into colorless glass, contain tiny crystals of augite and magnetite. (See fig. 27.) The glass has an index of refraction of 1.496, which is identical to the index of interstitial glass in the andesite. These glass veinlets probably are similar in composition to the andesitic liquid that became mixed in various proportions with the fused sand and formed the liquid from which cordierite, hypersthene, and plagioclase crystallized.

Table 3. Chemical analyses of four rocks from an andesite dike-fused sand complex in the Valles Mountains, New Mexico.

	1	2	3	4
SiO_2	79.52	82.02	74.54	62.76
Al_2O_3	8.92	8.11	11.99	16.20
Fe_2O_3	2.56	1.28	2.33	2.93
FeO	.19	.14	1.04	1.53
MgO	.46	.55	1.53	2.59
CaO	1.26	.63	1.41	5.10
Na_2O	1.87	1.08	1.63	3.98
K_2O	2.22	3.05	3.05	2.48
H_2O -	.77	.65	.34	.20
H_2O +	1.37	1.93	1.27	.97
TiO_2	.41	.29	.49	.67
CO_2	.02	.00	.01	.01
P_2O_5	.09	.04	.09	.34
Cl	.01	.01	.01	.02
F	.02	.01	.06	.03
MnO	.03	.02	.05	.07
BaO	.12	.09	.10	.25
Total	99.82	99.90	99.94	100.13
Less O	.01	.00	.03	.01
	99.81	99.90	99.91	100.12

1. Arkosic sand
2. Fused arkosic sand
3. Hybrid rock
4. Andesite

Analyst: L. N. Tarrant, U. S. Geological Survey, Denver, Colorado

CHEMISTRY

Field relationships and mineral assemblages, as seen in thin section, indicate that many of the rocks in the fused zone, in particular those near andesite contacts, originated by the intermixing of andesite and fused arkosic sand. This is borne out also by the chemical composition of the rocks.

Chemical analyses of four of the typical rocks in the area are given in Table 5. Column 1 is an analysis of unaltered sand from beyond the zone of fusion. Column 2 is an analysis of a specimen of fused sand collected several feet from the west side of the andesite dike. It is slightly higher in SiO_2 and K_2O and lower in Fe_2O_3, CaO, and Na_2O than the unaltered sand, but these differences are probably original and not the result of exchange of material with the andesite. The rock consists of about 22 percent relict quartz grains, 5 percent relict plagioclase, and the rest is glass containing microlites of tridymite, cordierite, and magnetite. The presence of cordierite in this rock is rather surprising since it contains only 0.55 percent MgO. This cordierite probably was derived from montmorillonite that was in the matrix of the sand.

Column 3 is an analysis of a black rock that was collected a few feet from the fused sand analyzed in column 2 and was adjacent to the western contact of the dike. It was interpretated on the basis of field relations and thin section study as having originated by the intermixing of fused sand and andesitic liquid. It consists of

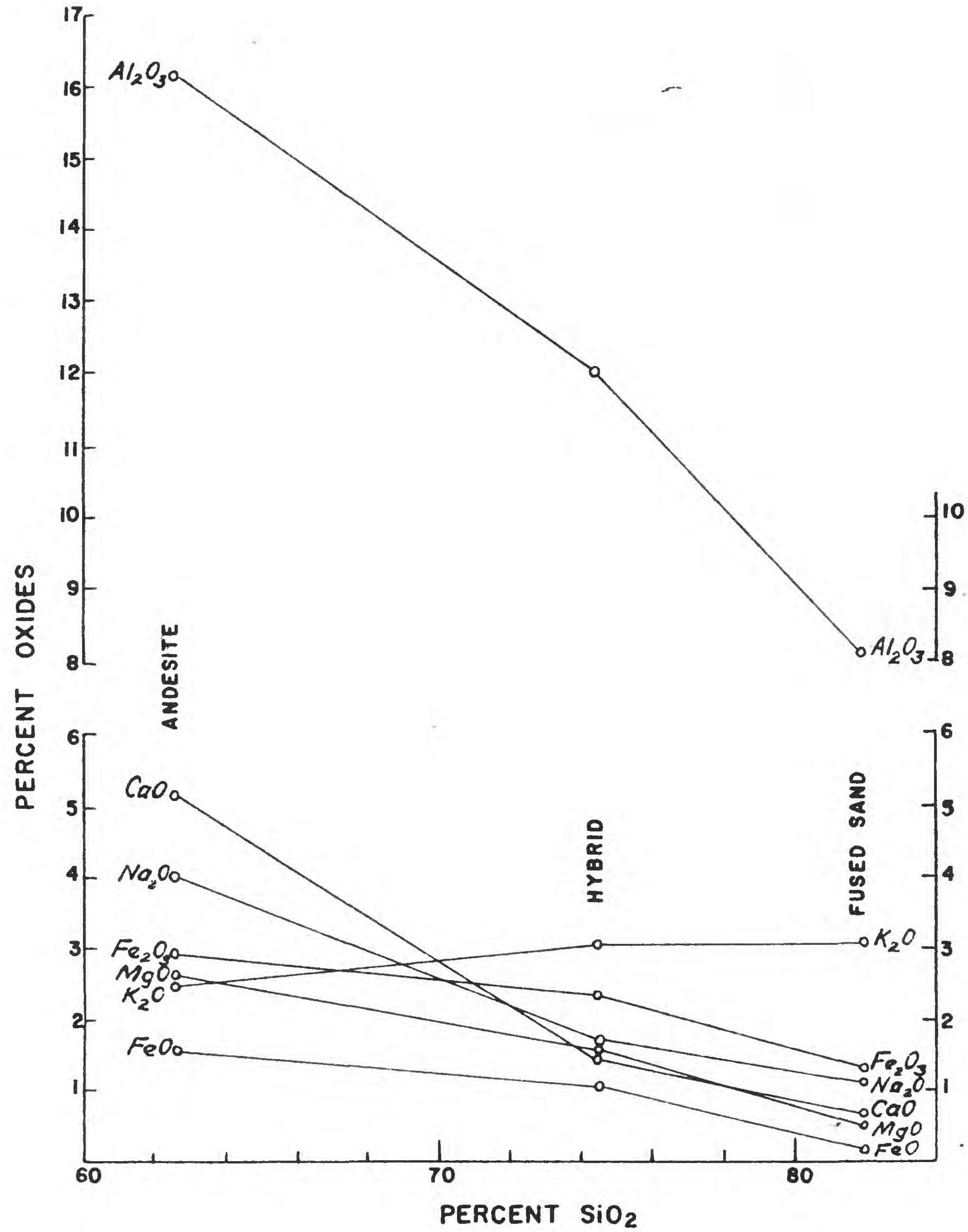


Figure 28. Variation diagram showing the composition of the hybrid rock as being intermediate between the andesite and the fused arkosic sand.

about 15 percent relict quartz grains in an extremely fine-grained matrix, rich in cordierite and magnetite and containing a very few microlites of labradorite similar to those in the andesite. In figure 28, the oxides of the fused sand, the hybrid rock, and the andesite are plotted against silica. It is clear from this diagram that the hybrid rock has a composition intermediate between the andesite and the fused sand, for there is a nearly straight line variation between the components in the three rocks.

TEMPERATURE OF FUSION

The temperature of crystallization of the andesite, as determined from the pyroxene inversion curve, was about 1120°C (p.37). If one accepts the thesis held by Bowen (1922, p. 520-523), that differentiated magmas do not have an appreciable amount of superheat, and the conclusion of Hess (1941, p. 582), that mafic magmas crystallize over a very short temperature range, probably not more than 40°C, it seems likely that the temperature of the molten andesite did not exceed 1200°C. Sosman and Merwin (1913) found that the basaltic facies of the Palisade diabase became completely molten in a crucible over a temperature range of 150°C (between 1150°C and 1300°C). Thus, at the most, the andesite could not have been hotter than 1300°C, and that is probably excessive.

Hydrothermal experiments performed in the laboratory and described in the appendix of this paper (p. 80) show that specimens of arkosic sand became partly fused in the presence of water at 1050°C. This temperature is 150°C lower than the minimum temperature to which the arkosic sand could have been subjected at the contacts of the dike. Therefore, a certain amount of fusion at the contacts is not difficult to explain.

The stability relations of orthoclase and biotite within the fused zone indicate that melting took place above 900°C. Orthoclase transforms to sanidine at 900°C or above, and Allen and Day (1913, p. 49), have demonstrated that biotite becomes reddened above 650°C and is altered rapidly to magnetite above 900°C. The inversion temperatures of the plagioclases, except for albite, ca. 700°C (Tuttle and Bowen, 1950), are not yet known; thus the partly fused plagioclases cannot be used as geologic thermometers. All the plagioclase in the sandstone is more calcic than albite and presumably would have a higher inversion temperature.

According to the work of Rankin and Merwin (1918) and Yoder (1952) two forms of cordierite are known - a high-temperature form (α) with indices of refraction of about 1.52 to 1.53, and a low-temperature form (μ) with indices of refraction ranging from 1.535 to 1.560. Hydrothermal experiments by Yoder (1952) indicate that the form with higher indices of refraction crystallizes between 530°C and 830°C, and that the form with lower indices forms above 830°C. The cordierite in these rocks has an index of refraction of about 1.540 and is therefore the low-temperature form. This may indicate that after fusion took place the resulting liquid remained molten below 830°C. Very little is known of the nature of the cordierite high-low inversion, however, and it is possible that the cordierite formed above 830°C and inverted to the low-temperature form on cooling.

VOLATILES

The pronounced effect that volatiles have in decreasing the temperature and time required for reactions between substances at elevated temperatures has been observed in many hydrothermal experiments. That volatiles associated with magmas should have similar effects on the reactions that take place between minerals in the wall rocks of igneous bodies is therefore to be expected, and is supported by an abundance of field data.

The association of zeolites with fused inclusions described by Richarz (1924) and the observations of Williams (1936, p. 157) and Larsen and Switzer (1939), that water was the only constituent added in quantity to fused rocks studied by them, suggest that volatiles play an important role in the formation of fused rocks. Some indication of the concentration of volatiles in this particular andesite dike may be obtained from the Fe_2O_3/FeO ratio of the andesite. Phemister (1934) and Kennedy (1948) have shown that the ratio of Fe_2O_3 to FeO in rocks may be used to determine the relative concentration of water in the magma at the time of crystallization - the higher the Fe_2O_3/FeO ratio, the higher the water concentration.

Chemical analyses of a number of andesites having compositions comparable to that of the andesite in this dike have Fe_2O_3/FeO ratios varying between 1:2 and 1:5. The andesite in this dike, however, has an Fe_2O_3/FeO ratio of 2:1, suggesting an unusually high concentration of volatiles. A high concentration of volatiles is further suggested by the abundance of deuteric alteration in the central part of the dike and by the abundance of gas-phase tridymite and cristobalite in vesicles.

COMPARISON WITH OTHER LOCALITIES

To the author's knowledge, only five localities comparable to this one have been described previously. Four of these are in the Navajo-Hopi country of northeastern Arizona and are described by Williams (1936, p. 157). The fifth is in Owens Valley, California, and is described by Knopf (1938). The Arizona localities are thin zones of vitrified sandstone at the contacts of volcanic necks of minette and monchiquite. The zones consist of spongy masses of glass surrounding grains of sanidinized and partly fused orthoclase, partly dissolved plagioclase, and corroded and embayed quartz.

The California locality is a basalt dike with a contact zone of partly fused granodiorite four to seven feet wide. Fusion has occurred mainly between the boundaries of quartz and feldspar grains, where sinuous films of glass containing tiny crystals of tridymite and hyperstheme have formed. Biotite in the California locality and also in some of the Arizona localities is not decomposed to magnetite but is reddish to brown, indicating that temperatures were slightly lower than at the Valles Mountains locality. In the Arizona and California localities, as in the Valles Mountains locality, pronounced columnar jointing perpendicular to the igneous contacts is characteristic of the fused zones.

In addition to these descriptions of partly fused wall rock, the literature contains a number of accounts of fused xenoliths, which have undergone chemical changes comparable to those described in this paper.

H. H. Thomas (1922) has described a number of very interesting aluminous xenoliths from tholeitic intrusives in the Island of Mull, which have melted and partly recrystallized as "sillimanite buchites". Some of the xenoliths have reaction rims of anorthite, corundum, and spinel, intergrown with partly resorbed sillimanite. Other xenoliths have rims of cordierite, plagioclase, and spinel that are similar to the cordierite - hypersthene - plagioclase - magnetite assemblage described in this paper. The main difference is the absence of hypersthene, indicating the introduction of less MgO.

Watson and Mathews (1948) have described partly fused xenoliths of granite and quartzite in pillow lavas in British Columbia. Spectrographic analyses show that Mg, Fe, and Ca were added to the glass in the fused granite xenoliths, and cordierite, hypersthene, and sanidine have crystallized from glass in the quartzite xenoliths. This mineral assemblage is also similar to the cordierite - hypersthene - plagioclase - magnetite assemblage of this paper. The presence of sanidine instead of plagioclase indicates a greater introduction of K_2O and Na_2O than CaO in the British Columbia rocks.

Microchemical analyses of glass from partly fused xenoliths of quartzite in alkalic mafic lavas in southwest Uganda, described by Holmes (1936), show that Al_2O_3, K_2O, and H_2O were introduced from the lava. All of these elements are known to act as fluxes and they probably facilitated fusion of the quartzite.

Larsen and Switzer (1939) have described a large inclusion of granodiorite in an andesite plug in San Diego County, California, chemical analyses of which show that the only constituent added to the inclusion was H_2O. The authors conclude that H_2O must have facilitated fusion, because lack of wall rock alteration and the shallow depth of the intrusion indicate that the andesite did not have an abnormally high temperature.

From the foregoing descriptions, it is clear that the fusion and solution of inclusions in mafic magmas is usually accompanied by the introduction of certain constituents from the magma. These constituents vary depending on the composition of the magma, but one of them that is very commonly present, and that is sometimes present in the absence of all others, is water. Since fused rocks are associated with intrusive rocks, varying in composition from minette to andesite, it seems necessary to attribute fusion to some other factor than abnormally high temperature. Hydrothermal experiments in the laboratory and chemical data from a number of fused rock localities suggest that this factor is volatile material, which acts as a flux and facilitates fusion at normal magmatic temperatures.

APPENDIX

LABORATORY FUSION EXPERIMENTS

Method of investigation

In an attempt to determine the temperature at which fusion took place, several samples of arkosic sand from the area were heated both dry and in the presence of water to temperatures between 800°C and 1050°C. Unfortunately lack of time, and difficulties with the equipment prevented satisfactory completion of the experiments. However, the data obtained are presented here for comparison with similar experiments carried out by other workers.

Experiment procedure

Materials

The arkosic sand used in the experiments was collected from the silicified zone and was considered representative of the sand in the area. In addition to quartz, orthoclase, and plagioclase, it contained minor amounts of clay and was poorly cemented with opal. The samples were shaped into small blocks 2 by 2 by 1 centimeters.

Equipment

A porcelain crucible or a Morey bomb was used in the experiments, depending on whether the sample was heated dry or in the presence of water. The vessels were heated externally in a vertical tubular resistance furnace, which was controlled with a Variac temperature regulator. The temperature was measured with a chromel-alumen thermocouple inserted through a hole in the cover of the crucible or in a well in the cap of the Morey bomb.

In the first few runs, the desired water pressure was obtained by adding carefully measured amounts of water that were calculated from the capacity of the bomb and the specific volume of water at the desired pressure and temperature of the run. In the last few runs, an arbitrary amount of water was added to the charge and then was bled off gradually until the correct pressure (measured on a Bourdon gauge) was attained at the maximum temperature of the run.

Procedure

Each sample was weighed both before and after heating. After the initial weighing, the sample was placed in the bomb with the required amount of water, or if dry, in a covered crucible. Oxygen was expelled from the charge with a jet of nitrogen gas in order to prevent the oxidation of iron, and the bomb was then sealed. Oxygen was removed from the system in order to duplicate more closely natural conditions. In the naturally fused sand, ferric iron was reduced to ferrous iron and caused the sand to change in color from buff to gray. At the end of each run, the charge was quenched with a blast of cool air directed against the bomb.

Table 4

Run	Temperature °C	H_2O Pressure Atmospheres	Time Hours	Remarks
1	805° ± 10°	1	21	No fusion. Iron oxidized.
2	860° ± 20°	1	26 } 44	
	1044° ± 5°	1	1	
	1005° ± 5°	1	18	No fusion. Iron oxidized.
3	870°-950°	?	2 } 44	25% water added but all escaped at some time during run.
	1050° ± 5°	?	3	15% of sample converted to glass; quartz and orthoclase fused.
	1000° ± 10°	?	39	Plagioclase unaltered.
4 } 5 }	800° ± 5°	?	65	4% H_2O added to charge but lost during run. No fusion observed but sample slightly more coherent.
6	800°-960°	?	24	4% H_2O added but lost. No fusion but sample more coherent.

Results

The data for each run are given in table 4. The only run in which fusion occurred was number 3. In this run the temperature was maintained at 1050°C for three hours and subsequently at 1000°C for 39 hours. Water equivalent to about 25 percent of the weight of the sand sample was added at the beginning of the run, but at some unknown time during the run all of it escaped. However, some water probably remained in the bomb until fusion occurred, because in run number 2, which was dry, almost the same temperatures were maintained for 18 hours, but the sand did not fuse. The longer duration of run number 3 may have had some effect on the amount of fusion that took place, but the presence of water as a flux probably made fusion possible at 1050°C, whereas its absence prevented fusion at the same temperature in run number 2.

Approximately 15 percent of the sample in run number 3 was converted to colorless glass with an index of refraction of about 1.490. Both quartz and orthoclase were partly fused, but plagioclase was not affected. All of the clay and opal was fused. The quartz grains were crackled and had irregular or scalloped edges similar to those seen in the naturally fused sand.

Films of glass formed along cleavage planes in the orthoclase, but instead of forming a reticulate network as in the naturally fused orthoclase, they were wide, irregular, and randomly spaced. None of the orthoclase appeared to be sanidinized.

The results of these experiments may be compared with the results of similar experiments made by Sosman and Merwin (1913) on inclusions of arkose collected from near the base of the Palisade sill. In the field the arkose showed no signs of fusion, but quartz, orthoclase, and hornblende had undergone "secondary growth". In the laboratory, specimens heated to 1025°C (dry) remained unaltered, but after 75 minutes at 1150°C, one half of the rock was converted to glass and only quartz and magnetite remained. A direct comparison between the behavior of these arkose inclusions and the arkosic sand that was fused in run number 3 is not possible, because the former was coarser grained and contained much more orthoclase (67 percent). However, the presence of water in run number 3 probably was responsible for the lower temperature of fusion of the arkosic sand.

REFERENCES

Bowen, N. L. (1922) The behavior of inclusions in igneous magmas: Jour. Geology 30, 513-570.

Bowen, N. L. and Schairer, J. F. (1935) The system MgO - FeO - SiO_2: Am. Jour. Sci., 5th ser., 29, 151-217.

Bryan, Kirk (1938) Geology and ground water conditions of the Rio Grande depression in Colorado and New Mexico: National Resources Committee, Regional Planning, Part VI, Upper Rio Grande, Vol. I.

Burbank, W. S. (1941) Structural control of ore deposition in the Red Mountain, Sneffels, and Telluride districts of the San Juan Mountains, Colorado: Colorado Sci. Soc. Proc., 14, 141-261.

Day, A. L. and Allen, E. T. (1925) The volcanic activity and hot springs of Lassen Peak: Carnegie Inst. Washington Publ. No. 360.

Denny, C. S. (1940) The Santa Fe formation in the Espanola Valley, New Mexico: Geol. Soc. America Bull. 51, 677-693.

Eskola, P. (1939) Die Entstehung der Gesteine (Barth, T. F. W., Correns, C. W., and Eskola, P.) Springer, Berlin.

Flett, J. S. (1911) Geology of Colonsay, Oransay, and part of the Ross of Mull: Scotland Geol. Survey Memoir.

George, W. O. (1924) The relation of the physical properties of natural glasses to their chemical composition: Jour. Geology, 32, 353-372.

Goranson, R. W. (1940) "Flow" in stressed solids: an interpretation: Geol. Soc. America Bull. 51, 1023-1034.

Griggs, David (1940) Experimental flow of rocks under conditions favoring recrystallization: Geol. Soc. America Bull. 51, 1001-1022.

Harker, A. (1932) Metamorphism: Methuen, London.

Hess, H. H. (1941) Pyroxenes of common mafic magmas: Am. Mineralogist, 26, 515-535, 573-594.

Hess, H. H. (1949) Chemical and optical properties of common clinopyroxenes: Am. Mineralogist, 34, 641-667.

Holmes, A. (1936) Transfusion of quartz xenoliths in alkali basic and ultrabasic lavas, southwest Uganda: Min. Mag. 24, 408-421.

Kaaden, G. van der (1951) Optical studies on natural plagioclase feldspars with high- and low-temperature optics: Thesis, Univ. Utrecht.

Kennedy, George (1948) Equilibrium between volatiles and iron oxides in igneous rocks: Am. Jour. Sci., 5th ser., 46, 524-549.

Knopf, A. (1938) Partial fusion of granodiorite by intrusive basalt: Am. Jour. Sci., 5th ser., 36, 173-176.

Kohler, Alexander (1949) Recent results of investigations of the feldspars: Jour. Geology, 57, 592-599.

Kuno, Hisashi (1954) Study of orthopyroxenes from volcanic rocks: Am. Mineralogist, 39, 30-46.

Lacroix, M. A. (1890) Enclaves dans les roches volcaniques: Bull. Geol. Soc. France, 18, 845-886.

Larsen, E. S., Jr. and Switzer, George (1939) An obsidian-like rock formed from the melting of a granodiorite: Am. Jour. Sci., 5th ser., 37, 562-568.

MacGregor, A. G. (1931) Clouded felspars and thermal metamorphism: Min. Mag., 22, 524-538.

Nadai, A. (1931) Plasticity, a mechanics of the plastic state of matter: McGraw-Hill, New York.

Phemister, T. C. (1934) The role of water in basaltic magma: Tschermaks Min. Pet. Mitt., 45, 19-77, 99-132.

Poldervaart, Arie and Hess, H. H. (1951) Pyroxenes in the crystallization of basaltic magma: Jour. Geology, 59, 472-489.

Poldervaart, Arie and Gilkey, A. K. (1954) On clouded plagioclase: Am. Mineralogist, 39, 75-91.

Rankin, G. A. and Merwin, H. E. (1918) The ternary system MgO - Al_2O_3 - SiO_2: Am. Jour. Sci., 4th ser., 301-326.

Richarz, S. (1924) Some inclusions in basalts: Jour. Geology, 32, 685-689.

Smith, H. T. U. (1935) The Tertiary and Quaternary geology of the Abiquiu quadrangle, New Mexico: Doctorate thesis, Harvard University.

Smith, H. T. U. (1938) The Tertiary geology of the Abiquiu quadrangle, New Mexico: Jour. Geology, 46, 933-965.

Sosman, R. B. and Merwin, H. E. (1913) Data on the fusion temperature of the Palisade diabase: Washington Acad. Sci. Jour., 3, 389-395.

Spencer, Edmondsen (1937) The potash felspars, I. Thermal stability: Min. Mag. 24, 453-494.

Stearns, C. E. (1953) Tertiary geology of the Galisteo-Tonque area, New Mexico: Bull. Geol. Soc. America, 64, 459-508.

Thomas, H. H. (1922) On certain xenolithic Tertiary minor intrusions in the Island of Mull: Geol. Soc. London Quart. Jour. 78, 229-260.

Tomkeieff, S. I. (1940) The dolerite plugs of Tieveragh and Tievebulliagh, near Cushendall Co. Atrim; with a note on buchite: Geol. Mag., 77, 54-65.

Turner, F. J. (1948) Mineralogical and structural evolution of the metamorphic rocks: Geol. Soc. America Mem. 30.

Tuttle, O. F. and Bowen, N. L. (1950) High-temperature albite and contiqueous feldspars: Jour. Geol. 58, 572-583.

Venkatesh, V. (1952) Development and growth of cordierite in paralavas: Am. Mineralogist, 37, 831-848.

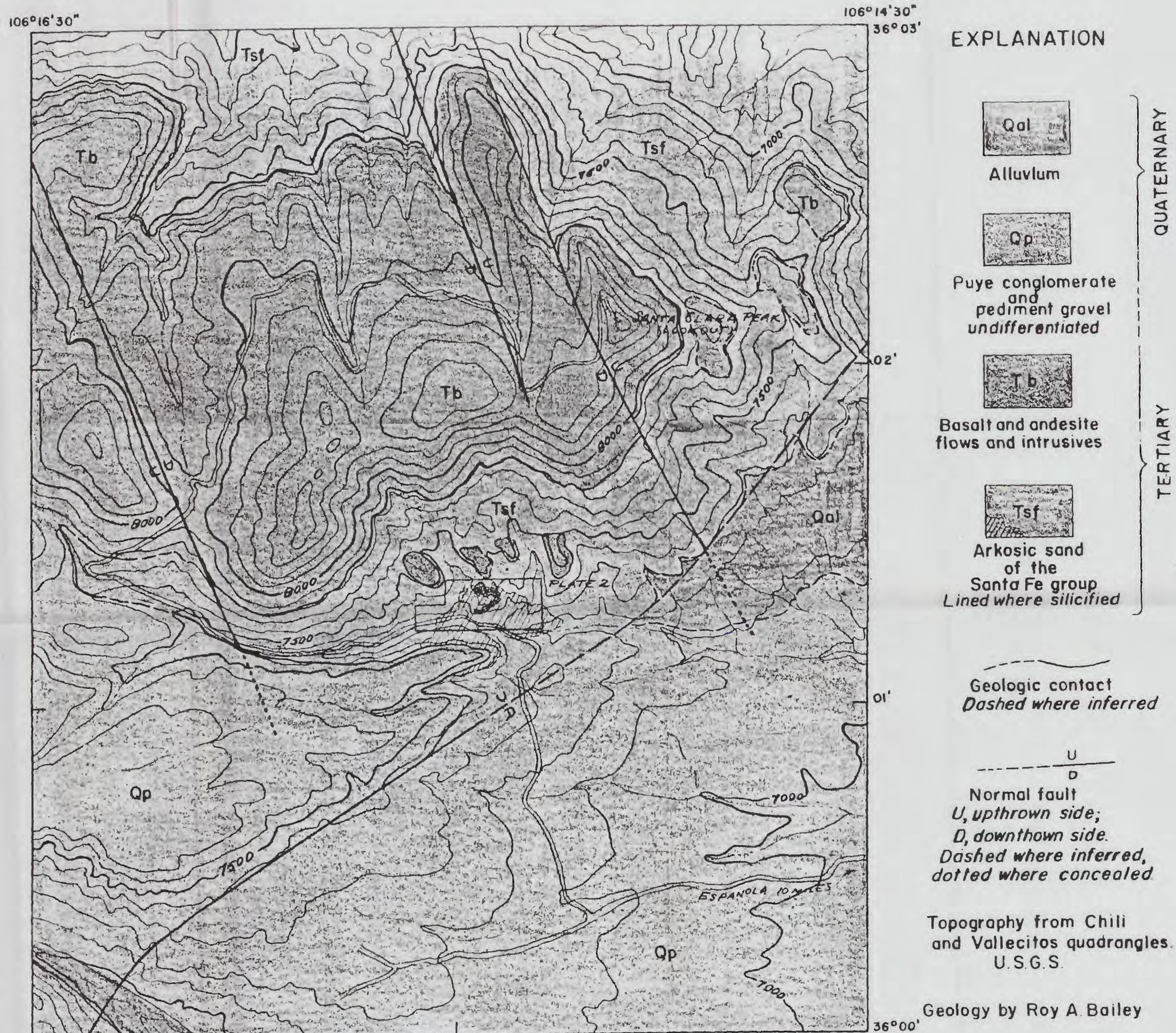
Watson, K. DeP. and Mathews, W. H. (1948) Partly vitrified xenoliths in pillow lava: Am. Jour. Sci., 5th ser., 46, 601-615.

Williams, Howel (1936) Pliocene volcanoes of the Navajo-Hopi country: Bull. Geol. Soc. America, 47, 111-171.

Yoder, H. S., Jr. (1952) The $MgO - Al_2O_3 - SiO_2 - H_2O$ system and the related metamorphic facies: Am. Jour. Sci., 5th ser., Bowen Volume, 569-627.

54-14

PLATE I



RECONNAISSANCE GEOLOGIC MAP OF THE AREA IN THE VICINITY OF SANTA CLARA PEAK, VALLES MOUNTAINS, NEW MEXICO

1 0.5 0 1 MILE

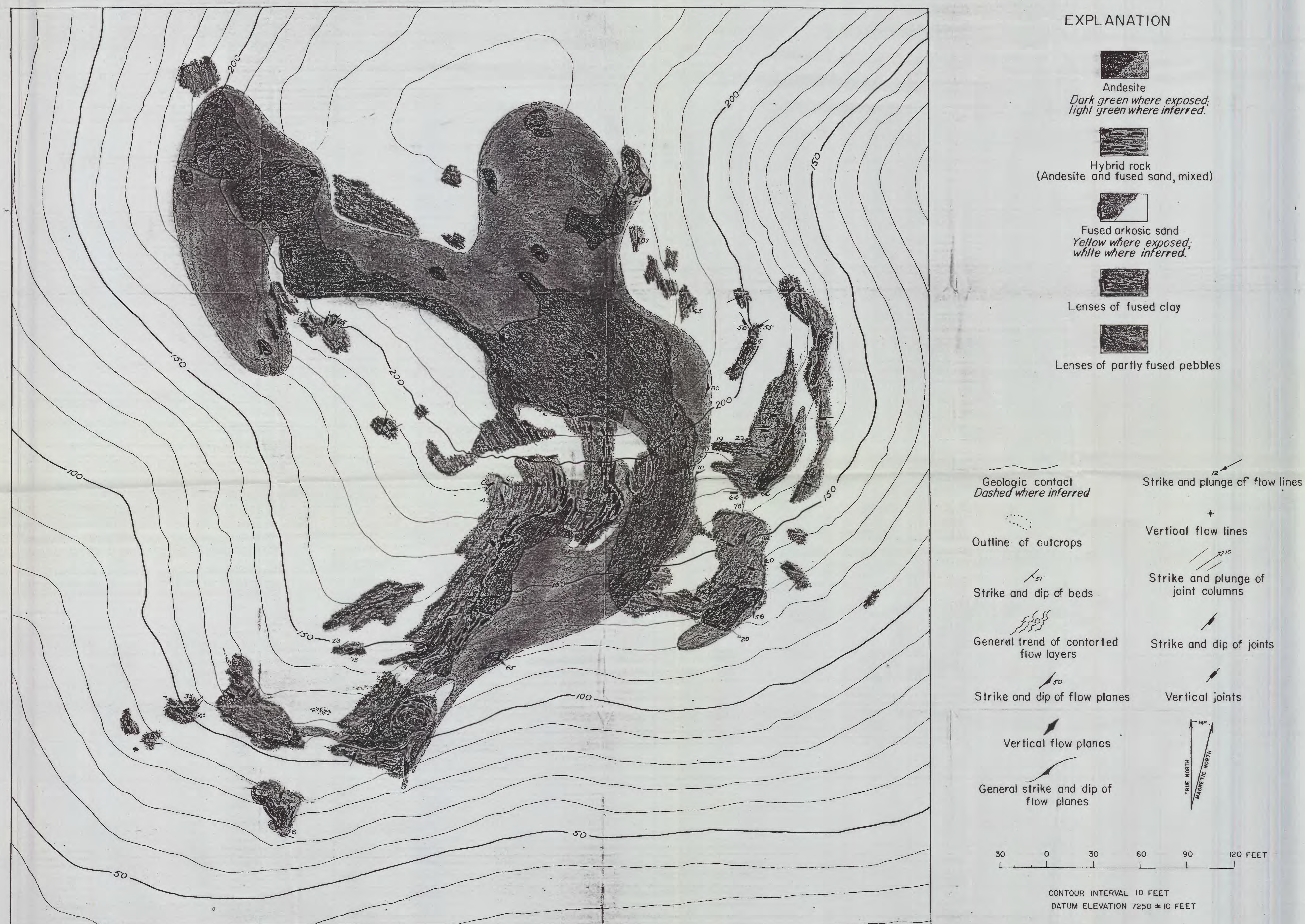
CONTOUR INTERVAL
100 FEET

54-14

PLATE 2

GEOLOGIC MAP OF AN ANDESITE DIKE IN THE VALLES MOUNTAINS, NEW MEXICO

PLATE 3



STRUCTURAL AND GEOLOGIC MAP OF AN ANDESITE DIKE IN THE VALLES MOUNTAINS, NEW MEXICO