Large Landslides, Composed of Megabreccia, Interbedded in Miocene Basin Deposits, Southeastern Arizona

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1008

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1977

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

Library of Congress Cataloging in Publication Data
Krieger, Medora Louise Hooper, 1905-
Large landslides, composed of megabreccia, interbedded in Miocene basin deposits, southeastern Arizona.
(Geological Survey Professional Paper 1008)
Bibliography: p. 24-25
Supt. of Docs. no.: I 19.16:1008
1. Landslides--Arizona--Gila Co. 2. Landslides--Arizona--Pinal Co. 3. Geology, Stratigraphic--Miocene.
I. Title. II. Series: United States. Geological Survey. Professional Paper 1008.
QE599.U5K75 557.3'08s (551.3'5) 76-608331

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402
Stock Number 024-001-03026-8

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LARGE LANDSLIDES, COMPOSED OF MEGABRECCIA, INTERBEDDED IN MIOCENE BASIN DEPOSITS, SOUTHEASTERN ARIZONA

By Medora H. Krieger

ABSTRACT

The landslides in the Kearny and El Capitan Mountain quadrangles, Pinal and Gila Counties, Ariz., are tabular or lenslike masses of megabreccia enclosed in Miocene basin deposits. The megabreccias within individual slide blocks are composed of pervasively brecciated Precambrian and younger formations that remain in normal stratigraphic sequence, indicating that each landslide moved as a fairly coherent mass. The megabreccias consist of fresh, mostly angular rock fragments in a comminuted matrix of the same composition as the fragments. The matrix ranges in amount from sparse to abundant. Where the matrix is sparse, the fragments fit tightly with little or no rotation. Locally fragments are rotated but not moved far; most units within a slide block are lithologically homogeneous.

The Kearny landslides are conformably interbedded in steeply east-dipping playa and alluvial deposits. They form map units from a few tens of meters to nearly 4 km long and from less than 1 to 270 m wide. Narrow ridges expose sections through the landslides at about right angles to the direction of movement. The upper (proximal) ends have been eroded; the lower (distal) ends are buried. The El Capitan landslide dips very gently southward. Although partly dissected during erosion of the enclosing alluvial and lakebed deposits, its approximate original outline is still preserved. It forms a thin sheet, 5–15 m thick and at least 3.8 km long; the maximum outcrop width, near its distal end, is about 1.5 km.

The Kearny landslides show little evidence of having exerted differential pressure on the underlying soft playa and alluvial deposits, and the contacts with the underlying sediments have little relief. The distal end of the El Capitan landslide, on the other hand, has considerable relief. As the landslide came to an abrupt stop, the end plowed into the underlying sediments, compressing them into folds and forming sandstone dikes. The source of the El Capitan landslide is a well-defined amphitheater on the south side of El Capitan Mountain 1,500 to more than 3,000 m above and 1.5–3 km north of the proximal end of the landslide. The long distance traveled on a very gentle slope indicates that the El Capitan landslide had a very low coefficient of friction, similar to some modern and prehistoric avalanches. According to Shreve, they may have traveled on a thin lubricating layer of compressed air. The coefficient of friction of the Kearny landslides cannot be determined. However, the nonturbulent character of both the Kearny and El Capitan landslides indicates that they slid rather than flowed.

INTRODUCTION

Large landslides in the Kearny and El Capitan Mountain quadrangles (fig. 1), Pinal and Gila Counties, Ariz. are tabular or lenslike masses of megabreccia composed of shattered but well-indurated Precambrian and younger rocks conformably enclosed in Miocene basin deposits. The term megabreccia is used in this report to describe the pervasive brecciation of mappable lithologic units within the landslides; these megabreccias are derived from recognizable named formations exposed in adjacent mountain ranges. Each megabreccia comprises fresh, mostly angular rock fragments in a comminuted matrix of the same composition as the fragments. Large blocks, 3 m long or more, are present, but most fragments are less than 25 cm in maximum dimension.[1] The amount of matrix ranges from sparse to abundant. Where matrix is sparse, the rock resembles a three-dimensional jigsaw puzzle. Locally fragments are rounded or rotated, but most have moved only slightly relative to their neighbors; adjacent formations are not mixed, except in a few isolated outcrops. This lithologic homogeneity distinguishes these landslides from debris flows or mudflows. Detailed study of the stratigraphy of the landslides and comparison with undisturbed stratigraphic units proves that many of the brecciated formations within individual slide blocks, although attenuated, are in normal stratigraphic sequence. For this reason and for simplicity, lithologic units within the landslides are referred to informally in the text and illustrations as Escabrosa megabreccia or Martin megabreccia, for example, instead of the correct but more cumbersome designations of megabreccia composed of the Mississippian Escabrosa Limestone or the Devonian Martin Formation. The normal stratigraphic sequence within a slide block proves that it must have moved as a unit. Most of the landslides represent single slide blocks, but one large mass is composite and consists of at least three slide blocks. Disruption or repetition of sequence in this block may be due to tectonic activity unrelated to emplacement; some disruption or repetition may be due to rapid emplacement of unrecognized slides or to imbrication during emplacement.

[1]Longwell (1951) called similar landslide masses near Lake Mead megabreccia and described them as large breccia masses that contain "***individual blocks of phenomenal size*** in unassorted masses that have large thickness and lateral extent."*** "Some individual fragments ***hundreds of feet long ***are minutely shattered***."

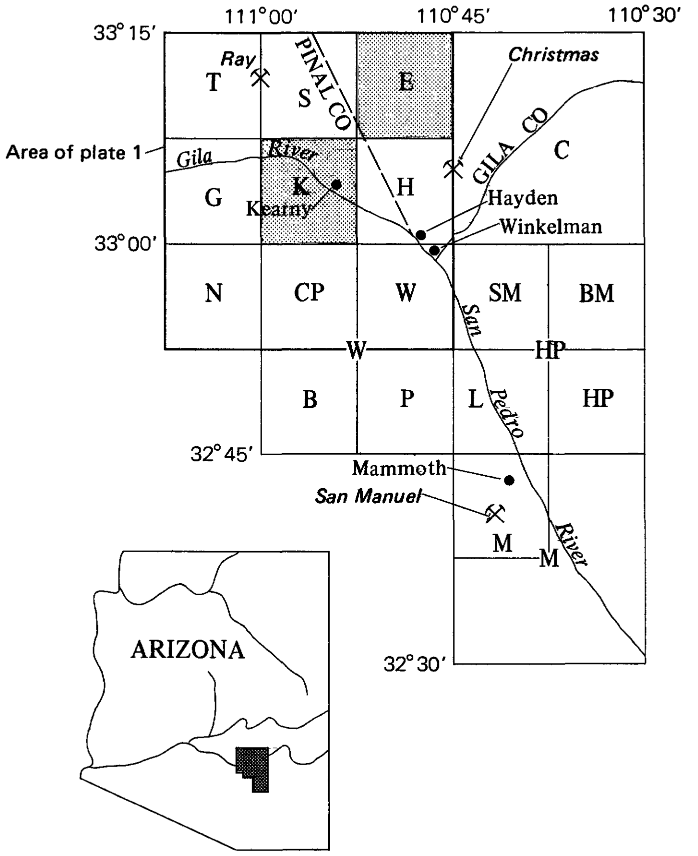

FIGURE 1.—Index map showing location of Kearny and El Capitan Mountain quadrangles (shaded), area of plate 1 (outlined), and other quadrangles and places referred to in text. Quadrangle names and published data (also for plate 1) identified as follows:

B, Black Mountain (Krieger, 1974d)
BM, Brandenburg Mountain (Krieger, 1968a)
C, Christmas (Willden, 1964)
CP, Crozier Peak (Krieger, 1974c)
E, El Capitan Mountain (Krieger, this report; Cornwall and Krieger, 1977)
G, Grayback (Cornwall and Krieger, 1975b)
H, Hayden (Banks and Krieger, 1977)
HP, Holy Joe Peak (Krieger, 1968b)
K, Kearny (Cornwall and Krieger, 1975a)
L, Lookout Mountain (Krieger, 1968c)
M, Mammoth (Creasey, 1965 for 7½-minute quadrangle; 1967 for 15-minute quadrangle)
N, Ninetysix Hills Northeast (Wilson and others, 1969)
P, Putnam Wash (Krieger, 1974e)
S, Sonora (Cornwall and others, 1971)
SM, Saddle Mountain (Krieger, 1968d)
T, Teapot Mountain (Creasey and others, 1975)
W, Winkelman (Krieger, 1974b for 7½-minute quadrangle; 1974a for 15-minute quadrangle)

Although the landslides in the Kearny and El Capitan Mountain quadrangles are inferred to be similar in origin, they differ markedly in general form and appearance, largely because of major differences in attitude and degree of erosion. The Kearny landslides are conformably interbedded in steeply east-dipping basin sediments, therefore forming map units from a few tens of meters to nearly 4 km long and from less than 1 to 270 m wide. Maximum exposed thickness of the largest landslide is about 180 m. The narrow ridges represent sections across the original landslide at about right angles to the direction of movement. The upper (proximal) ends have been eroded; the lower (distal) ends are buried.

In contrast, the El Capitan landslide dips very gently southward. Although partly dissected during erosion of the enclosing basin deposits, its approximate original outline is still preserved. It forms a thin sheet 5–15 m (locally 35 m) thick and at least 3.8 km long. Its width increases from zero at its upper end to about 1.5 km near its lower end.

The Kearny landslides show little evidence of having exerted differential pressure on the underlying soft playa and alluvial deposits; the contacts with the underlying sediments have little relief, no sandstone dikes were found, and shattering is no more intense at the base than higher in the slide block. The proximal part of the El Capitan landslide also exerted little differential pressure on the underlying alluvial deposits, and its contacts with the underlying sediments have little relief. Its distal end, however, exerted considerable pressure on the underlying deposits. The contact has moderate relief in part because the landslide plowed into the underlying lakebeds; sandstone dikes forced their way into the overlying slide block, the lakebeds were locally thrown into folds, and gougelike zones occur at and near the base of the slide block. These features probably are present in the Kearny landslides but were not observed because their distal ends are buried.

The El Capitan landslide came from an amphitheater, enlarged by subsequent erosion, on the south side of El Capitan Mountain, 2–3 km north of the northern (proximal) end of the slide block.

The source of the Kearny landslides cannot be determined from geomorphic evidence. Westward coarsening and imbrication of pebbles in the alluvial deposits that enclose the landslides indicate that the source was to the west or southwest. This probable source area has since been almost completely stripped of the formations (Precambrian and Paleozoic sedimentary rocks and Cretaceous volcanic rocks) that make up most of the landslides and much of the enclosing sedimentary rocks.

The Kearny and El Capitan landslides clearly slid into their present positions; they did not move as debris flows. Air-layer lubrication as proposed by Shreve (1966, 1968a) may have been the mechanism of support and transport for at least the Kearny landslides;

movement of the El Capitan landslide may have been aided by a conglomeratic mudflow at its base. Shreve concluded that geologic evidence and eyewitness reports indicate that ancient landslides such as the Blackhawk and Silver Reef in southern California, and modern ones such as the Sherman in Alaska, Elm in Switzerland, and Frank in Alberta, share characteristic features. Shreve (1968a, p. 1) stated that they "***started as huge rockfalls, which were launched into the air and then traversed the gently inclined, relatively smooth slopes below as nearly nondeforming sheets of breccia sliding at high speed on a relatively thin, easily sheared lubricating layer." This layer consisted of compressed air. The blocks were brecciated during initial fall and subsequently not much deformed.

ACKNOWLEDGMENTS

I thank my colleagues of the U.S. Geological Survey, particularly M. G. Johnson, M. C. Crittenden, Jr., S. C. Creasey, H. R. Cornwall, and N. G. Banks, for stimulating discussion and critical review of the manuscript and suggestions concerning interpretation of the breccias. Thanks are also extended to R. L. Shreve for his excellent papers on origin of landslides of this type, information that I have used extensively during this study.

GEOLOGIC SETTING

The Kearny and El Capitan landslides are in part of the Basin and Range province in Arizona, a region of northwest-trending mountain ranges that contain Precambrian to early Tertiary rocks and basins filled with Cenozoic sedimentary deposits. The general geologic setting of the area is shown on plate 1. The oldest rocks in the area are the Pinal Schist and Ruin Granite (Precambrian X and Y, respectively). These rocks are overlain with profound angular unconformity by the Apache Group and Troy Quartzite (Precambrian Y). Both were intruded about 1,200 million years ago by diabase, mostly as sills in the sedimentary rocks and as sill-like masses in granite and schist parallel to the contact with the overlying Apache Group. Paleozoic strata were deposited on the Precambrian sedimentary rocks with apparent conformity in most places. Cretaceous volcanic rocks—largely the Williamson Canyon Volcanics—overlie the older rocks unconformably. Cretaceous and early Tertiary igneous rocks intrude older rocks as dikes, sills, and stocks. Cenozoic sedimentary rocks include the steeply tilted playa and alluvial deposits of the early Miocene San Manuel Formation (Krieger and others, 1974). They are composed of detritus from most of the older rocks, especially the Troy Quartzite, diabase, Martin Formation, Escabrosa Limestone, and Williamson Canyon Volcanics. The Cenozoic section also contains undeformed alluvial and lakebed deposits of Dripping Spring Valley, which probably are younger than the San Manuel Formation. The Mescal Mountains north of the valley are a block of Paleozoic and older rocks that were tilted 20°–30° southwestward. Before the emplacement of the landslide, the Naco Limestone and the upper part of the Escabrosa Limestone had been largely stripped from this block.

KEARNY LANDSLIDES

Small landslides, originally identified by Creasey (1965) as sedimentary (monolithologic) breccias, were first described in the Mammoth quadrangle (fig. 1) in both the San Manuel Formation (lower member of the Gila Conglomerate) and in the Cloudburst Formation. Krieger (1974c, d, e) described similar small landslides in the Winkelman 15-minute quadrangle in the San Manuel and Cloudburst Formations and called them megabreccias. Large landslides, extensively exposed in the Kearny quadrangle (Cornwall and Krieger, 1975a), were originally identified as bedrock faulted into basin deposits by Ransome (1919) and Wilson, Moore, and Cooper (1969).

The two large landslide masses in the Kearny quadrangle are here referred to as the northern landslide (pl. 1) and the southern (pl. 2) landslide. The southern landslide is composite. Smaller landslides crop out west of and stratigraphically below the larger ones (pls. 2, 3); other, more isolated ones are known in the Kearny and Crozier Peak quadrangles (pl. 1). The large landslides consist of abundant material derived from the Escabrosa Limestone and the Martin Formation, as well as smaller amounts of other rocks. In addition, the southern landslide contains abundant material derived from diabase, Troy Quartzite, and Williamson Canyon Volcanics, and minor amounts of other formations.

SAN MANUEL FORMATION

On the geologic map of the Kearny quadrangle, the San Manuel Formation adjacent to the landslides has been separated by Cornwall and Krieger (1975a) into seven units, four of alluvial deposits and three of playa deposits. The depositional history of the San Manuel Formation has helped to interpret the landslides, the environment in which they were deposited, and their probable source.

ALLUVIAL DEPOSITS

The alluvial deposits, typical of fans around the margin of a playa basin, are lithologically separable into granitic conglomerate, limestone conglomerate, quartzite conglomerate, and dark nongranitic conglomerate.

Granitic conglomerate (pl. 2) contains detritus of Ruin Granite, minor amounts of clasts of the Precambrian Apache Group and diabase, Creteceous and early Tertiary intrusive rocks, and locally Paleozoic limestone. Pebble imbrication and the progressive westward and northwestward coarsening of the conglomerate indicate a source from the west or northwest.

Limestone conglomerate (pl. 2) is composed of both Escabrosa and Naco Limestones and various amounts of other clasts.

Quartzite conglomerate (pls. 2, 3) is composed largely of clasts derived from the Apache Group, mostly the lower (Barnes Conglomerate) and middle members of the Dripping Spring Quartzite.

The dark nongranitic conglomerate (pl. 3) is composed of the Late Cretaceous Williamson Canyon Volcanics and Tortilla Quartz Diorite, Late Cretaceous and early Tertiary intrusive rocks (mainly rhyodacite and related porphyries), Tertiary(?) andesite, Paleozoic limestones, and some diabase and Precambrian sedimentary strata. The conglomerate becomes coarser grained southward and probably was derived from the south and southwest. It represents a lobe or fan that interfingers northward with the dark nongranitic playa deposits (pl. 3). Precambrian and Paleozoic sedimentary rocks, now exposed in the steeply dipping to overturned belt southwest of this area, mostly in the Crozier Peak quadrangle, probably were buried when the dark conglomerate was being deposited.

PLAYA DEPOSITS

The playa deposits are lithologically separable into dark nongranitic playa deposits, playa sandstone, and playa claystone.

The dark nongranitic playa deposits (pls. 2, 3) are identical in composition to the dark nongranitic conglomerate but are characterized by planar bedding surfaces (fig. 2). They are composed of interbedded sandstone, granule conglomerate, thin silt and clay seams, and some coarse conglomerate. Curled mud chips (some probably transported) are common in or on sandstone beds (fig. 3) and sand-filled mud cracks occur in granule conglomerate beds, some of them extending through a bed 0.3 m thick. The conglomerate beds range in thickness from 5 cm to 1 m. Large cobbles and boulders are concentrated in the middle of some beds. These conglomerate beds rest with remarkably smooth

FIGURE 2.—Typical bedding in dark nongranitic playa deposits, dipping 45° E. West side of Hackberry Wash, east of center of sec. 5, T. 5 S., R. 14 E.

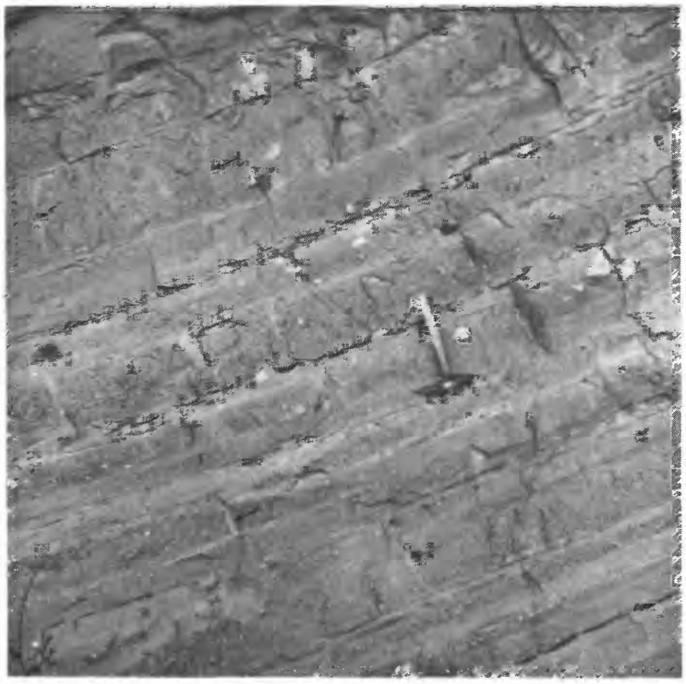

FIGURE 3.—Curled mud chips and sand-filled mud cracks (arrows) in dark nongranitic playa deposits indicate deposition in an alternately wet and dry playa environment. East side of Hackberry Wash, about 0.6 km north of south edge and 0.3 km east of west edge of sec. 33, T. 4 S., R. 14 E.

surfaces on sandstone or siltstone (fig. 4). The presence of mud chips and mud cracks prove that the dark nongranitic playa deposits formed in an alternately wet and dry environment, and the pronounced planar bedding surfaces indicate a flat lake or playa surface. The coarse conglomerate beds probably came out as mudflows into temporary lakes. Local pebble imbrication indicates a source from the southwest.

Playa claystone (pls. 2, 3) is brown to light brownish gray and very thin bedded; it contains some thin interbeds—mostly 1.25–2.5 cm thick—of gray sandstone and locally a few olive-gray beds of granule to small-pebble conglomerate, mostly less than 15 cm thick. Gypsum beds and veins 1.25–10 cm thick occur in the claystone west of and stratigraphically below the northern landslide 600–860 m north of its south end (pl. 2) and also below the southern landslide about 150 m south of the gulch that bisects it (pl. 3). The playa claystone, although containing some silt- to very fine sand-sized grains of granitic(?) quartz and feldspar, was probably derived largely from the same source as the dark playa deposits and dark conglomerate.

Playa sandstone (pls. 2, 3) is mostly a fine- to medium-grained light-gray to yellowish-gray poorly indurated thin-bedded to thinly laminated locally crossbedded sandstone. Thin beds and seams of brown claystone and layers of curled mud chips are common.

FIGURE 4.—Dark nongranitic playa deposits with coarse conglomerate bed; pebbles, cobbles, and small boulders are concentrated in middle of conglomerate bed, which rests with very smooth planar bedding surface on sandstone. Sandstone shows no evidence of having been channeled or disturbed. Mud cracks (arrow) occur in underlying massive sandstone; mud chips occur in overlying thin-bedded deposits. West side of Hackberry Wash, east of center of sec. 5, T. 5 S., R. 14E. (a little more than 1 km south of north edge of map, pl. 3).

The sandstone probably was derived from granitic rocks.

Within the Kearny quadrangle, the dark nongranitic conglomerate and the dark nongranitic playa deposits constitute a large part of the San Manuel Formation, underlying an area of at least 25 km^2; they accumulated to a thickness of over 1.8 km and contain a tremendous volume of detritus derived from Precambrian and Paleozoic sedimentary strata and Cretaceous volcanic rocks in a source area now largely stripped of these rocks.

Gypsum in claystone beneath, and claystone and sandstone that partly surround, the two large landslides indicate the approximate center of the playa basin at the time of emplacement. Because of the eastward dip and burial by younger deposits, the locations of the north and east margins of the playa basin are not known. The San Manuel Formation becomes coarser grained to the west and south. Later faulting has obscured the position of the west and south margins of the basin, but they must have been somewhere beyond the faults that dropped the San Manuel Formation down into contact with bedrock (pl. 1).

LARGE NORTHERN LANDSLIDE

The large northern landslide (pl. 2) crops out as a symmetrical steeply east-dipping lens consisting of Escabrosa megabreccia to the east and Martin megabreccia to the west, in normal stratigraphic sequence. It forms a narrow north-trending ridge (fig. 5) that is about 2.9 km long and as much as 250 m wide; the maximum stratigraphic thickness is about 150 m. The ridge exposes a section through the landslide at right angles to the direction of movement. The landslide rests with a smooth planar surface on underlying sandstone, claystone, and, at the extreme north end, on granitic and limestone conglomerate of the San Manuel Formation.

Escabrosa and lower Martin megabreccias in the large northern landslide form bold outcrops, whereas upper Martin megabreccia forms a slope (fig. 6). Escabrosa megabreccia consists mostly of angular fragments of white to light- and dark-gray fine- to coarse-grained fossiliferous limestone and dolomite, containing chert nodules. Except for the brecciation, it is typical of bedrock outcrops. Locally, thin distinctive beds of white limestone can be traced for at least 100 m.

Martin megabreccia consists of an upper part composed largely of shale, a lower part largely of dolomite, and a thin basal sandstone. It closely resembles the

FIGURE 5.—The large northern landslide, viewed from south; it stands as a steeply east-dipping narrow ridge overlying claystone and sandstone of San Manuel Formation. Ridgetop is mostly lower Martin megabreccia; upper Martin megabreccia and most of Escabrosa megabreccia (not visible) are east of ridge crest. Southernmost small slide block (pl. 2) shows up as thin white line (arrow) west of ridge crest. Base of southern landslide in right foreground.

Martin Formation exposed to the southwest in the northwestern part of the Crozier Peak quadrangle (Krieger, 1974c), suggesting a source from that direction. The slope-forming upper Martin megabreccia (fig. 7) is composed of light-olive-gray brownish-gray- to yellowish-brown-weathering shale and some grayish-orange to pale-brown marly and dolomitic beds at the top and bottom. The shale has been locally thickened or thinned; in places it has been squeezed out so that Escabrosa megabreccia rests directly on lower Martin megabreccia (pl. 2). Although some thin (0.3–0.6 m) beds of gray limestone in the shale have been disrupted and locally rotated, in many areas the shale appears to have been little disturbed.

Lower Martin megabreccia (fig. 7) consists of mostly angular fragments of aphanitic to fine-grained laminated light-olive-gray to yellowish-gray dolomite and limestone. A dark-gray crystalline limestone megabreccia, referred to here as the black bed, forms a distinct horizon near the base of the lower Martin megabreccia for nearly 1.6 km ranging in thickness from 0.6 to 3 m. Lithologically similar black limestone is prominent in bedrock outcrops in the northwestern part of the Crozier Peak quadrangle (Krieger, 1974c). It also forms part of the O'Carroll bed at the Christmas mine (fig. 1; Willden, 1964) and the ore horizon at the Magma mine at Superior (Peterson, 1969), about 10 miles north of Ray (fig. 1). At Superior it is 3–9 m thick and occurs 3–6 m above the base of the formation.

Martin sandstone megabreccia, 1.5–15 m thick locally, is present at or near the base of the northern slide block for a distance of about 1.6 km (pl. 2). It consists of light-brown to grayish-orange medium- to coarse-grained sandstone, dolomitic sandstone, and sandy dolomite, similar to basal sandstone in bedrock outcrops.

Beneath the Martin sandstone megabreccia in many places, but mapped only locally, is a thin layer of diabase megabreccia, and locally Troy megabreccia (too small to map). A lens of light-colored dolomite megabreccia, like that above the sandstone breccia, is present below it for about 150 m south of the latitude of hill 2,680. Although locally in bedrock outcrops sandstone is interbedded in light-colored dolomite, this lens may belong higher in the section, the sequence having been disrupted by preemplacement faulting.

A thin layer of upper Abrigo megabreccia underlies Martin sandstone megabreccia about 1 km south of the north end of the slide block (pl. 2). It is distinguished from Martin sandstone megabreccia by the presence of phosphatic brachiopods.

Rhyodacite megabreccia occurs as narrow sill-like masses near the contact between Escabrosa and Martin megabreccias and as crosscutting dikelike masses

FIGURE 6.—East face of north half of northern landslide, viewed from northeast. Landslide and individual lithologic units within it dip east. Bold outcrops to the north and low down to the south are Escabrosa megabreccia (A); slopes beneath it (to the west) are upper Martin megabreccia (B), underlain by lower Martin megabreccia (C). Williamson Canyon megabreccia (D), not in normal stratigraphic sequence, is between two peaks at right. San Manuel Formation east of landslide is largely covered with talus.

FIGURE 7.—East side of northern landslide, looking north from contact between Escabrosa and Martin megabreccias about 1.1 km south of north end of slide block. Lower Martin megabreccia (A) with crackle brecciation (lower left) is overlain by slope-forming upper Martin megabreccia, which here consists, from bottom to top, of yellow dolomite (B), brown shale (C), and locally brown and yellow fossiliferous dolomite and marly beds (D). Escabrosa megabreccia (E) is on top.

in Martin megabreccia. These sills and dikes are approximately in their original intrusive positions. Some rhyodacite megabreccia exhibits a chilled contact against the adjacent Escabrosa megabreccia.

Megabreccia derived from grayish-purple to brownish-gray andesitic volcanic breccia and agglomerate and grayish-green flows of the Williamson Canyon Volcanics is exposed in two places on top of Escabrosa megabreccia, 600 and 900 m north of the south end of the slide block. Although in most bedrock outcrops to the east it rests on the Pennsylvanian Naco Limestone, it may be in normal stratigraphic position here. Sill-like masses, shown on the map as Williamson Canyon megabreccia in the Escabrosa megabreccia, 700 and 900 m south of the north end of the slide block, are basaltic sills that are in their original intrusive position. They are questionably related to the volcanic rocks. The presence of Williamson Canyon megabreccia between Martin and Escabrosa megabreccias to the north is difficult to explain. Most of it is clearly derived from the Williamson Canyon Volcanics and as such is not in normal stratigraphic position. Some may represent the Tortilla Quartz Diorite that was intruded into the Paleozoic limestones; brecciated diorite may locally be difficult to distinguish from volcanic rocks.

In spite of the brecciation of the formations and local squeezing out of shale, the stratigraphic sequence of this slide block in most places is normal.

SMALL NORTHERN LANDSLIDES

Four small landslides are exposed west of (stratigraphically below) the large northern landslide (pl. 2). The two westernmost ones, 460 and 920 m long (half of the northern one is north of area shown on pl. 2), are composed of Ruin and diabase megabreccias. In the second one from the north, Pioneer megabreccia (sec. *A–A'*), and some breccia derived from the basal Scanlan Conglomerate Member (not mapped), appear to be in sedimentary contact with Ruin megabreccia. The relations in both northern slide blocks are similar to those observed in bedrock outcrops, where diabase was commonly intruded either as sills at or just above the Ruin Granite-Pioneer contact or as sill-like masses in Ruin Granite below but parallel to that contact.

The two small southern landslides consist largely of Naco megabreccia, but other formations are present, not in normal stratigraphic sequence. Locally there has been some mixing of lithologies. The northern landslide is nearly 920 m long and has a maximum outcrop width of about 30 m. Beneath the Naco megabreccia is a megabreccia, identified on the map as diabase but possibly consisting partly or largely of Williamson Canyon Volcanics and Tortilla Quartz Diorite. Dripping Spring or Williamson Canyon megabreccias locally overlie Naco breccia; Williamson Canyon Volcanics overlying and Tortilla Quartz Diorite intrusive into Naco Limestone are normal relations, the others are not. Ruin breccia, or possibly a coarse talus deposit, forms the north end of the lens. The southern lens is about 600 m long and has a maximum outcrop width of less than 8 m. In many places it is less than 3 m wide. Williamson Canyon, rhyodacite, and diabase(?) megabreccias, too narrow to map, underlie, overlie, and locally occur within the Naco megabreccia, and local rounded clasts of rhyodacite prophyry are enclosed in Naco megabreccia, suggesting that there was imbrication or some sort of turbulence during emplacement. The contact with underlying granitic conglomerate in both lenses appears smooth and planar in most places. Although the length to thickness ratio and the local mixing of lithologies of these two slide blocks suggest that they may have been emplaced as debris flows, the brecciation for the most part is similar to that in the large landslides. Because of their small volume, they may have been emplaced as small, somewhat turbulent landslides rather than as catastrophic avalanches as assumed for the large landslides.

LARGE SOUTHERN LANDSLIDE

The large southern landslide (pl. 3; fig. 8) is about 4 km long and extends about 300 m south of the map area. It has a maximum outcrop width of about 525 m and is made up of at least three slide blocks (fig. 9),

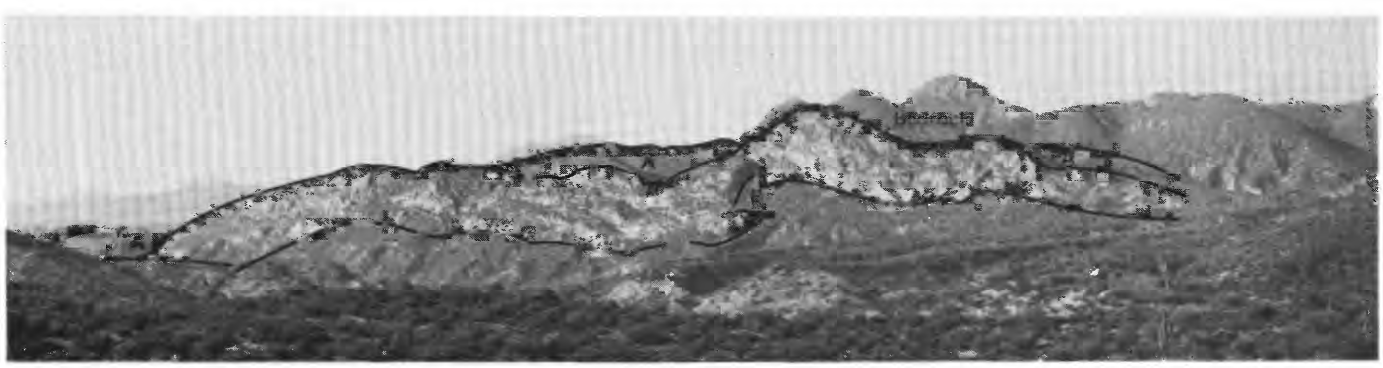

FIGURE 8.—Northern 1.8 km of east face of southern landslide. Escabrosa megabreccia forms rough outcrops. Martin, Troy, and diabase megabreccias (A) are locally visible near top of ridge. Higher hills in distance are bedrock. Talus-covered reentrant (B) probably represents an offset on a younger fault or faults. View looking southwest from east of Hackberry Wash.

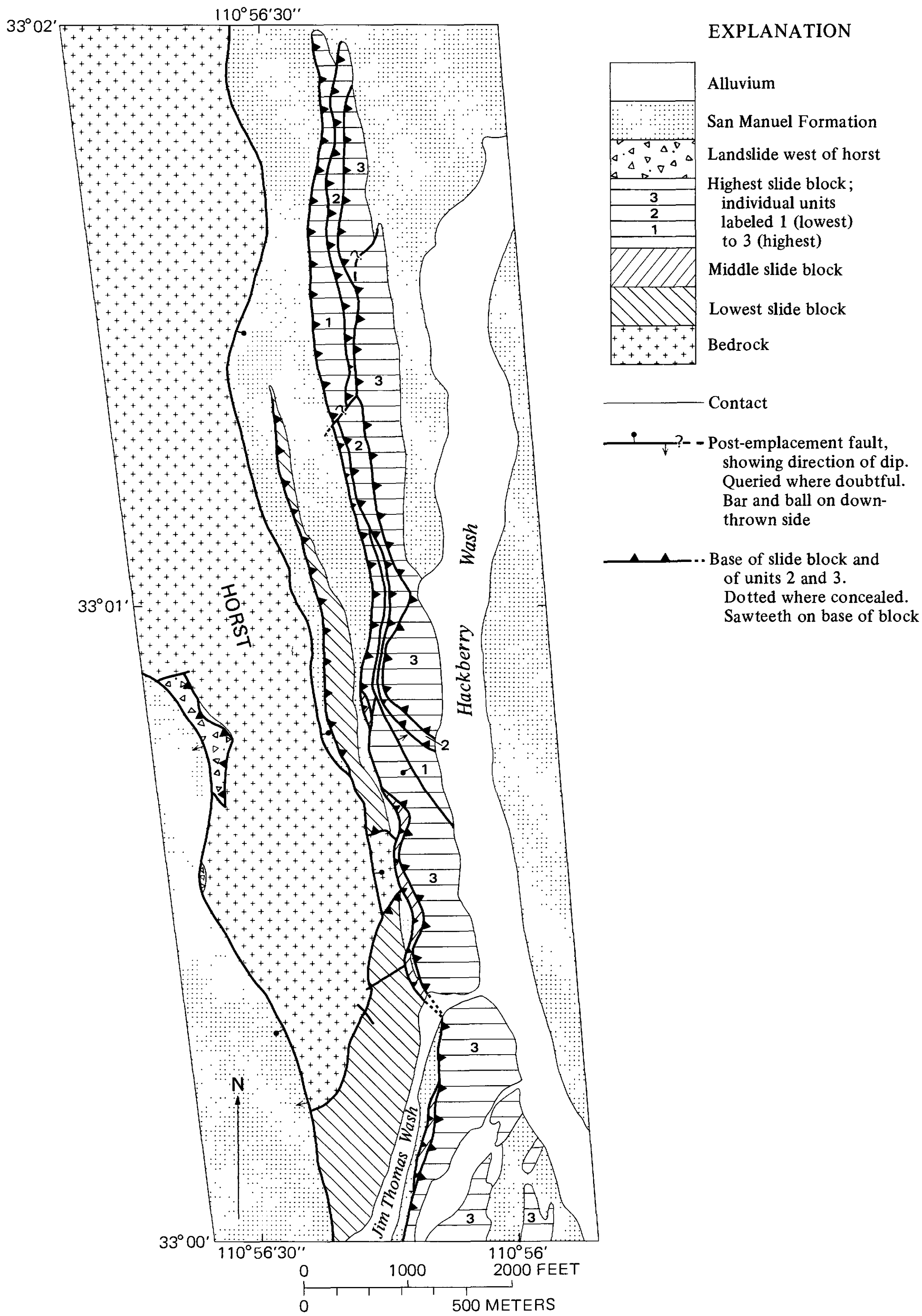

FIGURE 9.—Slide blocks in southern landslide, showing individual units in highest slide block.

separated in part by sedimentary strata. The slide block highest in the section constitutes the bulk of the landslide and contains three distinct units, the lowest of which probably represents a single slide block. The other two units may also represent individual slide blocks, but they could have formed by emplacement of a single block in which the formations had previously been disrupted by preemplacement faults, or possibly by imbrication during emplacement. They have been modified slightly by postemplacement faulting. The composite landslide consists of the same Paleozoic formations as exposed in the northern one, as well as more abundant masses of Troy, diabase, and Williamson Canyon megabreccias.[2]

LOWEST SLIDE BLOCK

The lowest slide block is separated into two segments by a prebasin topographic high. The northern segment is about 1.4 km long (including the two small outcrops north of the main mass) and at most about 100 m wide. It consists of Troy, upper and lower Martin, Williamson Canyon, and some Abrigo and Mescal megabreccias. The slide block rests on claystone and quartzite conglomerate, except at the south end, where both fault and sedimentary contacts with bedrock are exposed. Possibly the north half of the segment is a normal sequence: the upper Martin Formation could have been deposited on an island of Troy Quartzite in the Martin sea, and the Williamson Canyon Volcanics could have been deposited on an erosion surface. Elsewhere in this and the southern segment, the normal sequence is disrupted, mostly without any clear indication of how the disruption occurred. The southern segment contains the same formations except the Abrigo and Mescal megabreccias; some rhyodacite megabreccia is also present. This segment is also about 1.4 km long, extending about 300 m south of the map area, and is up to 200 m wide. The sedimentary contact with bedrock at the north end of the southern segment is not exposed; elsewhere the segment is in fault contact with bedrock or with dark nongranitic playa deposits.

MIDDLE SLIDE BLOCK

The middle slide block extends intermittently southward for nearly 1.6 km from northwest of Hackberry Spring. It consists entirely of Williamson Canyon megabreccia and has a maximum outcrop width of about 30 m. It rests, from north to south, on claystone, bedrock, claystone, the north end of the southern segment of the lowest slide block, and dark conglomerate. It is overlain by the highest slide block, except just north of Jim Thomas Wash, where dark nongranitic conglomerate separates the two slide blocks. The presence of this conglomerate and the contrast in lithology suggest that the middle slide block is a separate unit.

HIGHEST SLIDE BLOCK

The highest slide block is about 4 km long extending 245 m south of the map area. It rests on sandstone or claystone except where it is underlain by the middle slide block or by dark conglomerate. It consists of three parts, called units 1–3 (bottom to top), each of which appears to be a nearly normal stratigraphic sequence. The highest slide block contains the same formations found in the lowest slide block, and also diabase megabreccia in the north half. Unit 1 consists of Troy megabreccia overlain by lower and upper Martin megabreccias and underlain in many places by diabase megabreccia that contains some unmapped lenses of Mescal megabreccia. Unit 2 is composed of Troy and diabase megabreccia and some Mescal megabreccia. Unit 3 consists largely of Escabrosa megabreccia, locally underlain by a small amount of upper Martin megabreccia and overlain by thin lenses of Williamson Canyon and rhyodacite megabreccias. South of Hackberry Spring, the highest slide block consists largely of unit 3. Unit 2 and the middle slide block are exposed in the anticline on the north side of Jim Thomas Wash. South of Jim Thomas Wash, small lenses of Troy, upper and lower Martin, and Williamson Canyon megabreccias in Escabrosa megabreccia may represent preemplacement fault slivers.

Unit 1.—This part of the highest slide block extends about 2.4 km south to the Hackberry mine. It is separated into two nearly equal segments by a postemplacement(?) fault, which may connect with the fault to the northeast that offsets the Escabrosa and Williamson Canyon megabreccias (pl. 3, sec. *A–A′*). The northern segment is the most complete and has a maximum outcrop width of 92 m. It rests on sandstone of the San Manuel Formation along a very smooth planar contact that is exposed in a number of places (fig. 15). The segment consists of a largely normal sequence, from bottom to top, of diabase, Troy, and lower and upper Martin megabreccias, cut in one place by a dike-like mass of rhyodacite megabreccia. Some Mescal megabreccia is present beneath diabase megabreccia near the north end of the unit, and small unmapped masses of Mescal and Troy megabreccias occur in diabase near the south end of the segment. In the extreme north end, diabase megabreccia overlies Martin megabreccia and appears to wrap around it, as though the formations had rolled over during emplacement;

[2]Martin sandstone megabreccia was not observed at the base of lower Martin megabreccia in the southern landslide; the black bed was observed in only one place (fig. 11). Except for their occurrence within the landslide, some of the large masses of Williamson Canyon megabreccia would have been considered bedrock.

some Mescal megabreccia is out of stratigraphic place in the Troy megabreccia nearby.

The southern segment of unit 1 consists of Troy and lower Martin megabreccias, overlain at the south by upper Martin megabreccia. Near Hackberry Spring the unit consists of lower and upper Martin breccias and is separated from the underlying unit 3 by a post-emplacement(?) fault. This fault is responsible for the cutting out and repetition of units north of the spring.

Unit 2.—This unit extends about 2 km from the north end of the slide block nearly to Hackberry Spring and has a maximum outcrop width of about 60 m. It rests on unit 1, except at the north end where it is underlain by playa claystone. The unit consists of diabase megabreccia overlain and locally underlain by Troy megabreccia, but neither is continuous. Diabase megabreccia contains abundant small masses of Mescal and basalt megabreccias (Apache Group basalt), unmapped except for Mescal megabreccia at the north end and about 400 and 1,500 m south of the north end of the unit. In bedrock outcrops, diabase commonly encloses small lenses of these rocks; hence the relations in the unit probably are normal. At the north end of the unit, mescal megabreccia, however, is above Troy megabreccia, probably indicating some sort of mechanical separation. The Troy megabreccia that underlies diabase megabreccia south of the fault that cuts unit 1 is below small unmapped lenses of Mescal and basalt megabreccia. This could be due to inflation by diabase sills that uplifted the Apache Group relative to the Troy Quartzite rather than mechanical displacement. A lens of rhyodacite megabreccia, composed of somewhat rounded clasts, is at the north end of the unit. Diabase megabreccia at the north end of unit 2 was separated from the adjacent diabase megabreccia at the top of unit 1 because small Mescal and basalt lenses are abundant in unit 2 and absent in unit 1.

Unit 3.—This unit extends the length of the highest slide block and has a maximum outcrop width of about 185 m. It is separated into two parts by a post-emplacement fault exposed about 150 m northwest of Hackberry Spring. The unit consists largely of Escabrosa megabreccia, underlain in some places by a small amount of upper Martin megabreccia and overlain locally by Williamson Canyon megabreccia. Sill-like masses of rhyodacite megabreccia are present within and at the base of the Escabrosa megabreccia. In a few places a white megabreccia, similar to a distinctive white bed in bedrock outcrops, can be traced for a few hundred meters. South of the mouth of Jim Thomas Wash, unit 3 also contains lenses of Williamson Canyon, Martin, and Troy megabreccias out of normal stratigraphic sequence, and some dark nongranitic conglomerate apparently interbedded in the unit. Some of these anomalous stratigraphic features may be explained by the folding of slide blocks 2 and 3 and the enclosing San Manuel Formation. The fold and associated faults in unit 3 near the mouth of Jim Thomas Wash (fig. 10) are interpreted as postemplacement features because small folds occur in the dark nongranitic conglomerate associated with the unit both north and south of the wash. East of the map area the conglomer-

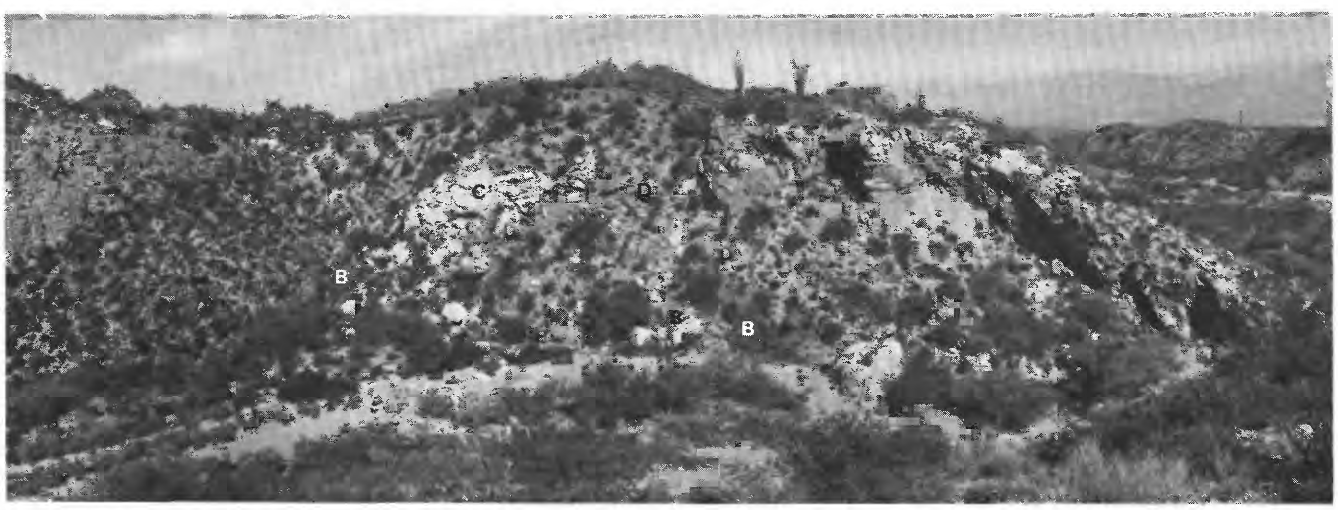

FIGURE 10.—View looking north across Jim Thomas Wash (foreground), just west of its junction with Hackberry Wash. On the left is lowest slide block (A), the upper part of which is composed of shattered Escabrosa megabreccia. Middle slide block (B), dark outcrops, composed of Williamson Canyon megabreccia, is west of and also near center of anticline, just above wash. Anticline is composed mostly of unit 3 of highest slide block; Escabrosa megabreccia (C) is underlain by upper Martin megabreccia (D). Talus covers much of the Martin and Williamson Canyon megabreccias and the playa clay and dark nongranitic conglomerate. Note contrast in types of brecciation in the same formation. Escabrosa Limestone on the left is greatly shattered and clasts somewhat rotated (see also closeup, fig. 13) whereas in the anticline it is little more than crackled.

ate is folded into small anticlines and synclines (Cornwall and Krieger, 1975a). This is the only place east of the horst block (fig. 9) where both megabreccia and enclosing sedimentary rocks show reversals from the steep eastward dips. The contact between Escabrosa megabreccia and overlying playa deposits about 600 m south of the north end of unit 3 (pl. 3, sec. *A–A'*; fig. 8) has been offset by a postemplacement fault. The small body of Williamson Canyon megabreccia exposed north of the fault probably rests on Escabrosa megabreccia, as it does in places south of the fault. This fault is shown as trending southwestward, for part of its length along the base of unit 3. It may connect with the fault to the southwest that offsets units 1 and 2. Branches of the fault may extend southward, parallel to some of the rhyodacite megabreccia "sills" in Escabrosa megabreccia. West of Hackberry Spring an 80° eastward-dipping high-angle reverse fault surface is exposed between Escabrosa megabreccia and the overlying lower Martin breccia of unit 1. Whether the dominant movement is dip-slip or strike-slip is unknown.

Units 1, 2, and 3 may have formed as three successive slide blocks, as a single slide block in which the units had been imbricated by preemplacement faulting, probably thrusting, or possibly by imbrication during sliding. Whether or not the highest slide block represents single or multiple slides, the disruption in sequence suggests considerable preemplacement faulting in the source area to the west. Because the Paleozoic and Precambrian sedimentary rocks that compose the slide blocks have been removed from this source area, it is not possible to prove that faulting occurred there. The presence of faults interpreted as tilted thrusts south and southeast of the Kearny quadrangle (Krieger, 1974a, 1974b, 1974c) suggests that the formations in the source area may also have been disrupted. The presence of claystone between units 1 and 2 at the north end of the highest slide block suggests two separate slide blocks. An alternative explanation is that the units are part of a previously disrupted slide block and that unit 2 was offset to the northeast over claystone after emplacement.

SMALL SOUTHERN LANDSLIDES

Small slide blocks are located west of, as well as on, the horst block. Those on the west side are, from north to south, (1) Mescal megabreccia, (2) undifferentiated Escabrosa, lower Martin, and Troy megabreccias, (3) Troy megabreccia, and (4) lower Martin megabreccia. The steep west dip of the slide blocks, the underlying claystone (sec. *C–C'*), and the overlying dark nongranitic playa deposits probably developed when the horst block was uplifted. The small masses of Troy and Mescal megabreccias on Tortilla Quartz Diorite bedrock probably are not xenoliths in the Tortilla. Their brecciation is similar to that in the other slide blocks. They probably are remnants of landslides that originally extended across the area of the horst.

MEGABRECCIA

Brecciation in the slide blocks and in the individual formations and beds that make up the Kearny landslides is pervasive but variable, both along strike and from bottom to top of a slide block. The rock is shattered into pieces of various size from fine sand to large blocks, and the finer material surrounding the larger clasts forms the matrix of the megabreccia. Matrix ranges from sparse to locally abundant. Most clasts in the megabreccias are less than 0.3 m in longest dimension; many are less than 0.15 m.

Crackle-brecciation, or three-dimensional jigsaw-puzzle brecciation (Shreve, 1966, 1968a), common in the Kearny landslides and described by Shreve as typical of many landslides of this type, contains angular rock fragments that fit tightly together with little or no matrix and with no rotation of clasts (lower Martin megabreccia, fig. 7). In places the rocks appear to have been only crackled (Escabrosa megabreccia in anticline, fig. 10). These crackle megabreccias grade into megabreccias in which clasts are separated by more

FIGURE 11.—Typical Troy megabreccia overlain by unshattered black bed, which shows distinct bedding. Many quartzite clasts are of uniform size (mostly less than 10 cm). Note hammer (outlined) for scale. Base of unit 1 of highest slide block, just south of fault that separates unit into two segments.

abundant matrix and locally rotated. In some places the clasts in megabreccia are fairly uniform in size (figs. 7, 11); in other places the size is variable (figs. 12, 13).

Some large unshattered blocks, which are rare, show distinct bedding (figs. 11, 14) parallel to the attitude of the megabreccia unit, indicating that the blocks have not been rotated. Most of the large unshattered blocks observed are near the base of the highest slide block of the southern landslide. Some of these unshattered blocks are more than 3 m long.

In contrast to the crackle megabreccias, some megabreccias have rotated clasts that are mostly angular but locally rounded (fig. 13). Even where clasts are rotated, matrix appears to fill the spaces between the clasts, and the megabreccias contain few voids. Although clasts at the top of the lowest slide block exposed along Jim Thomas Wash (figs. 10, 13) appear loosely packed, finer material may have been removed from the upper surface by erosion following emplacement. A few of the megabreccias with rotated clasts superficially resemble debris flows, but only locally is there any mixing of lithologic types (see discussion of small northern slide blocks composed largely of Naco megabreccia, p. 8 and pl. 2).

In spite of the generally pervasive brecciation and regardless of whether clasts have been rotated, individual beds can be traced for considerable distances. Examples are the black bed, a white bed in the lower part of the Escabrosa megabreccia (visible in places in the highest slide block), and the Martin sandstone megabreccia (pl. 2). All of these generally are thoroughly shattered; the sandstone megabreccia was traced for 1.6 km.

The amount of brecciation may depend on the original brittleness of the formation involved. For example, the Troy Quartzite (pl. 3) in the southern landslide is

FIGURE 12.—Lower Martin megabreccia with large angular fragments in finer grained matrix. North side of gulch, near north end of southern landslide.

FIGURE 13.—Escabrosa megabreccia with rotated clasts. More shattering may have occurred here because it was the unconfined top of lowest slide block. It grades downward into less shattered rock. West side of Jim Thomas Wash 470 m north of south border of plate 3.

FIGURE 14.—Unshattered block of Mescal Limestone showing distinct bedding parallel to attitude of slide block and of underlying sandstone. Near base of northern segment of unit 1 of highest slide block, north of fault that separates the two segments.

well shattered, except for the lower part which is less quartzitic and therefore less brittle. A formation may also be brecciated in different ways under different conditions, as illustrated in figure 10. The Escabrosa Limestone in the lowest slide block near the mouth of Jim Thomas Wash contains clasts that have been somewhat rotated and locally slightly rounded, but there is relatively little matrix (fig. 13). Possibly the limestone was more thoroughly fragmented here because it was the unconfined top of the lowest slide block. In the highest slide block to the east, nonrotated clasts fit tightly together and some of the formation is only crackled. The underlying shale from the upper Martin Formation may possibly have taken up the stresses and protected the limestone from greater shattering. In other parts of the landslides, however, limestone above shale is generally well shattered. The shale clearly protected thin limestone interbeds; the beds were broken into long blocks and locally rotated but not shattered.

CONTACT RELATIONS

In the Kearny quadrangle, contacts between individual slide blocks and the underlying playa and alluvial deposits appear to be smooth, tilted planar surfaces. However, most contacts can be located only to the nearest meter or two; therefore details cannot be observed, but the general impression in walking out contacts is of almost no relief. A few short segments of contacts are well exposed; here the underlying sedimentary strata (mostly soft sand and clay) show no evidence of having been channeled or in any way disturbed. Some of the areas where contacts are well exposed are shown on the maps by triangles (pls. 2, 3). The best exposures (fig. 15) are beneath the north end

FIGURE 15.—Knife-edge contact between diabase megabreccia (A) and underlying gray sandstone (B), largely concealed by talus (C). Sandstone shows no evidence of having been disturbed by landslide, and bedding is completely parallel to contact. Diabase and thin lens of rhyodacite megabreccia above diabase pinch out a short distance to the north, where Troy megabreccia locally rests directly on sandstone. Note typical brecciation of diabase. Base of southern landslide about 450 m south of north end.

of the highest slide block, especially 460 m south of the north end (pl. 3.)

SOURCE OF THE KEARNY LANDSLIDES

The Kearny landslides are derived mostly from Precambrian and Paleozoic sedimentary strata, diabase, and Williamson Canyon Volcanics. These rocks are widely distributed northeast of the Gila and San Pedro Rivers. They crop out a short distance southwest of the Kearny landslides but were buried during deposition of the older part of the San Manuel Formation; they are not exposed for 100 km to the southwest. These strata must once have extended across most of the intervening area. Before deposition of the San Manuel Formation, they had been repeated by thrusts, later tilted along monoclinal folds, faulted, and generally uplifted higher than the area to the east and northeast (Krieger, 1974a). From this elevated area the Precambrian and Paleozoic sedimentary strata were completely stripped during and after deposition of the San Manuel Formation, including its landslides. Much of the stripping may have been completed before all the San Manuel was laid down, as the younger part of the formation in both the Kearny quadrangle (Cornwall and Krieger, 1975a) and Crozier Peak quadrangle (Krieger, 1974c) is composed largely of granitic detritus. A western or southwestern source for the landslides is also indicated by the westward coarsening of the playa and alluvial deposits in which the landslides are interbedded. Still another reason for assuming a southwestern source is that the stratigraphy of the Martin megabreccia is similar to its bedrock stratigraphy in the northwestern part of the Crozier Peak quadrangle (Krieger, 1974c): an upper member largely of shale, a lower member largely of dolomite, and the black bed and underlying sandstone at the base. To the east the formation consists largely of shale (Krieger, 1968a–d).

EL CAPITAN LANDSLIDE

The El Capitan landslide is interbedded with basin deposits on the north side of Dripping Spring Valley, El Capitan Mountain quadrangle (pls. 1, 4); it slopes gently southward.

BASIN DEPOSITS

The basin deposits consist of alluvial fans and lakebeds of Tertiary age. Alluvial deposits that underlie and overlie the northern part of the landslide are conglomerate composed of Paleozoic limestone clasts. The conglomerate grades basinward into lakebeds that, near the center of the basin, consist of light-brown clay with variable amounts of interbedded silt and fine sand. A transition zone between conglomerate and clay, near the southern part of the landslide, is about 900 m wide. This zone consists of medium- to coarse-grained sandstone, granule and small-pebble conglomerate, freshwater limestone, lenses of silt and clay, and some thin rhyolite tuff beds. The transition zone, which probably reflects fluctuations in the level of the lake, is included in the lakebed facies because of the abundance of freshwater limestone beds and of interbeds of fine-grained material. The contact between alluvial and lakebed material is arbitrarily located.

The alluvial and lakebed deposits probably are of Miocene or Pliocene age. In some respects the lakebed facies resembles the Quiburis Formation along the San Pedro River (pl. 1) and the alluvial facies resembles some of the Big Dome Formation south of the Dripping Spring Mountains. These formations were assigned middle Pliocene and late Miocene ages, respectively, by Krieger, Cornwall, and Banks (1974; see also Cornwall and Krieger, 1975a, Krieger, 1974b, 1968d). According to the Cenozoic time scale of Berggren (1972), however, the Quiburis is late Miocene or early Pliocene and the Big Dome is middle Miocene.

THE SLIDE BLOCK

The El Capitan landslide is a thin undeformed partly dissected slide block (pl. 4; fig. 16) that still retains much of its original shape. The distal end probably split into lobes; the lobate appearance has been accentuated by subsequent erosion of the slide block and the enclosing basin deposits. The slide block is now about 3.8 km long. Its width increases from zero at the proximal end to 1.5 km near its distal end. The slide block is 5–10 m thick in the upper part but 10–15 m thick in the lower part (fig. 17), except in the southwestern part where it is locally at least 35 m thick.

The slide block consists of Escabrosa megabreccia underlain intermittently by lower Martin megabreccia. A thin zone of upper Martin megabreccia, not mapped separately, is present in many places and can be recognized by scattered flakes of shale on a narrow shelf or slope between limestone megabreccia above and dolomite megabreccia below, or abundant shale on a fairly wide slope. Thus, exposures in many places resemble bedrock outcrops of the Martin and Escabrosa Formations (fig. 18).

A small landslide composed of lower Martin megabreccia rests on alluvial deposits that overlie the proximal part of the El Capitan landslide. It apparently slid only a short distance. Brecciation is not nearly so pervasive as in the larger landslide and many outcrops resemble bedrock. It was not studied in detail.

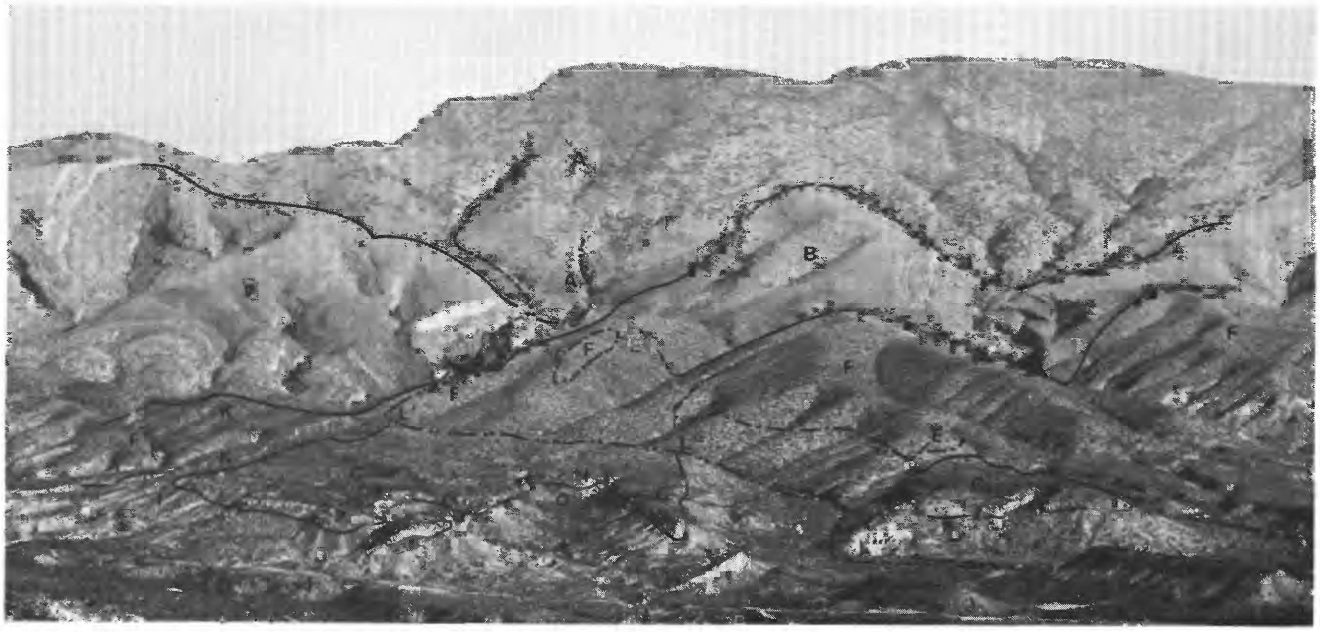

FIGURE 16.—Panorama of El Capitan landslide from Tam O'Shanter Peak (pl. 1), about 6.5 km southwest of south end of slide. Source area high on El Capitan Mountain is underlain by Troy Quartzite (A) and has been stripped of its cover of Paleozoic formations (B) (see fig. 27) by landslide and subsequent erosion. Southern part of landslide (C) rests on lakebeds (D); upper part (E) is interbedded with conglomerate (F); G is hill around which figures 18, 21, 23–26 were taken; H is location of figure 22; I is location of figures 19 and 20; J is State Highway 77; K is jeep road. Main gulch (*L–L'''*) is concealed by canyon rim where it dissects landslide from northwest to southeast (*L'–L''*).

FIGURE 17.—El Capitan landslide (cliff-forming layer near top of slope) interbedded with lakebeds; west side of eastern prong. Note regular character and extreme thinness (about 12 m) of landslide. Upper half consists of Escabrosa megabreccia, lower half of Martin megabreccia.

MEGABRECCIA

Crackle breccias are present in some places in the El Capitan megabreccia but are not as common as in the Kearny landslides. A general upward coarsening occurs in both Escabrosa and lower Martin megabreccias. Much of the Escabrosa megabreccia consists of mostly angular clasts that vary widely in size, even in a single exposure (fig. 19). Although many clasts are rotated, matrix is generally not abundant. Voids (fig. 20) in the megabreccia are fairly common; they may have formed during brecciation or later by removal of matrix during erosion. Very large unshattered blocks are common, especially on the top of the slide block; where blocks are unrotated and exposures are poor, the blocks resemble bedrock outcrops. Dolomite of the lower Martin Formation is more thoroughly shattered than the Escabrosa Limestone, but some large unshattered blocks occur in the upper part; some of them are rotated. Fine-grained almost gougelike material (figs. 18, 21), not observed in the Kearny landslides, occurs at and near the base of the lower Martin megabreccia, especially near the distal end of the slide block. The gouge contains sparse to abundant, small, mostly angular carbonate and chert clasts. This material is generally lighter colored than the coarser megabreccia. Subparallel sheeted zones (figs. 21, 22) are also common in lower Martin megabreccia and less so in Escabrosa megabreccia. They were probably zones of considerable movement within the slide block.

CONTACT RELATIONS

Contacts between the basin deposits and the overlying slide block are generally not well exposed, except around the distal end, where exposures in many places are excellent. The contact appears to be one of little relief (fig. 17) in the proximal two-thirds of the land-

FIGURE 18.—Southern part of El Capitan landslide, showing typical exposures of formations composing landslide. Escabrosa megabreccia (A) at top is underlain by upper Martin megabreccia (B, slope) and lower Martin megabreccia (C, lower cliff). Southernmost tip (right) is keel shaped (see fig. 23). In center, contact with lakebeds (D) is nearly horizontal. Light areas (E) in and near base of breccia are gougelike zones (see fig. 21). To the left contact dips steeply east (light areas are sandstone dikes, F) and beyond picture contact rises so that Escabrosa breccia rests on lakebeds. West side of southernmost isolated mass, east of center of west edge of sec. 26, T. 3 S., R. 15 E. Approximate distance across picture is 100 m.

slide. The contact under the distal one-third, on the other hand, has considerable relief. The greatest relief, 15 m or more, appears to depend on the presence or absence of Martin megabreccia above the lakebeds (pl. 4). Some of the relief is due to the apparent pulling apart of the Martin megabreccia at the base of the slide, causing the soft lakebeds to fill in the resulting space. Locally Escabrosa megabreccia drapes down over lower Martin megabreccia onto the lakebeds, suggesting that the Escabrosa slid over the underlying units (fig. 22) as the slide block came to rest. The southernmost end of the isolated mass (fig. 18) is keel shaped; lakebeds and the lower Martin megabreccia are tilted eastward on the west side and westward on the east side (figs. 23, 24). The bending of the slide block suggests that it was flexible when emplaced. Underlying lakebeds and a conglomeratic mudflow have locally been squeezed up into the overlying slide block (figs. 18, 25). In other places the lakebeds were thrown into folds (fig. 26).

Structureless mudflowlike material with subrounded and angular clasts of limestone is exposed at the base of the south half of the slide block (figs. 21, 22, 24). It ranges in thickness from 0 to about 6 m. Locally it is thickest where Martin megabreccia is absent.

FIGURE 19.—Escabrosa megabreccia, southern part, just west of line between secs. 26 and 27, T. 3 S., R. 15E. Note wide variation in size of clasts.

FIGURE 20.—Closeup of Escabrosa megabreccia in general area of figure 19. Clasts are surrounded by varying amounts of matrix. Voids may represent original porosity or result from subsequent erosion.

FIGURE 21.—Gougelike zones (A) at base of darker colored lower Martin megabreccia. Thin bed of conglomeratic mudflow material (B) at base rests on undisturbed lakebeds (C) largely concealed; note sheeted zone (D) in megabreccia. See hammer for scale (details of central part of fig. 18).

When first observed, this material was interpreted as indicating some erosion of the basin deposits before emplacement of the megabreccia. However, the presence of identical lakebed and alluvial material above and below the slide block indicates little or no interruption of basin filling before or after emplacement. The mudflow material is now believed to represent alluvial material that was picked up by the landslide and carried forward over the lakebed material. The angular clasts probably were derived from the landslide; the rounded pebbles and rare large cobbles must have come from the limestone conglomerate that underlies the proximal half of the slide block. They clearly are waterworn clasts, but they have not been impacted during transport; they were surrounded and protected by the mudflow material, which may include some churned-up lakebeds.

SOURCE AND VOLUME OF THE EL CAPITAN LANDSLIDE

The source of the El Capitan landslide was on the south side of El Capitan Mountain (pl. 1; figs. 16, 27), 1.8–3 km north of and probably 1,500 m to more than 3,000 m above its proximal end, from which it descended southward 3.8 km to its distal end 300 m below. The slope on which it slid may have had a dip of 6°–8° in its upper part (pl. 4, secs. *A–A′* and *B–B′*) but only 1°–2° in its lower half.

Before filling of the Dripping Spring Valley and emplacement of the landslide, the Mescal Mountain block (pl. 1) had been tilted 20°–30° southwestward, and most of the Naco Limestone and upper part of the Escabrosa Limestone had been stripped from the source area. Strata below the Martin Formation, however, had not been exposed, as indicated by the absence in the alluvial deposits to the south of clasts derived from older rocks. The source area is now underlain by dissected Precambrian Troy Quartzite (figs. 16, 27). Any Cambrian Bolsa and Abrigo Formations originally present and any Devonian Martin and Mississippian Escabrosa Formations not removed by the landslide have since been eroded. The total thickness of the Escabrosa in the source area probably was not much more than 60 m. This is suggested by the amount of the formation present beneath a few meters of conglomerate that underlies the upper part of the slide block and in bedrock outcrops to the east and west of the northern tip. An equal thickness of the Martin Formation prob-

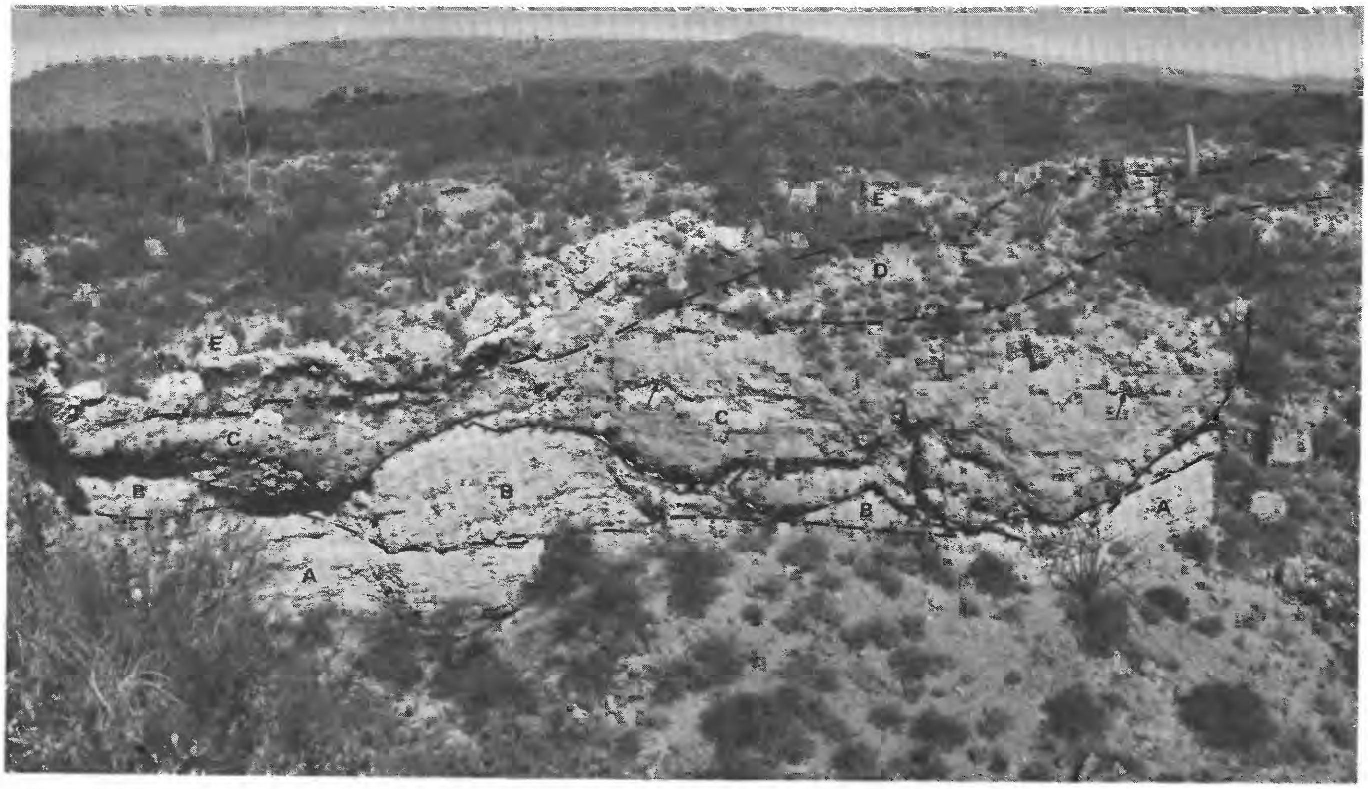

FIGURE 22.—Typical exposure of distal part of slide block, showing contact relations with well-bedded fine-grained alluvial material (A) and structureless conglomeratic mudflow (B), which locally has been squeezed up into overlying megabreccia. Note sheeted zones (arrows) in lower Martin megabreccia (C). Slope of upper Martin megabreccia (D) is in center and right side of picture, where it is overlain by Escabrosa megabreccia (E, light colored). To the left the Escabrosa megabreccia is draped down over lower Martin megabreccia. Looking north at contact, west side of western branch of gulch, 170 m north of south border and 480 m east of west border of sec. 23, T. 3 S., R. 15 E.

ably was involved in the landslide. Thus, a block about 120 m thick was transformed into a mass of megabreccia whose average thickness was perhaps 15 m. Assuming an areal extent of $\frac{1.5\times 3.8\ \text{km}^2}{2}$, the volume of the debris would be 40×10^6 m^3. The block that produced this volume of debris may have had an areal extent at right angles to bedding of perhaps 400×900 m; if, however, the debris included considerable porosity, the volume of the source block would have been somewhat less. During emplacement, the formations were thinned by lateral and forward spreading out of the landslide material. This produced the extreme thinness (5 to locally 35 m thick) of the slide block in relation to its original thickness in the source area (120 m) and to its horizontal extent, a feature typical of many avalanche deposits. The source block may have separated along a bedding plane and joints at right angles to bedding, or along a curving plane, possibly explaining the greater thickness of the southwestern part and the absence of the Martin megabreccia on the upper northern part.

ORIGIN AND MODE OF EMPLACEMENT OF CATASTROPHIC LANDSLIDES

Lenticular or tabular masses of unusual brecciated rocks similar to the Kearny and El Capitan landslides are widespread in and around Cenozoic basins in the southwestern United States. Diverse origins have been suggested, including thrust sheets, gravity slides, and landslides. Noble (1941) first described a mosaic of large, minutely shattered blocks in Death Valley as "chaos" and interpreted it as part of a composite thrust plate. At least part of the "chaos" of Noble (1941) was reinterpreted as debris flows (Noble and Wright, 1954). Similar outcrops have also been interpreted as debris waves and landslip masses (Jahns and Engel, 1949), sedimentary landslides (Grose, 1959), sedimentary breccias of landslide or mudflow origin (Creasey, 1965), sedimentary breccias or landslide deposits derived from areas of great relief (Moores (1968), and landslides and gravity slides (Hall, 1971). The monolithologic character of many of the breccias has been recog-

FIGURE 23.—East side of keel-shaped prong (southernmost isolated mass) showing tilted lower Martin megabreccia (A), underlying conglomeratic mudflow material (B), and lakebeds (C) (largely concealed). A short distance below contact the lakebeds are horizontal. Conformity of lithologic units in megabreccia to contact suggests that slide block was flexible when it came to rest.

FIGURE 24.—Tilted conglomeratic mudflow (A) and overlying lower Martin megabreccia (B), lower part of which is locally gougelike (C), east side of keel-shaped tip of slide block.

nized (Jahns and Engel, 1949, 1950; Hewett, 1956; Grose, 1959; Kupfer, 1960; Hall, 1971). Following Longwell (1951), they have been called megabreccia by Kupfer (1960), Burchfiel (1966), Krieger (1974c, d, e), and Cornwall and Krieger (1975a). Many of these large breccia masses are now known to be of landslide origin, but whether they all moved very rapidly (up to 335 km/hr) and were nonturbulent is uncertain.

An origin as catastrophic avalanches has been proposed for some landslides by Shreve (1966, 1968a, b), who studied the prehistoric Blackhawk and the underlying Silver Reef landslides in southern California, and the Sherman landslide triggered by the 1964 Alaska earthquake. He concluded that the prehistoric landslides and many modern ones, such as the Sherman, the 1881 Elm, Switzerland, and the 1903 Frank, Alberta, Canada, landslides, have many features in common and must have had a common origin. They clearly started as huge rockfalls that traversed the gently inclined slopes below at speeds estimated at 105–338 km per hour (Shreve, 1966, p. 1640). Single large blocks were fractured by the impact and subsequently not much deformed, producing the pervasive crackle brecciation ("three-dimensional jigsaw-puzzle effect"). Shreve interpreted the low friction, high speed, flexible nondeforming motion, and great distances traveled on gentle slopes as due to sliding on a thin, easily sheared lubricating layer of compressed air. This air lubrication greatly reduced friction on the underlying surface. The sudden stop was due to rapid escape of air.

Shreve (1968a, p. 30; 1966, p. 1641) emphasized the fact that landslides of the type he describes slid rather than flowed. If they had flowed, the material beneath the forward part of the landslide should have arrived there by way of the upper surface. However, he found a wedge of distinctive material at the base of the distal end of many landslides of the Blackhawk type. This material could only have come from beneath the proximal part of the landslide. This wedge of "bulldozed and transported debris" was cited by Shreve as further proof that these landslides did not flow.

Shreve (1968a, p. 37) discussed the possibility of other lubricants to reduce friction on the bottom of the slide, such as water and mud, known to have been present beneath the Frank slide. However, he doubted that water and mud could have been present beneath many of the other landslides. Shreve also stated (1968a, p. 43) that a basal layer of lower permeability must be present in order for air-layer lubrication to occur. It can consist of various materials, such as sandstone (Blackhawk), soil and mud (Elm and Frank), or dirty snow (Sherman) scraped up from beneath the upper parts of the landslides.

FIGURE 25.—Sandstone dike (A), composed of disturbed lakebeds mixed with conglomeratic mudflow and some angular megabreccia clasts, has been squeezed up into overlying megabreccia (B). Conglomeratic mudflow (C) at left separates megabreccia from underlying lakebeds (D).

Plafker (1977) concluded that air lubrication, as proposed by Shreve (1968a), or fluidization within the avalanche mass, as suggested by Kent (1966), are the only mechanisms proposed that account for the low ratio of vertical fall to horizontal runout. This ratio has been used by Shreve and others as the coefficient of friction. Plafker also summarized the important geomorphic and lithologic criteria that distinguish catastrophic avalanche deposits from other types of landslides or debris flows.

The presence of large avalanche deposits on the moon (Howard, 1973), where neither water nor air was available as a lubricant, led Hsü (1975) to propose reduction of frictional resistance by colliding blocks dispersed in a dust suspension. Shreve (1968a, p. 44, 1968b; and R. L. Shreve, oral commun., 1975), however, believed that neither Kent's nor Hsü's theory can be the primary mechanism in landslides of the Blackhawk type because fluidized material flows rather than slides.

Data presented by Plafker (1977), Shreve (1966, 1968a), and others have been used to compile table 1, which compares the Kearny and El Capitan landslides with some catastrophic avalanches. The movement in some of them may have been turbulent. For instance, Crandell and Fahnestock (1965) refer to the 1963 avalanches from Little Tahoma Peak, Wash., as rock-

FIGURE 26.—Folded lakebeds (A) beneath lower Martin megabreccia (B). Northeast side of southernmost isolated mass of westernmost prong, north of where Martin megabreccia is absent (pl. 4).

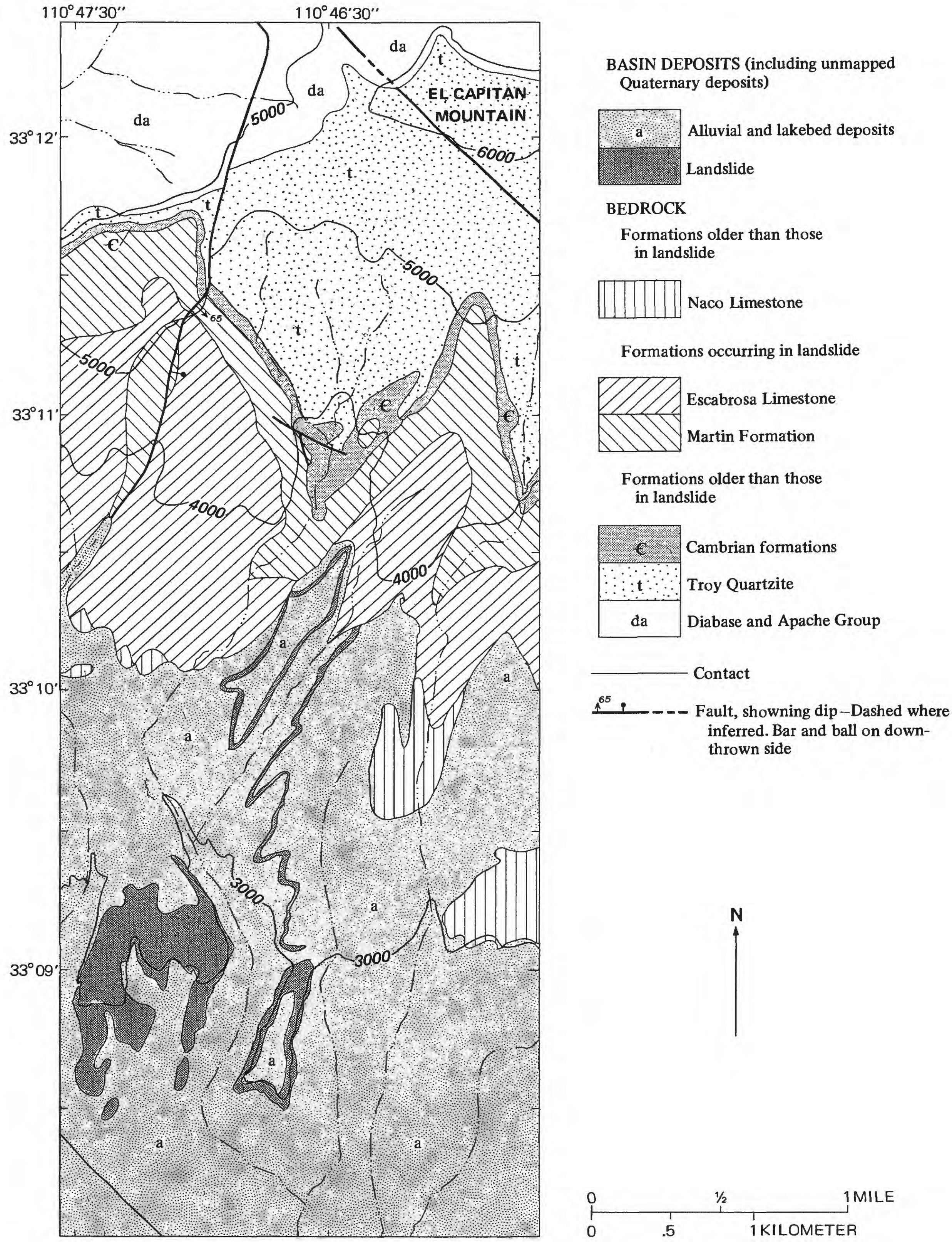

FIGURE 27.—El Capitan landslide and its source area on El Capitan Mountain. Reduced from geologic map of El Capitan Mountain quadrangle (Cornwall and Krieger, 1977).

TABLE 1.—*Distinctive features of catastrophic avalanches*
[× =observed]

Landslide	*Historic*				*Prehistoric*			
Location and reference	Elm, Switzerland (Shreve, 1968a; Heim, 1932)	Frank, Alberta (Shreve, 1968a)	Little Tahoma Peak, Wash. (Crandell and Fahnestock, 1965)	Sherman Glacier, Alaska (Shreve, 1966; Plafker, 1977)	Blackhawk, Calif. (Shreve, 1968a)	Saidmarreh, Iran (Harrison and Falcon, 1938)	El Capitan, Ariz.	Kearny, Ariz.
Date	1881	1903	1963	1964	Pleistocene(?)		Late Miocene(?)	Early Miocene(?)
Geomorphic features:								
Very thin sheets relative to areal extent.	×	×	×	×	×	×	×	Probable.
Lobate form	×	×	×	×	×	×	×	Do.
Relatively low relief of lobes from head to toe.	×	×	×	×	×	×	×	Do.
Arcuate ridges and furrows.	×	×	×	Not pronounced	×	Not mentioned	Not observed	Not observed.
Pressure ridges and distal rim.	×	×	Not mentioned	×	×	do	do	Do.
Movement up or over ridges or slopes.	×	×	×	×	×	×	No hills in its path.	Not known.
Lateral ridges	×	×	Probable		×	Not mentioned	No, possibly eroded.	Do.
Volume of deposit in millions of cubic meters.	11	37	11	26	283	20,840	40	Do.
Area of deposit (km²).	.6	2.7	2.5	8.5	14.0	165.0	2.8	Do.
Maximum vertical drop (km).	.5	.9	1.9	1.1	1.3	1.0	1.3	Do.
Maximum horizontal distance moved (km).	1.6	3.2	6.9	5.3	9.7	15.6	6.8	Probably large.
V/H[1] or coefficient of friction.	.26	.28	.27	.21	.13	.10	.19	Not known.
Minimum velocity (km/hr).	160	180	155	185	120	335	Not known	Do.
Lithologic features:								
Angularity and poor sorting of clasts including exceptionally large blocks.	×	×	×	×	×	×	×	×
Limited amount of, or absence of, abrasion of constituent clasts.	×	Clasts are bruised.	Not mentioned	×	×	×	×	×
Similarity of rock types to source area, except for material picked up en route.	×	×	×	×	×	Probably	×	×
Crackle breccia-tion.	Not observed	Not observed	Not mentioned	×	×	Not mentioned	×	×
General absence of size sorting from proximal to distal end of deposit.	×	×	do	×	×	do	×	Probable.
Relic stratigraphy (local homogeneity).	×	×	do	×	×	do	Pronounced	Pronounced.
Local internal imbricate structure, especially near distal margin.	×	×	do	×	×	do	Probable	Not known.
High porosity	Not mentioned	Not mentioned	× (due to inclusion of air and snow).	Relatively nonporous, except near surface.	Not mentioned, but less recemented than underlying Silver Reef slide.	do	No	No.
Remarks	Destructive to life and property; triggered by quarry operations.	Destructive to life and property.	Composed of a series of avalanches, at least one of which probably slid on an air cushion.	Deposited largely on glacier. Triggered by earthquake.	Resembles many monolithologic breccia deposits of southwestern United States.	Largest known terrestrial avalanche deposit.	Preservation of stratigraphic sequence.	Best examples of preservation of stratigraphic sequence.

[1]Ratio of net vertical drop (from top of source scar to toe of avalanche deposit) to horizontal distance traveled.

fragment flows, some of which probably rode on a cushion of air. Use of the term "flow" implies to me some turbulence within the mass.

The absence of mixed lithologies, the preservation of stratigraphic sequence, and the long distances traveled indicate that the Kearny and El Capitan landslides slid on a lubricating layer of some sort and that their motion was nonturbulent. The undisturbed character of the contact beneath the Kearny landslides is evidence of little differential pressure exerted by the slide block and indicates that the slides were not in contact with the underlying soft clay and sand until they came to a sudden stop as the air escaped. The Kearny landslides, because of their present attitude, do not exhibit many of the characteristic geomorphic features of catastrophic avalanches, but their presence out in a flat playa indicate a long runout. Most of the lithologic features listed in table 1 are very characteristic of both the Kearny and El Capitan landslides. High porosity, however, is not characteristic of them or of the Silver Reef landslide that underlies the Blackhawk. Shreve (1968a, p. 16 and 17) stated that the Silver Reef is completely recemented but only the surficial 3–5 m of the Blackhawk is cemented, suggesting that the amount of cementation, and therefore the amount of porosity, is due to the age of the landslide. The El Capitan and Kearny landslides have a closely packed matrix around and of the same composition as the clasts, thus a very low porosity. The absence of voids may have been due to a relatively complete lack of turbulence during emplacement. There appears to be little later cementation.

CONCLUSIONS

An origin as catastrophic avalanches is proposed for the Kearny and El Capitan landslides because of their similarity to some known catastrophic avalanches that traveled at high speed for long distances on gentle slopes.

The El Capitan slide block unquestionably originated as a landslide. Because the Kearny slide blocks are interbedded in playa and alluvial deposits, they also must be of landslide origin. Any mode of emplacement proposed for the landslides must explain the following features. The landslides clearly moved as nonturbulent masses, as shown by thin beds that can be traced for more than a kilometer, by the preservation of stratigraphic sequence, and by the absence of mixed lithologies within a slide block. The exposed parts of the Kearny landslides show little evidence of having exerted differential pressure on the underlying clay and sand (fig. 15) on which they came to rest: These soft sediments were not disturbed, nor were they injected into the overlying megabreccia as sandstone dikes. The proximal part of the El Capitan landslide, likewise, did not disturb the underlying sediments, perhaps in part because these sediments were alluvial fans that were less likely to be disturbed than finer grained softer sediments. Differential pressure at the distal end of the El Capitan landslide, however, was sufficient to throw the underlying lakebeds into folds (fig. 26) and to force them into cracks in the megabreccia (fig. 25).

The conglomeratic mudflow beneath the distal part of the El Capitan landslide may have served as the lubricant during emplacement, but nothing similar was observed in the Kearny landslides. Air lubrication would result in an abrupt stop as air escaped and could produce the features seen in the distal end of the El Capitan landslide. The mudflow material is interpreted as "bulldozed and transported debris" characteristic of the landslides Shreve (1968a, p. 30) studied. It may also have served as the basal layer of lower permeability that, according to Shreve (1968a, p. 43), must be present beneath a landslide for air-layer lubrication to occur.

The El Capitan landslide probably started as a rockfall rather than as a rockslide along a bedding plane. It seems unlikely that sliding would have resulted in a high enough speed to account for the horizontal distance traveled, and it is doubtful that sliding alone would result in the pervasive brecciation found in the landslide; but sliding may have produced the gougelike brecciation near the base of the landslide at its distal end. The pervasive brecciation in the Kearny landslides probably resulted from rockfall impact. Conceivably, the rocks could have been brecciated during thrusting or faulting prior to emplacement, but no such prior brecciation occurred in the El Capitan source area.

The force with which the distal end of the El Capitan landslide plowed into the underlying lakebeds, developed sheeted zones in the megabreccia, and caused the Escabrosa megabreccia to drape down over lower Martin megabreccia and locally onto the lakebeds suggests that the landslide mass was traveling at high speed and came to an abrupt stop. Other features in the El Capitan landslide that must be considered are (1) the flexible character of the landslide, as indicated by the bending of the distal end as it plowed into the lakebeds; (2) the significance of the conglomeratic mudflow material at the base of the landslide; (3) the relief on the lakebed surface which in places reflects the presence or absence of Martin megabreccia beneath the Escabrosa megabreccia; (4) the pervasive brecciation, including the crackle brecciation, and (5) the gougelike zones. Finally, many of the large breccia masses in the southwestern United States should be reexamined to determine whether they show evidence of turbulent or nonturbulent movement.

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