Structural Geology of the Santa Rita Mountains, Southeast of Tucson, Arizona

GEOLOGICAL SURVEY PROFESSIONAL PAPER 748

Structural Geology of the Santa Rita Mountains, Southeast of Tucson, Arizona

By HARALD DREWES

GEOLOGICAL SURVEY PROFESSIONAL PAPER 748

A description of the abundant and locally complex systems of faults, folds, and structurally controlled intrusives and an analysis of their development

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1972

UNITED STATES DEPARTMENT OF THE INTERIOR

ROGERS C. B. MORTON, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

Library of Congress catalog-card No. 72-600231

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402
Stock No. 2401-00239

CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

TABLE

STRUCTURAL GEOLOGY OF THE SANTA RITA MOUNTAINS, SOUTHEAST OF TUCSON, ARIZONA

By Harald Drewes

ABSTRACT

The Santa Rita Mountains and the hills to the southwest are underlain by an extensive sequence of sedimentary, volcanic, and metamorphic rocks of Precambrian to Holocene age. This sequence is more complete than any similar sequence in other mountains of southeastern Arizona. The structural record of the area is also extensive. Faults are the most abundant structural features; intrusive bodies are numerous, and many of them are structurally controlled; and folds are common in some parts of the mountains. The structural features, however, have not obliterated the stratigraphic record, because areas of complexly deformed rocks are separated by areas of only slightly deformed rocks. The succession of structural events is thus decipherable, and many of the events are geologically closely dated by radiometric ages of the igneous rocks and by a few faunal ages of the sedimentary rocks. The Santa Rita Mountains are, therefore, a key area for understanding the regional tectonic development.

The major structural features of the Santa Rita Mountains are the northwest-trending high-angle fault zones—the Santa Rita fault zone to the southwest and the Sawmill Canyon fault zone to the northeast. These fault zones are of Triassic to about Paleocene age. They separate three major structural units whose general attitudes and internal minor structural features differ considerably from each other. The Santa Rita fault zone contains a record of great vertical movement and of possible lateral movement; however, successive plutonic intrusions have obliterated all but small remnants of this zone. The Sawmill Canyon fault zone contains a record of repeated vertical movement, some thrust faulting, and possibly some left-lateral movement.

The southwestern major structural unit, lying southwest of the Santa Rita fault zone, contains two areas in which faulting and magmatic activity are closely related. The first of the two areas, the San Cayetano Mountains–Grosvenor Hills area, was both intruded and covered by a granodiorite-rhyodacite complex of late(?) Oligocene age. After the time of magmatic activity, deep-level intrusives of the San Cayetano Mountains were raised along a large normal fault to the level of the shallow intrusives of the Grosvenor Hills area and the Grosvenor Hills Volcanics. Abundant small normal faults border some of the shallow intrusives, chiefly laccoliths, that were emplaced in the volcanic pile. Several graben blocks foundered into parts of the volcanic pile. In the second of the areas, the Montosa Canyon area, remnants of a thrust plate and tear fault show evidence of both northeastward and southwestward transport during Late Cretaceous to early Tertiary time. The younger southwestward movement was accompanied by the emplacement of an extensive igneous sheet containing abundant and large exotic blocks, believed to be largely foundered remnants of the roof of a shallow sill that was emplaced beneath the thrust plate about the time that the thrust plate moved southwestward. Large stocks intruded the Montosa Canyon area volcanic complex only a few million years after the last major volcanic eruption.

The central major structural unit, between the Santa Rita and Sawmill Canyon fault zones, is for the most part a simple eastward-dipping homoclinal block. In the northeast corner of the unit, Upper Cretaceous rocks are tightly folded along northwestward-trending axes. Several swarms of dikes and one of quartz veins, all of early Tertiary age, trend east to northeast across the unit.

The northeastern major structural unit, northeast of the Sawmill Canyon fault zone, is cut by many northwest-trending tear and normal faults, as well as by thrust faults of two ages. The rocks in thrust plates of late Late Cretaceous age are disharmonically folded, chiefly along northwest-trending axes and southwest inclined axial planes, showing that the plates were transported northeastward. Small stocks cut some of these thrust faults. Other thrust faults and northwest-trending left-lateral tear faults of late Paleocene age show evidence of a northwest transport direction. Some of these faults cut the stocks. Plugs and dikes associated with ore deposits intrude many of the younger faults and the axial planes of some folds. Structural features are especially complex where younger faults that are associated with northwest transport are superposed on segments of older faults or folds associated with northeast transport. Inconspicuous or short range-front faults lie along both flanks of the northern part of the mountains.

The tectonic development of the area, indicated by an analysis of the structural record presented here and the sedimentary record presented in supplementary reports, is similar to that of the surrounding region, and only the local record of the development during the Mesozoic is more complete than the regional record. The most ancient rocks, the Pinal Schist and Continental Granodiorite, show effects of the Mazatzal Revolution, which are typical of central Arizona. Alternating upward and downward epeirogenic movements throughout the Paleozoic Era are recorded by a marine sequence whose continuity is interrupted by several disconformities. Strong vertical movements, largely on faults, occurred at intervals from the Triassic to the Early Cretaceous; two stocks were injected into the rocks of the area, at about the end of the Triassic and during Middle Jurassic time.

During the Laramide Orogeny, which lasted from about 90 to 53 m.y. (million years) ago, the area was severely deformed. The orogeny apparently took place in two phases, an early (Piman) phase and a late (Helvetian) phase, which were separated by a period of tectonic quiescence 10–20 m.y. in duration. The Piman phase began with folding in the early Late Cretaceous and culminated with northeast-directed thrust faulting of what was probably a single relatively thin plate mainly composed of bedded rocks. Abundant subsidiary tear faults and folds deformed the plate during the Piman phase, and some favorably oriented segments of older faults were reactivated. The Piman phase ended

with the emplacement of several large stocks in the late Late Cretaceous. The Helvetian phase of late Paleocene age comprised northwest-directed thrust and tear faulting and emplacement of small stocks. At the close of the Helvetian phase, plugs and dikes of quartz latite porphyry intruded the faults, and mineralizing fluids associated with these intrusive rocks spread along the faults.

In post-Laramide time the area was deformed largely by normal faults. Many of these faults were associated with late(?) Oligocene volcanism; others were related to intrusion of several dike and vein swarms into east- to northeast-trending tension fractures. During the late Tertiary the area was tilted gently southeast on a range-front fault, along which the youngest movement was late Pleistocene.

INTRODUCTION

LOCATION AND OBJECTIVES

The geology of the Santa Rita Mountains was intensively investigated during the years 1962–69. Geologic mapping of the Mount Wrightson and Sahuarita quadrangles, lasting a total of about 350 days during 1962–68, showed the mountains to be underlain by a stratigraphic sequence that is unusually complete for southeastern Arizona. Consequently, the structural development of the area may be interpreted in greater detail than is possible elsewhere in this part of the State. An understanding of the succession of structural events in the Santa Rita area can assist similar studies throughout the region and may be especially useful in nearby areas where the geologic record is less complete and the interest in reconstructing that record is greater because of the mining activity.

The Santa Rita Mountains are the first range southeast of Tucson. They extend more than 25 miles (40 km) southward, from Pantano Wash, along which the main highway and railroad east of Tucson lie, to Sonoita Creek, about 12 miles (20 km) from the Mexican border (fig. 1). The mountains commonly reach heights of 6,000–7,000 feet (2,000 m), but Mount Wrightson reaches an elevation of 9,453 feet (2,881 m). The broad valley to the east of the mountains lies at about

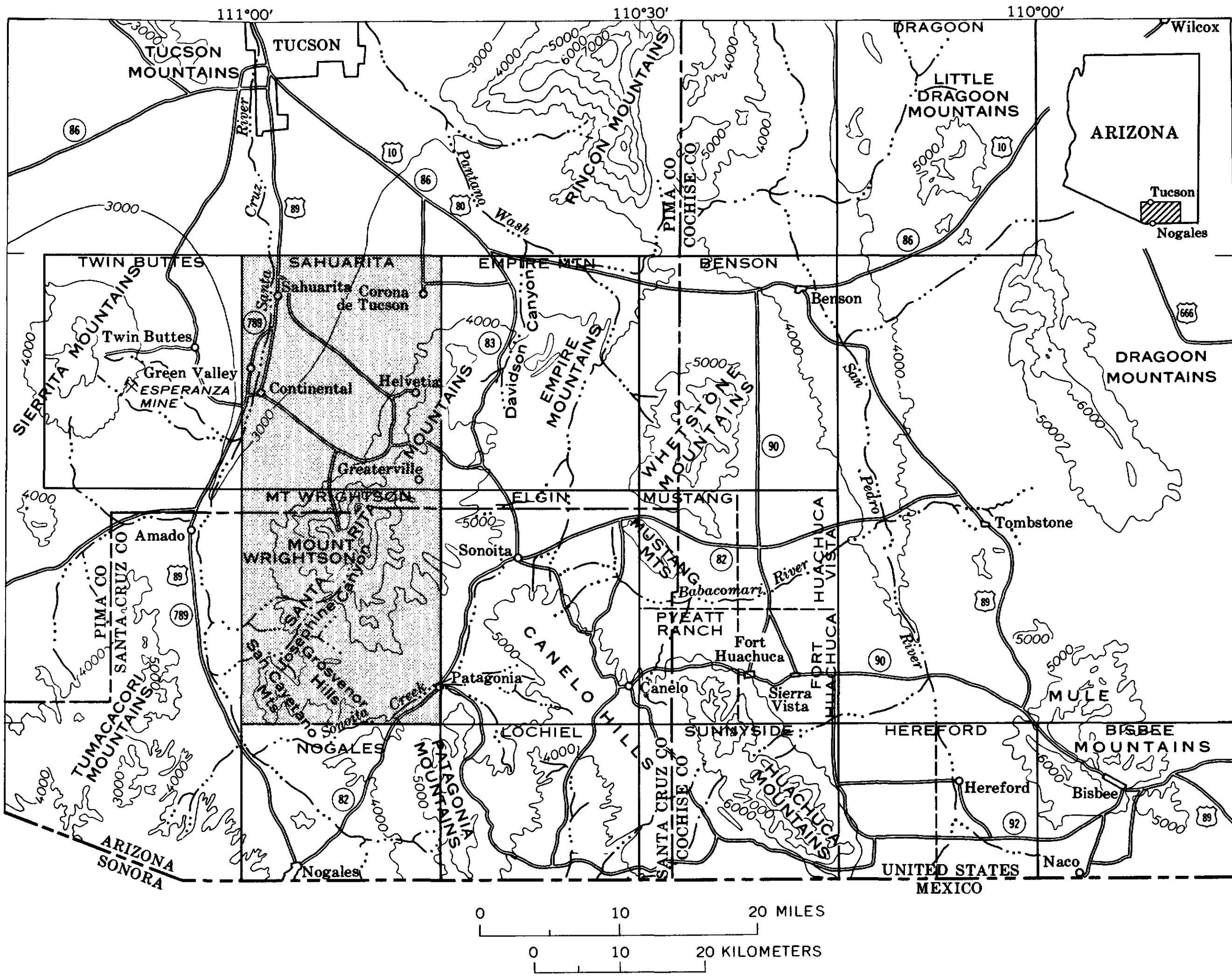

FIGURE 1.—Location of the Santa Rita Mountains in southeastern Arizona. Shaded areas show location of Sahuarita and Mount Wrightson quadrangles.

4,500 feet (1,400 m), whereas that to the west is only 3,000 feet (900 m) high. The mountains thus are sufficiently high to receive enough orographic rainfall to support extensive, largely scrubby forests, which contrast markedly with the grasslands to the east and the Sonoran Desert vegetation to the west.

The objectives of this report are to describe and interpret the structural features of the Santa Rita Mountains. More specifically, the area studied is the Mount Wrightson quadrangle (Drewes, 1971b) and the Sahuarita quadrangle (Drewes, 1971a); thus the area includes the smaller San Cayetano Mountains and Grosvenor Hills, which lie to the southwest of the Santa Rita Mountains, but it does not include the northeast tip of the Santa Rita Mountains. Detailed systematic descriptions of rocks are avoided here by referring to the topical reports, chiefly by Drewes (1971c, 1972a) and to unpublished data by Drewes; other reports are cited in the text. The local stratigraphic section is summarized in table 1. Some pertinent details, however, are repeated or expanded in this text because of the frequent close connection between the sedimentary, plutonic, and volcanic records and the structural record. The interpretation of the regional tectonics will be presented in a separate report.

The geologic investigation of the Santa Rita Mountains is part of a larger program of the U.S. Geological Survey to map and interpret the geologic history of all ranges roughly between Tucson and Bisbee. Many geologists are involved in this program, and most of the field studies are completed. J. R. Cooper has mapped the Sierrita Mountains, T. L. Finnell the Empire Mountains, Creasey (1967) the Whetstone Mountains, R. B. Raup the Canelo Hills, F. S. Simons the Patagonia Mountains, Hayes and Raup (1968) the Huachuca and Mustang Mountains, respectively, and Hayes and Landis (1961, 1964) the Mule Mountains.

ACKNOWLEDGMENTS

The geologic investigation of the Santa Rita Mountains was facilitated by many people. Foremost among these were my colleagues, J. R. Cooper, T. L. Finnell, P. T. Hayes, R. B. Raup, and F. S. Simons, whose work in the adjacent areas progressed concurrently with the Santa Rita study. The development of a local stratigraphic sequence, so important to a structural study, benefited directly from some data obtained from adjacent areas. Without any doubt, some structural interpretations also benefited from frequent discussions with my colleagues; the interpretations presented here, however, are my own responsibility. Additional discussions in the field with J. H. Courtright, S. C. Creasey, M. D. Crittenden, Jr., P. H. Pickard, and R. E. Wallace helped to clarify some structural problems and to raise others, for which I am particularly grateful.

Fieldwork was facilitated by many other people. Invaluable assistance in mapping and sampling was provided by G. C. Cone, Bruce Hansen, C. W. Norton, F. W. Plut, J. R. Riele, R. G. Rohrbacher, Arthur Sutheimer, and W. M. Swartz during the years 1962 through 1968. The courtesies of George Bradt, Roy Green, Dewey Keith, and George Yakobian of the communities around the Santa Ritas are recalled with pleasure; and those of Professors John Anthony, D. L. Bryant, and Evans Mayo of the University of Arizona are likewise acknowledged.

Further invaluable support was obtained from many laboratories. Some radiometric dates were obtained from Prof. P. E. Damon before their publication, and many other dates were provided by R. F. Marvin, T. W. Stern, S. C. Creasey, and their colleagues. The efforts of many other analysts, whose work is acknowledged more specifically in the collateral reports, are indirectly reflected in this study. G. C. Cone also ably assisted in many phases of the preparatory work.

The results of a few earlier geologic studies provided useful background information. Schrader (1915) made a pioneer reconnaissance of the area. Creasey and Quick (1955) mapped some of the mines and structural features of the Helvetia district. Several theses describe parts of the Santa Rita Mountains, of which those by Anthony (1951), Heatwole (1966), Heyman (1958), Lutton (1958), and Michel (1959) contribute considerably to the understanding of certain local structural units.

STRUCTURAL FEATURES

The rocks of the Santa Rita Mountains are abundantly faulted and less commonly folded. Most faults are high-angle structures that comprise many normal faults and some reverse and tear faults. Other faults are low-angle structures, which are mainly thrust faults but which include some faults whose genetic environment is unknown. A few thrust faults are steeply inclined owing to tilting or to local irregularities along the fault plane. Most folds are small open flexures or drag folds, but a few are nearly isoclinal and of large amplitude.

The Santa Rita Mountains consist of three major structural units, whose internal characters vary from unit to unit and whose boundaries are marked by major fault zones. The units are referred to here as the southwestern, central, and northeastern units (pl. 1). The rocks in the southwestern unit are typically gently inclined to the south and are cut by many normal faults. The rocks in the central unit are inclined moderately to the east and are cut by only a few faults,

TABLE 1.—*Rocks of the Santa Rita Mountains, Arizona*

[Broken lines indicate that the adjacent formations are contemporaneous or that their relations are uncertain]

Age			Groups, formations, and members			Description	Estimated thickness (ft)
Quaternary	Holocene		Youngest gravel and low-level terrace deposits			Gravel and intercalated sand; infantile gray soil on low-level terrace gravel.	0–300±
	Pleistocene	Late Pleistocene	Intermediate-level pediment and terrace deposit			Gravel and sand; capped by weakly developed red soil.	0–400±
		Middle Pleistocene	High-level pediment deposits			Gravel and sand; capped by well-developed red soil.	0–50±
	Pleistocene and Pliocene		Basin-fill gravel			Gravel, sand, and silt, commonly pinkish-gray and slightly indurated; locally includes tuffaceous beds.	0–2,000±
Tertiary	Pliocene and Miocene(?)		Gravel of Nogales			Gravel, sand, and silt; rich in volcanic clasts; commonly pale red, poorly sorted, and slightly indurated.	0–1,000±
	Late(?) Oligocene		Rhyolite intrusives of the northern Santa Rita Mountains			Rhyolite porphyry of a plug and of the Gardner Canyon and Box Canyon dike swarms.	
			Igneous complex of the southern Santa Rita Mountains	Dikes and stock of the San Cayetano Mountains		Rhyodacite porphyry dike swarm and medium-coarse-grained light-gray granodiorite.	
				Dikes and laccoliths in the Grosvenor Hills area		Rhyodacite vitrophyre, medium-gray to light-gray.	
				Grosvenor Hills Volcanics	Rhyodacite member	Rhyodacite lava flows, agglomerate, tuff, and welded tuff.	150–2,200
					Rhyolite member	Rhyolite tuff; a little welded tuff and lava.	500+
					Gravel and silt member	Gravel and silt; a little limestone and shale.	0–200
	Oligocene to Paleocene		Quartz vein swarm			Mineralized quartz veins of the southern Santa Rita Mountains.	
			Rhyolitic volcanics			Rhyolitic tuff and lava of Wasp Canyon.	0–100
			Olivine andesite plugs			Vesicular and amygdaloidal plugs at Deering Spring.	
			Andesite dikes and sills			Small andesite intrusives; include some dacite and diorite intrusives.	
	Paleocene		Greaterville intrusives			Quartz latite porphyry dikes and plugs, light-gray to grayish-orange-pink; contains stubby bipyramidal quartz phenocrysts; associated with mineralization.	
			Helvetia stocks			Granodiorite to quartz monzonite stocks and a quartz diorite stock, medium coarse grained.	
			Cottonwood Canyon dike swarm			Quartz latite porphyry, finely porphyritic to coarsely porphyritic.	
			Gringo Gulch plugs			Hornblende dacite porphyry; partly very coarsely porphyritic; microgranodiorite in core of one plug.	
	Paleocene(?)		Volcanics of Red Mountain			Rhyolitic and andesitic pyroclastic rocks, intensely altered.	
			Gringo Gulch Volcanics		Upper member	Rhyolitic to dacitic tuff, sandstone, and a capping andesite lava.	900+
					Lower member	Rhyolitic and dacitic pyroclastic rocks and some flows; contains intercalated epiclastic rocks.	700+
Cretaceous	Late Cretaceous		Elephant Head Quartz Monzonite			Stocks of coarse-grained quartz monzonite and an aplitic phase.	
			Madera Canyon Granodiorite			Stock of coarse-grained hornblende granodiorite, and porphyritic and leucocratic phases.	
			Josephine Canyon Diorite			Large stock of fine-grained diorite and quartz diorite and a late quartz monzonite phase.	
			Salero Formation		Upper member	Sedimentary and volcanic rocks.	3,500±
					Arkose member	Arkose and conglomerate; largely facies of welded tuff member.	500±
					Welded tuff member	Rhyodacite welded tuff.	1,200+
					Exotic block member	Dacitic volcanics containing large exotic blocks.	1,000±
					Lower member	Dacitic volcanics.	400±
			Fort Crittenden Formation		Upper red conglomerate member	Volcanic conglomerate; some sandstone and siltstone.	1,400+
					Rhyolitic tuff member	Tuff, in part intercalated in upper red conglomerate member.	0–650
					Brown conglomerate member	Arkosic conglomerate; some sandstone and siltstone.	2,000+
					Lower red conglomerate member	Volcanic conglomerate; some sandstone and siltstone.	800–1,200
					Shale member	Fossiliferous gray shale; some sandstone and conglomerate.	4,550+

TABLE 1.—*Rocks of the Santa Rita Mountains, Arizona*—Continued

[Broken lines indicate that the adjacent formations are contemporaneous or that their relations are uncertain]

Age		Groups, formations, and members			Description	Estimated thickness (ft)
Cretaceous	Early Cretaceous	Bisbee Group	Turney Ranch Formation		Sandstone and red siltstone.	1,500+
Cretaceous	Early Cretaceous	Bisbee Group	Shellenberger Canyon Formation		Siltstone and arkose.	1,600+
Cretaceous	Early Cretaceous	Bisbee Group	Apache Canyon Formation		Arkose and siltstone; some limestone lenses.	1,500–2,000
Cretaceous	Early Cretaceous	Bisbee Group	Willow Canyon Formation		Arkose and conglomerate.	2,200+
Cretaceous	Early Cretaceous	Bisbee Group	Glance Conglomerate		Limestone- and granite-cobble conglomerate.	0–1,500+
Cretaceous	Early Cretaceous	Bathtub Formation		Upper member	Dacitic volcanics and tuffaceous sandstone.	0–1,500
Cretaceous	Early Cretaceous	Bathtub Formation		Middle member	Rhyolitic to andesitic volcanics.	800–1,500
Cretaceous	Early Cretaceous	Bathtub Formation		Lower member	Conglomerate and volcanic sandstone.	700±
Cretaceous	Early Cretaceous	Temporal Formation		Upper member	Conglomerate and rhyolitic volcanics.	600–1,000
Cretaceous	Early Cretaceous	Temporal Formation		Middle member	Rhyolitic to latitic volcanics and conglomerate.	100–400
Cretaceous	Early Cretaceous	Temporal Formation		Lower member	Rhyolitic to dacitic volcanics and fanglomerate.	200–1,300
Jurassic		Squaw Gulch Granite			Large stock of coarse-grained pink rock ranging in composition from granite to quartz monzonite.	
	Early Jurassic and Late Triassic	Canelo Hills Volcanics			Arkosic sandstone and conglomerate, tuff and tuffaceous sandstone, and quartzite.	600+
Triassic		Piper Gulch Monzonite			Stock of very coarse grained dark-gray rock ranging in composition from monzonite to quartz monzonite.	
Triassic		Gardner Canyon Formation		Upper member	Red mudstone, dacitic volcanics, and conglomerate.	1,800+
Triassic		Gardner Canyon Formation		Lower member	Red siltstone and chert-pebble conglomerate.	200
Triassic		Mount Wrightson Formation		Upper member	Eolian sandstone and andesitic to rhyodacitic volcanics.	2,000+
Triassic		Mount Wrightson Formation		Middle member	Rhyolitic to latitic volcanics; some sandstone and conglomerate.	5,000±
Triassic		Mount Wrightson Formation		Lower member	Dacitic to andesitic volcanics and sandstone.	1,500+
Permian	Early Permian	Naco Group	Rainvalley Formation		Limestone and dolomite; a little sandstone.	0–300
Permian	Early Permian	Naco Group	Concha Limestone		Limestone, thick-bedded, cherty, dark-gray.	400–575
Permian	Early Permian	Naco Group	Scherrer Formation	Upper quartzite member	Quartzite, pale-reddish-gray, fine-grained.	140±
Permian	Early Permian	Naco Group	Scherrer Formation	Middle dolomite member	Dolomite, light- to medium-gray.	120±
Permian	Early Permian	Naco Group	Scherrer Formation	Lower quartzite and basal siltstone members	Quartzite, pale-yellowish-gray, fine-grained; basal reddish-gray siltstone.	460±
Permian	Early Permian	Naco Group	Epitaph Dolomite	Upper member	Limestone, moderately thick bedded, medium-gray, slightly cherty.	380±
Permian	Early Permian	Naco Group	Epitaph Dolomite	Lower member	Mainly light-brownish-gray marlstone and dolomitic siltstone; locally contains some argillite and gypsum; basal 180 ft contains intercalated dark- to medium-gray medium-thick-bedded dolomite.	620±
Permian	Early Permian	Naco Group	Colina Limestone		Limestone, dark-gray, medium-thick-bedded.	350±
Permian / Pennsylvanian	Early Permian and Late Pennsylvanian	Naco Group	Earp Formation		Siltstone and shale, reddish-gray; contains some sandstone and chert-pebble conglomerate.	800±
Pennsylvanian	Late and Middle Pennsylvanian	Naco Group	Horquilla Limestone		Limestone, fine-grained, thin-bedded to moderately thick bedded, medium- to light-gray; contains siltstone beds in upper half and two thin conglomerate beds near base.	1,000±
Mississippian		Escabrosa Limestone			Limestone, coarse-grained, thick-bedded, cherty, medium-gray, crinoidal.	560±
Devonian		Martin Formation			Brown dolomite, gray limestone, siltstone; some sandstone.	400±
Cambrian	Late and Middle Cambrian	Abrigo Formation			Shale, quartzitic sandstone, and thin-bedded limestone.	740–900
Cambrian	Middle Cambrian	Bolsa Quartzite			Quartzite, coarse-grained, thick-bedded, light- to brownish-gray and purplish-gray; thin basal conglomerate.	460±
Precambrian		Continental Granodiorite			Granodiorite porphyry and quartz monzonite porphyry; contains aplite and fine-grained quartz monzonite intrusives.	
Precambrian		Pinal Schist			Hornblende gneiss, granite gneiss, and schist.	

but in places they are tightly folded. The rocks of the northeastern unit are also commonly inclined moderately to the east, but they are cut by many thrust and tear faults and in many places are folded. The three units have, at times, developed rock sequences independently of each other, because of differences in their structural position and magmatic history.

The major fault zones separating the three structural units are belts along which rocks are more abundantly and complexly deformed than the rocks within the units themselves. The Sawmill Canyon fault zone separates the central unit from the northeastern one, and the Santa Rita fault zone and fault scar separate the southwestern and central structural units. These fault zones are identifiable in the mountains southeast of the Santa Rita Mountains, and they may be recognizable to the northwest as well.

The major structural units are composed of smaller structural blocks that are separated from each other by subsidiary faults that are confined to individual major units. These smaller structural blocks have been given the names of local geographic features and are described, together with the structures within the blocks and with the faults separating them from the adjacent blocks to the south or east, under the major structural unit.

The young range-front faults at the foot of the northwest flanks of the Santa Rita and Patagonia Mountains are described independently of the structural blocks described in the text, because too little is known of structures of the rocks on their downfaulted sides to compare them with the systems of major and minor faults.

SOUTHWESTERN STRUCTURAL UNIT

The southwestern structural unit underlies the southwest flank of the Santa Rita Mountains and also underlies the smaller Grosvenor Hills and San Cayetano Mountains (pl. 1). The unit extends northeastward to the Santa Rita fault zone and scar, a fault zone which has largely been obscured by a succession of Mesozoic plutons. The stratigraphic section of the southwestern structural unit consists mainly of a Precambrian basement—schistose and gneissic rocks correlated with the Pinal Schist and Continental Granodiorite—overlain by Upper Cretaceous and Tertiary volcanic and sedimentary rocks that commonly dip gently southward. In addition, Mesozoic plutonic rocks underlie some of the area.

Four structural blocks, referred to as the San Cayetano, Grosvenor Hills, Salero, and Montosa Canyon blocks, are recognized within the southwestern structural unit. The first three of these blocks have structural features in common that are distinctive from those in the blocks of the other major structural units, such as the gentle southerly dip of the rocks, the predominance of small normal faults, and the virtual absence of Paleozoic rocks. The fourth block, the Montosa Canyon block, however, has structural features that resemble those in some blocks of the other major structural units. Nevertheless, the Montosa Canyon block is more conveniently described with the others of the southwestern unit because of its location several miles southwest of the Santa Rita fault scar.

SAN CAYETANO BLOCK

The San Cayetano block, the southwestern most of the structural blocks, underlies the San Cayetano Mountains. It extends several miles (3 to 5 km) into the pediment area north of the mountains (pl. 1) and an unknown, but probably short, distance to the south into the Nogales quadrangle south of the area of plate 1. The San Cayetano block is separated from the Grosvenor Hills block to the east by the north-trending San Cayetano fault, across which the rocks and styles of deformation differ slightly.

Within the San Cayetano block, structural features are relatively simple. The southern two-thirds of the block is underlain by a gently southward-dipping sequence of volcanic and sedimentary rocks of the upper members of the Salero Formation of late Late Cretaceous age (Drewes, 1969a, 1971c), which are intruded by Josephine Canyon Diorite of latest Late Cretaceous age and by a quartz monzonite plug and a swarm of quartz latite porphyry dikes of Oligocene age (Drewes, 1971b, 1972a). The northern third of the block consists chiefly of Tertiary volcanic and sedimentary rocks which dip very gently eastward or westward.

Faults are abundant only near Josephine Canyon, between the two parts of the structural block. They are mainly normal faults along which the southern part of the block is raised at least several hundreds of feet with respect to the northern part. Subsidiary normal and reverse faults, mostly trending north or N. 70° W., have broken the northeast corner of the southern part of the block. A single short low-angle fault that separates a competent quartzite sequence from relatively incompetent tuffaceous rock probably resulted from adjustments to stresses brought about by the movement on the normal faults dividing the block. The dikes of the swarm in the southern part of the block also trend largely N. 70° W., but these dikes seem to follow joints rather than faults. Faulting of the block is probably related to some local folding. Some of the Tertiary rocks are slightly warped along the northern part of the San Cayetano fault, and the Cretaceous

Salero Formation is more strongly warped along the southern part of that fault.

The San Cayetano fault is a normal fault that strikes generally northward and appears to dip almost vertically. Only near its northern end does it strike gradually westward. In most places it is a discrete plane, but southwest of Sheuy Well (pl. 1) it is a narrow zone in which rocks of the adjacent blocks have been dragged many hundreds of feet from their original position. West-southwest of the well a sliver of gravel of the basal member of the Grosvenor Hills Volcanics, of late(?) Oligocene age, is either dragged up from its position to the east or dragged down from its former extension to the west. South-southwest of the well a sliver of volcanic rocks, like those capping the San Cayetano Mountains, now lies well above the level of the trace of the fault. About 1 mile (1.5 km) north of Josephine Canyon, the fault splits into two branches, between which the rocks have moved to intermediate structural levels.

Movement along the San Cayetano fault has been chiefly of Tertiary age, but it has been recurrent and has varied in direction and magnitude from place to place. Along the southern half of the fault, the east side has had an estimated cumulative displacement, east side down, of at least 1,000 feet (300 m), and perhaps as much as 2,500 feet (800 m), the amount of movement being obtained by adding the probable depth of the base of the Grosvenor Hills Volcanics to the east to the height of the mountains, presumed to have been capped by the volcanics, to the west. These mountains are younger than the volcanics, for the basal gravel of the volcanics near the edge of the mountains contains small rounded clasts derived from some distance to the east rather than angular detritus derived from nearby to the west. Just north of Josephine Canyon, the cumulative displacement along the fault is smaller—perhaps only a few hundred feet (a hundred meters); it further decreases northward, and ultimately the relative displacement of the blocks is reversed. Although the cumulative displacement along the fault may have varied as on a scissors fault, at least some of the reverse displacement is the result of relatively late downward movement of the northern third of the San Cayetano block with respect to both the southern two thirds of the block and the northern part of the Grosvenor Hills block, as indicated by the faulting and tilting of gravel of Pliocene and Pleistocene age in this area.

Several other features indicate that movement on the San Cayetano fault was recurrent. Successive flows, welded tuff, and agglomerate sheets of the Grosvenor Hills Volcanics to the east thicken westward toward the fault (Drewes, 1972a), suggesting that movement may have been continuous or recurrent through the late Oligocene. Furthermore, the upper member of the Salero Formation, which caps the San Cayetano block, is absent from the western part of the Grosvenor Hills block, suggesting that during the early Tertiary the San Cayetano block may have been downfaulted in such a manner that this member was preserved during the time of its erosion farther east. The structural position of the San Cayetano block with respect to that of the Grosvenor Hills block would then have been reversed during late Oligocene time.

GROSVENOR HILLS BLOCK

The second structural block of the southwestern unit, the Grosvenor Hills block, lies between the San Cayetano fault and the Salero fault zone. Its dominant geologic feature is the Grosvenor Hills Volcanics, consisting of a basal gravel and silt member, a tuff-rich rhyolite member, and a capping rhyodacite member, all of late(?) Oligocene age (Drewes, 1972a). To the east and north, the underlying upper Upper Cretaceous rocks extend from beneath the volcanic field and are seen to overlie some Jurassic and Precambrian rocks. The dominant dip of the rocks in this block is gently southward, but the bedding-plane(?) foliation of the Precambrian gneiss dips moderately steeply southwestward. The absence of older Mesozoic bedded rocks and of virtually all Paleozoic rocks is typical of the San Cayetano and Grosvenor Hills blocks.

Most faults of the Grosvenor Hills block are restricted to the volcanic field itself, and all of them are steep normal faults or reverse faults. Many of these faults fall into two sets, one set trending north and the other N. 60°–70° W. The present remnants of the volcanic field are almost wholly restricted to a downdropped area between the San Cayetano fault to the west and the Hangmans fault to the east (pl. 1). Many of the individual volcanostratigraphic units in this area thin eastward, and some of them change from flows to rubble sheets or from coarse-grained rubble sheets to fine-grained rubble sheets eastward, suggesting that their source lay to the west. The volcanic field not only dropped between its bounding faults, but the numerous southwest dips of the western part of the volcanics show that the field was tilted gently westward during or after the effusion of the volcanics. Some young westward tilting of this area is also indicated by the local westward dips, as much as 25°, of the gravel of Nogales that overlaps the volcanics along the southern part of the San Cayetano fault (Drewes, 1971b).

The Sheuy and George Wise faults (pl. 1), the largest faults of the conspicuous fault set that trends N. 60°–70° W. across the volcanic field, form the margins of a graben that extends almost entirely across the volcanic field. The rocks within the graben are chiefly welded tuffs and intercalated unwelded tuffs of the youngest member of the Grosvenor Hills Volcanics; this member is absent from the hanging walls of the graben. Locally, a deposit of coarse sedimentary breccia, probably of talus origin, lies between the tuff sequence and the rocks of the hanging wall of the Sheuy fault. A similar but smaller graben lies 1½ miles south of the George Wise fault.

Rhyodacite vitrophyre dikes and laccoliths intrude the Grosvenor Hills Volcanics, mainly the lower two members. They are distributed in a broad eastwardly convex arc, except for one laccolith that lies outside the arc at George Wise Spring. Most dikes trend N. 60°–70° W., parallel to one of the fault sets and the grabens. Other details of these intrusives are described in another report (Drewes, 1972a).

The faults that trend N. 60°–70° W. across the volcanic field are believed to be genetically related to the effusion of the volcanics as well as to the intrusion of rhyodacite vitrophyre. The maps (pl. 1 of this report and Drewes, 1971b) show that these features occur together spatially. Several lines of evidence suggest that they are contemporaneous as well: (1) The graben between the Sheuy and George Wise faults is filled with welded and unwelded tuffs that do not occur in the adjacent rocks, yet no marked unconformity was recognized at the stratigraphic level of the tuff sequence; furthermore, the same lava flow caps rocks both within and adjoining the graben. Apparently, therefore, the tuffs were deposited only in the graben. (2) The tuff sequence laps onto an old talus deposit along part of the north wall of the graben, indicating that it was deposited in a trough, possibly of fault origin, that was a young feature at that time. The wedging out of individual tuff sheets southeastward along the graben, as well as southwestward across it, shows that the graben was being tilted concurrently with the effusion of the tuffs. Tilting of such limited extent again suggests faulting. The combined evidence demonstrates that the effusion of the tuffs was penecontemporaneous with the development of the N. 60°–70° W.-trending faults.

The Sheuy and George Wise faults are probably also penecontemporaneous with the emplacement of the rhyodacite dikes and laccoliths, inasmuch as they cut some of the intrusives. The George Wise fault, however, is intruded by dikes that merge with, and apparently are a feeder of, the laccolith at George Wise Spring. This laccolith lies at the east end of the large transverse graben and is out of line with the other intrusives. Perhaps an eastward shift of the rhyodacite magma out of line of the arc of intrusives to become the laccolith mass at George Wise Spring produced the collapse of part of the volcanic field to form the graben.

Many of the other small faults in the volcanic field are clustered both southeast of Josephine Canyon and west of George Wise Spring. Some of these concentrations of faults, especially those near the spring, may simply reflect the presence of abundant marker beds, whose recognizable offsets facilitate geologic mapping. The abundance of small faults southeast of Josephine Canyon is probably related to the local abundance of laccoliths. Some of these faults are peripheral to laccoliths; others abut the laccoliths, where they simply end against the massive intrusive bodies or are cut by the laccoliths. The close spacing of faults and the occurrence of many small triangular blocks, together with the peripheral and truncated faults, suggest that the faults were formed as a result of the collapse of the volcanics into which the rhyodacite magma was intruded.

Not only are the faults genetically related to the volcanism and the intrusion of the laccoliths, but also the volcanics and laccoliths are closely related. Petrographically, chemically, and spectrographically, the extrusive and intrusive rocks are shown to be virtually identical, and isotopic ages of the extrusives and the intrusives are identical (Drewes, 1969a, 1971b, 1972a). Apparently then, during Oligocene volcanism in the Grosvenor Hills area, most of the magma reached the surface, but some of it reached only the earliest formed volcanic deposits in the subsurface, which were partly pushed aside and partly collapsed around the larger intrusives.

The few faults in the Grosvenor Hills block east of Hangmans fault are short nearly vertical normal faults, whose displacement is at most a few tens of feet. Most of them parallel the nearby east-trending segment of the Salero fault zone, but a few trend about north. Some Tertiary quartz veins and rhyolite dikes also follow east-trending fractures, thus showing that they and the east-trending small faults are related to the development of a single relatively young tension fracture system, which will be described with structural features of the Salero block.

The Salero fault zone extends in a northwesterly direction from its southeast limit near Patagonia, past the Salero mine and Salero Ranch, to the pediment area west of the Glove mine. From there, the Salero fault zone, or a fault branching from it, extends northward beyond lower Cottonwood Canyon to lower Agua Caliente Canyon (pl. 1). The Salero fault zone is steep and for most of its length strikes about N. 45° W., but near Patagonia it swings nearly east and at its other end it trends more northerly. Through its central reaches, the fault zone is narrow or is a single plane, in places marked only by intensely silicified, mineralized, or otherwise altered rock. Southwest of the Glove mine, the fault branches; one strand is almost entirely covered by pediment gravel and much of another strand is likewise concealed. Southeast of the Salero mine area, the fault zone crosses a belt of stocks and splays out into a zone about 1 mile wide. Here the fault zone is marked only by strongly silicified rocks and by exceptionally long quartz veins. Farther southeast, the fault forms the south contact of the stock of Squaw Gulch Granite and probably offsets the Santa Rita fault zone. Near Patagonia, it is covered by young gravel.

The stratigraphic displacement on the Salero fault probably increases to the northwest. Near the Glove mine, Paleozoic and Triassic rocks are absent southwest of the fault, but their presence in the Montosa Canyon block northeast of the fault suggests many thousands of feet (a few kilometers) of uplift and erosion of the Salero block in pre-Salero Formation (late Late Cretaceous) time. The offset of upper Upper Cretaceous rocks northwest of the Salero mine indicates that movement was renewed and was down to the northeast during or shortly before the Tertiary. The offset of the Gringo Gulch Volcanics of Paleocene(?) age west of Patagonia shows that movement on part of the Salero fault zone was reversed during the Tertiary. The flexure in the gravels of Nogales of late Tertiary age, west of the Glove mine and near the fault, may indicate additional minor movement on the fault near the end of the Tertiary.

The actual nature of the displacements along the Salero fault zone is uncertain. By analogy with other strongly developed northwest-trending faults in the Santa Rita Mountains, some left-lateral displacement may have occurred along the fault during the Laramide Orogeny, but rotational normal movement may also explain the displacement of Laramide age. Pre-Laramide and post-Laramide movement need only to have been normal.

MONTOSA CANYON BLOCK

The Montosa Canyon block is a small structural block lying between the northern ends of the Grosvenor Hills block and the Salero block. It is bounded to the northeast by the Agua Caliente thrust fault, to the southeast by the Montosa tear fault, and to the northwest by the Elephant Head fault, a young range-front fault. The rocks of the Montosa Canyon block are anomalous to others of the southwestern structural unit in that they include some Precambrian rock, the entire Paleozoic sequence, and substantial parts of the Mesozoic sequence. The rocks commonly strike northwestward and dip moderately steeply southwestward. They are abundantly faulted and locally are also folded, chiefly parallel to the general strike of the beds.

One of the major faults within the Montosa Canyon block is the Montosa thrust fault (pl. 1). It extends from the Montosa tear fault northwestward to the Elephant Head fault, beyond which it is covered by young gravel. Along the fault, Permian formations are emplaced on the Lower Cretaceous Bisbee Group. Near Agua Caliente Canyon, the thrust fault is cut by an unnamed north-trending transverse fault that produces more than half a mile of separation of the trace of the thrust fault. West of the transverse fault, the Montosa thrust fault follows a string of small fault slices of Permian Concha Limestone that separate overlying Upper Cretaceous Fort Crittenden rocks from underlying Bisbee rocks. East of the transverse fault, the plate of Paleozoic rocks is thick, and rocks ranging in stratigraphic position from the Pennsylvanian Horquilla Limestone to the Permian Rainvalley Formation are thrust upon the Bisbee. A subsidiary branch of the thrust fault (pl. 2) follows the base of the Concha Limestone, which is brought against various members of the relatively incompetent Permian Scherrer Formation. Half a mile (about 1 km) south of Agua Caliente Canyon (pl. 1), the thrust fault dips 35°–45° SW., and in adits is seen to follow mineralized gouge. On the spur north of Montosa Canyon (hill 5012 on pl. 2), the fault dips as little as 10°, but the dip increases to about 60° in the unnamed canyon north of the spur. In this area, the fault consists of two tight shear planes separated by a sheet of gouge a few feet thick. The adjacent rock is rarely brecciated, but locally it is sheared. Here too, iron and copper oxides occur along the shear surfaces. The overlying rocks are inclined subparallel to the thrust fault; but the underlying beds are near vertical and truncated, and the truncated ends are bent southwestward, indicating the relative direction of *some* movement of the upper plate.

Two additional but minor thrust faults disrupt the formations between Montosa Canyon and the Glove mine (pl. 2). About half a mile (1 km) northeast of the mine, the thrust fault, lying between the upper quartzite member of the Scherrer Formation and the overlying Concha Limestone and dipping 40° N., is interpreted (pl. 2, section *C–C′*) to be an extension of the upper limb of the Montosa thrust fault. The second minor thrust fault, near the mine, trends northwest and is inferred to follow the 30°–70° NE.-dipping contact between the metamorphosed Pennsylvanian Horquilla Limestone and the overlying Pennsylvanian and Permian Earp Formation, whose thickness increases abruptly across a north-trending subsidiary fault in the Earp and overlying rocks. The movement direction on this thrust fault is presumed to be like that of the nearby Montosa thrust fault.

The rocks of a small part of the area of plate 2, south and west of the Glove mine, are so abundantly faulted and so intensely contact metamorphosed that their identification and correlation remain partly uncertain. For many rocks an alternative correlation to the one presented on the detailed map would change the interpretation of the structural development of the area relatively little. For instance, small structural blocks of some beds of the Permian Concha Limestone resemble Permian Colina Limestone; metamorphosed beds high in the Horquilla Limestone resemble the basal member of the Permian Scherrer Formation; and small masses of hornfelsed Middle and Upper Cambrian Abrigo Formation look like some parts of the Devonian Martin Formation. For a few rocks, however, an alternative correlation would change the inferred structural development considerably. Thus, should the rhyolitic volcanics cut by the large northwest-trending fault half a mile (about 1 km) west of the mine be part of the rhyolite member of the upper(?) Oligocene Grosvenor Hills Volcanics, rather than the tuff member of the lower Upper Cretaceous Fort Crittenden Formation as is proposed on plate 2, then that fault would be late Tertiary rather than Laramide or younger. Similarly, if the quartz monzonite of the Glove mine should correlate with the upper Upper Cretaceous Elephant Head Quartz Monzonite rather than with a northern quartz monzonite facies of the Jurassic Squaw Gulch Granite, then the structural relations between the thrust fault and the quartz monzonite on the left half of section *B–B′* would have to be reinterpreted to show the base of the quartz monzonite as rooted rather than faulted. The correlation of the quartz monzonite at the Glove mine with the northern facies of the Squaw Gulch Granite is suggested by the apparently unconformable relations between the quartz monzonite and the dated overlying Salero Formation. The correlation of the quartz monzonite of the Glove mine area with the Squaw Gulch Granite of Jurassic age is also indicated by the absence from the adjacent part of the Salero Formation of the strong contact metamorphism found in the Paleozoic rocks nearby.

Many high-angle normal faults further complicate the structure of the Montosa Canyon block. One of the largest of these faults extends from the Montosa tear fault northwestward to a point 1 mile (1.5 km) southwest of Yoas Mountain (pl. 1). South of Montosa Canyon (pl. 2) the stratigraphic displacement along this fault is only a few hundred feet (about 100 m), bringing beds low in the Concha Limestone against rocks of the Rainvalley Formation, youngest of the Permian rocks. However, north of the canyon, red beds of the Fort Crittenden Formation are juxtaposed against the Rainvalley, and the southwest side rather than the northeast side is down. Very likely some of the relatively large movement and reversal on the northern part of this fault is taken up along a transverse fault that trends northeastward 1 mile (1.5 km) northwest of the Glove mine.

West and south of the Glove mine (pl. 2) abundant high-angle faults occur in contact-metamorphosed Paleozoic rocks and in quartz monzonite correlated tentatively with the Squaw Gulch Granite of Jurassic age. Nearby, several of these faults are cut by the quartz monzonite and are unconformably overlain by Upper Cretaceous rocks; others cut the quartz monzonite. Small dikes of andesite and of quartz latite porphyry, which cut some of these faults and which seem to postdate all structural features in the block, are assigned a Paleocene age, for they cut rocks of about 68–65 m.y. in age (Drewes, 1971b); some of these dikes are correlated with dikes dated about 60 m.y. (Drewes, 1972a). Thus, most of the faulting in this area is Late Cretaceous or Paleocene, but some of it is Jurassic or older Mesozoic. Very likely the intrusion of the quartz monzonite of the Glove mine area is associated with the extra degree of complexity of the structural features near the mine.

The rocks of the foothills and of the pediment north of Montosa Canyon and west of the limestone hills in the northwest end of the Montosa Canyon block are also much faulted. Because of the extensive gravel cover, details of these faults are poorly known; however, the westernmost fault (pl. 1 of this report; Drewes, 1971b) brings Grosvenor Hills Volcanics to the west against the Mount Wrightson Formation of Triassic age to the east, and so is younger than others in the Montosa Canyon block. Conceivably, this fault is a strand of the Salero fault; if it is, it would form the west margin of the Montosa Canyon block.

The Agua Caliente thrust fault is a northwest-trending low-angle fault of Late Cretaceous age, whose development is imperfectly understood. Northwest of Agua Caliente Canyon, the fault is mostly covered by surficial deposits or is intruded by dikes and veins. Along the canyon and to the southeast, the fault is sporadically exposed as a sheared and mylonitized zone separating an overlying sheet of epidotized and hornfelsed siltstone, sandstone, and conglomerate of the Bisbee Group from underlying relatively unaltered granitoid rocks. Toward the southeast, the Agua Caliente fault appears to end against, or merge with, the Montosa tear fault; only a small branch of the thrust fault is inferred to extend a short distance into the granitoid rocks near the junction of the thrust fault and the tear fault. At its other end, the Agua Caliente fault is probably truncated and offset by the Elephant Head fault. The deflections of the trace of the fault across the local hills indicate that the northwestern part of the Agua Caliente fault is steeply inclined to the southwest and that the southeastern part is gently inclined to the southwest. A dip of 50° is estimated at the mine shaft near the southeast end of the fault, which penetrates through the Bisbee and ends in granitoid rocks 150–200 feet (45–60 m) down. The apparent continuity of the Agua Caliente fault with the northeast-trending Montosa tear fault suggests that the upper plate of the 50°-dipping fault moved either northeastward (suggestive of a thrust fault) or southwestward (perhaps suggestive of only a low-angle normal fault). Whichever the direction, the amount of movement on the fault was not large—at most a few miles—because the granitoid rocks almost certainly produced the metamorphism of the overlying Bisbee rocks, there being no other known large post-Bisbee intrusives in the area. Comparison of the Agua Caliente fault with the other nearby thrust faults and with the Montosa tear fault, described below, indicates that it had a complex history involving early northeastward thrusting and late minor reversal of movement.

The Montosa tear fault lies along most of the southeast margin of the Montosa Canyon structural block, extending from its junction with the Agua Caliente fault to a point about three-fourths mile (slightly more than 1 km) east of the Glove mine (pl. 2), where it is covered by the welded tuff member of the Salero Formation. The tear fault reappears from beneath the welded tuff but remains poorly exposed south of Cottonwood Canyon and extends southwestward to merge with, or to be truncated by, the Salero fault zone. The northern part of the Montosa tear fault separates extensively faulted rocks of the Montosa Canyon block on the northwest from the relatively undeformed exotic block member of the Salero Formation on the southeast. The tear fault is slightly sinuous, is nearly vertical, and is marked by a zone of fault slivers, sheared rock, and gouge as much as a few hundred feet (many tens of meters) thick. Locally, some small dikes of andesite and of quartz latite porphyry intrude the fault, and others abut it, following other fractures across the fault rather than being offset along the fault.

The direction of movement on the Montosa tear fault is inferred to be right lateral. That the fault is a tear is suggested by the termination of the thrust faults within the Montosa Canyon block against it and by its apparent merger with the Agua Caliente thrust fault. Several small folds in the Paleozoic rocks immediately northwest of the tear fault also terminate against it and die out within 1 mile (1.5 km) of it. The thickness of the gouge and the abundance of fault slices along the fault also suggest that it is a tear fault. The direction of displacement of the fault slices with respect to their correlative rocks in the Montosa Canyon block shows that the relative movement along the Montosa tear fault is right lateral. Likewise, the southwestward inclination, at about 70°, of the axial planes of several of the folds in the Montosa Canyon block favor a right-lateral movement on the tear fault. The axial planes of other small folds are vertical (and the plane of one is also faulted), but they also would be inclined southwestward toward the underlying thrust fault if that fault were rotated to a horizontal position.

Major movement along the Montosa tear fault is dated as late Late Cretaceous, probably only slightly earlier than 72 m.y. ago. The faulting occurred after the emplacement of the exotic block member and before the deposition of the welded tuff member, both of the Salero Formation. The Salero overlies the Fort Crittenden Formation, whose fossils date it as Late (but not latest) Cretaceous. The welded tuff member is isotopically dated as 72 m.y., or late Late Cretaceous. The time interval between the emplacement of the welded tuff member and of the underlying exotic block member of the Salero is believed to have been very short, inasmuch as there are no signs of erosion or of deposition of clastic rocks beneath the welded tuff. Apparently the volcanism of the Salero was synchronous with, and bracketed the time of, the thrust and tear faulting.

At the time of tear faulting, and perhaps as a result of a vertical component of displacement during faulting, the relief was locally rugged. The welded tuff sheet that unconformably covered the exotic block member and the newly formed tear fault has a sheeting, believed to have formed by flowage. In most places the sheeting dips gently south or southwest, parallel to the contacts of the sheet (Drewes, 1971b); but along the contact with the Paleozoic rocks east of the Glove mine, where the tear fault is buried by the tuff, the sheeting strikes northeast and dips steeply southeast without the welded tuff being sheared against the Paleozoic rocks. This local change in the attitude of the sheeting suggests that the welded tuff flowed against or along a scarp, which lay nearly coincident with the tear fault. Some of the small masses of Epitaph(?) Dolomite in the welded tuff member near this contact are out of line with respect to the main mass of Epitaph and therefore are probably remnants of fault slivers along the concealed extension of the tear fault, where they are partly buried beneath the welded tuff.

SALERO BLOCK

The northeasternmost and the least disturbed of the structural blocks of the southwestern unit is the Salero block, which lies between the Agua Caliente and Salero faults to the southwest and the Santa Rita fault scar to the northeast. The block is underlain mainly by granitoid rocks of Jurassic and Cretaceous ages, but a thin cover of gently southward dipping Upper Cretaceous volcanic and sedimentary rocks of the Salero Formation overlies the Jurassic Squaw Gulch(?) Granite and is intruded by the Cretaceous granitoid rocks. Several swarms of dikes and quartz veins intrude these rocks.

A few small faults and a fold occur in the Salero block (pl. 1). North of Agua Caliente Canyon several north- to northwest-trending normal faults offset dikes and igneous contacts. South of Cottonwood Canyon, a transverse fault offsets the Salero fault, and a similar fault also offsets the remnant of the Santa Rita fault zone near the south end of the block. Finally, the Salero Formation is folded into an open anticline 1–2 miles (2–3 km) northeast of the Salero Ranch. The scarcity of structural features seems to reflect the kind of rocks that are dominant in this block—massive granitoid rocks that can resist deformation.

The orientation of the several vein and dike swarms (Drewes, 1972a) shows that during Tertiary time fracture systems developed across the northwest-trending structural grain of the Santa Rita Mountains. The Cottonwood Canyon dike swarm consists of about a dozen nearly vertical quartz latite porphyry dikes that extend from Josephine Canyon west-northwestward to near the Glove mine; other, shorter, randomly oriented dikes in the swarm are of little interest here. The dikes intrude rocks as young as the stocks of latest Cretaceous age and are dated by isotopic analyses as probably Paleocene.

The southwest ends of the Box Canyon and Gardner Canyon dike swarms also extend into the northwestern and central parts, respectively, of the Salero block. These swarms consist of rhyolite porphyry dikes, most of which trend N. 50°–60° E. and dip nearly vertically. In the Salero block, however, the westernmost dikes strike more nearly east-west. Two dikes of the Box Canyon swarm, about 1 mile (1.5 km) southwest of Yoas Mountain trend N. 70° W. in the Montosa Canyon block just beyond the margin of the Salero block. The westernmost dikes of the Gardner Canyon swarm trend toward the main group of dikes of the Cottonwood Canyon swarm, suggesting that the two swarms may have been injected along separate parts of the same set of fractures. However, the dikes of the Gardner Canyon swarm are assigned to the late(?) Oligocene through isotopic dating (Drewes and Finnell, 1968; Drewes, 1972a).

In the southern part of the Salero and Mount Wrightson blocks, a swarm of more than 300 quartz veins, of Paleocene to Oligocene age, cuts rocks as young as the Gringo Gulch Volcanics, of Paleocene (?) age. With very few exceptions, these veins lie south of the Gardner Canyon dike swarm in a broad fan-shaped pattern, which trends N. 80°–90° W. in the Salero block and N. 70°–90° E. farther east. All veins are steeply inclined, dipping both ways with equal frequency. A few veins are injected along the Salero fault zone and other faults; other veins lie closely parallel to faults or are in line with them.

The dike and vein swarms make a consistent pattern, trending at about right angles to the structural features of Late Cretaceous and Paleocene age. They thus seem to occupy a set of tension fractures that developed after the compressive forces of the Laramide Orogeny were relaxed. Tension in the north-northwest direction is also reflected in the range-front faults.

The characteristics of the exotic block member of the Salero Formation and the relation of the member to adjacent rocks provide important clues about local structural features. A detailed description of these rocks appears in Simons, Raup, Hayes, and Drewes (1966) and in Drewes (1971c). In brief, the exotic block member is a dacite breccia believed to be partly an unroofed sill emplaced along a thrust fault and partly a flow. It contains abundant fragments, as much as 1,000 feet (300 m) across, of a wide assortment of pre-Salero rocks, among which volcanic rocks of the Triassic Mount Wrightson Formation and Paleozoic limestones are the most abundant. The breccia is believed to have moved southwestward down an available slope, largely cut on Squaw Gulch Granite, shortly before the emplacement of the welded tuff member of the Salero Formation, about 72 m.y. ago. A southwestward slope of the terrain during this time is indicated by such evidence as the direction of decrease in size of clasts in the arkose member of the Salero Formation and the direction of penecontemporaneous gravity gliding of the Montosa thrust plate. The close temporal association of the exotic block and the welded tuff members with the movement on the Montosa tear and thrust faults has already been described. This association is even more significant because the assortment of exotic blocks is like the rocks now present only in the Montosa Canyon block, from which the member itself is absent. It is conceivable that these rocks once extended well across the Salero block, for they now appear in that block as inclusions and possibly as roof pendants in plutons and appear a short distance east of the block as extensive wallrocks of plutons. The source of the exotic fragments of the exotic block member is, therefore, believed to have been in the Salero block, east or southeast of the Montosa Canyon block, and the source of the dacitic volcanics may have been in the same area or farther to the east. This inferred source area of the dacitic volcanics is now partly occupied by plutonic rocks, which are chemically similar to the dacite and which were emplaced a little more than 67 m.y. ago (Drewes, 1969a, and unpub. data; Simons, 1972).

SANTA RITA FAULT SCAR

A major structural feature trends northwestward across the southern Santa Rita Mountains from near Patagonia in the southeastern part of the report area to about Madera Canyon in the northwestern part (pl. 1). This structural feature mostly is unmarked by either a conspicuous fault zone or the linear features of topography or vegetation that are commonly found along structural elements. Rather, its presence is indicated by alined edges of elongate intrusive masses, by septa in the intrusives, and by major differences in stratigraphic sequence and in rock attitudes of the areas adjacent to the intrusives. Evidence is sufficient to show that initially the structural feature was a large fault zone, along and near which the granitoid stocks of Mesozoic age were emplaced. The fault zone thus "healed" by these intrusives was not affected by the latest Cretaceous and Tertiary deformation that is so abundant in the adjacent areas and may have also remained unaffected by this deformation because of the "healing." The fault zone is referred to here as the Santa Rita fault zone, and its projection through the extensively intruded terrane is referred to as the Santa Rita fault scar.

A remnant of the Santa Rita fault zone is exposed as a 2-mile-long (3-km-long) zone of upended rhyolite and intercalated quartzitic sandstone of the Mount Wrightson Formation of Triassic age along, and west of, Temporal Gulch, some 2 miles (3 km) northwest of Patagonia. In general, the Lower Cretaceous Temporal and Bathtub Formations lie with marked angular unconformity upon the upended rocks of the fault zone as well as upon the Squaw Gulch Granite west of the upended rocks, but locally the Temporal and Bathtub Formations are faulted against the upended rocks.

Southeast of the exposed remnant of the Santa Rita fault zone, Bathtub rocks and younger volcanic rocks and gravel cover the fault, but the fault probably continues beneath the lowlands of Sonoita Creek, inasmuch as a similar fault zone has been recognized in the Patagonia Mountains less than 1 mile (about 1 km) west of the southeast corner of the Mount Wrightson quadrangle (the southeast corner of pl. 1). Upended volcanic rocks that are probably correlative with the Mount Wrightson Formation continue for about 6 miles (10 km) southeastward, roughly along Flux Canyon and the crest of the Patagonia Mountains, as mapped by Simons (1972).

Northwest of the exposed remnant of the Santa Rita fault zone, Cretaceous rocks cover the upended volcanics and quartzitic sandstone for several miles, and plutonic rocks emerge beyond this cover; but linear features in the plutonic rocks provide an approximate basis for projecting the Santa Rita fault scar many miles farther to the northwest. Septa of Piper Gulch Monzonite (pl. 1) are strongly alined south of Mansfield Canyon, and scattered inclusions of the monzonite follow this trend as far northwest as the ridge west of Madera Canyon (Drewes, 1971b). North of Mansfield Canyon a prong of Josephine Canyon Diorite and another of Madera Canyon Granodiorite also lie roughly along the fault scar. The fault scar is inferred to extend to the edge of the piedmont gravel and is presumed to be offset by the younger Elephant Head fault beneath the gravel cover.

The Santa Rita fault zone and fault scar separate rocks that have different structural characteristics. This structural contrast across the range supports the idea of a major fault zone, and the extent of the bedded rocks that have the different structural features helps to delineate the fault zone. Northeast of the fault scar, rocks chiefly of Triassic and Cretaceous ages, but not including the Salero Formation, form a homoclinal sequence that dips 20°–35° E. Because of the structural simplicity of these rocks, it is likely that the normal Paleozoic sequence underlies the Triassic rocks. On the other hand, the rocks southwest of the fault scar, except for the plutonic rocks, consist chiefly of the Salero that dips 10° S. to 10° SW. Where present, the Triassic and Paleozoic rocks are severely faulted. In at least part of the area, Precambrian rocks directly underlie the Salero.

Northwest of the Santa Rita Mountains, on the east side of the Sierrita Mountains, mapping by Cooper (1970) showed complex structural features, some of which I believe are a continuation of the Santa Rita fault zone and fault scar. The east margin of the main intrusive body of the Paleocene Ruby Star Granodiorite resembles most strongly the fault scar in that it forms a long and regular contact that separates rock sequences whose gross lithology and structure differ from each other. To the southwest, Cooper showed the host rock of a series of plutonic rocks of Mesozoic age to be mainly Mesozoic volcanic and sedimentary rocks which are scarcely deformed and which dip gently southwestward. To the northeast, he showed the rocks to include much granitoid rock of Precambrian age and sedimentary rock of Paleozoic age; easterly dips prevail, and the rocks were complexly deformed both during and after Mesozoic time.

Because the record of movement on the Santa Rita fault zone is fragmentary and evidence for the fault scar within the Santa Rita Mountains is indirect, the displacement on the zone is unknown, although a large vertical component is required to place Upper Cretaceous rocks to the southwest against Triassic rocks to the northeast. Movement on the fault is suspected to be recurrent, with at least major deformation occurring in the Early Jurassic or pre-Jurassic (pre-Squaw Gulch Granite time), in the Late Jurassic or Early Cretaceous (post-Squaw Gulch Granite and pre-Temporal Formation time), and again in the late Late Cretaceous (post-Salero Formation and pre-Josephine Canyon Diorite time). The earliest movement may even date back to Triassic (Piper Gulch Monzonite time), inasmuch as the Piper Gulch Monzonite seems to have been injected along a narrow zone. The narrow body of Triassic(?) diorite northeast of Mount Wrightson (pl. 1) may similarly have been injected along an obscure fault zone of this age. The magnitude of movement and the complexity of the Santa Rita fault zone suggest that the zone may be a near-surface expression of a major structural element in the basement rocks.

CENTRAL STRUCTURAL UNIT

The central structural unit extends across the breadth of the Santa Rita Mountains from the Santa Rita fault scar in the southwest to the Sawmill Canyon fault zone in the northeast (pl. 1). The central unit is underlain by a thick sequence of Triassic Mount Wrightson Formation and by thinner sequences of Lower Cretaceous Temporal and Bathtub Formations and Bisbee Group and Upper Cretaceous Fort Crittenden Formation. These rocks are intruded by a few small stocks and plugs and by swarms of dikes and quartz veins. The central structural unit consists of two blocks, the Mount Wrightson block to the west and Adobe Canyon block to the east. The rocks of the Mount Wrightson block and of a small part of the Adobe Canyon block dip homoclinally 20°–35° E., but in much of the Adobe Canyon block the simplicity of the homoclinal structure is considerably modified by folds.

MOUNT WRIGHTSON BLOCK

The Mount Wrightson block extends northeastward from the Santa Rita fault zone and fault scar to the Big Casa Blanca Canyon fault. The block is underlain almost entirely by Triassic and Lower Cretaceous volcanic and sedimentary formations that dip moderately steeply eastward, but a small part of it is underlain by intrusives and veins. Structurally, it is the simplest block in the Santa Rita Mountains.

Only few faults cut the rocks of the Mount Wrightson block. In the northern part of the block, several small normal faults cut the upper member of the Mount Wrightson Formation. Two of these faults seem to splay out of the Big Casa Blanca Canyon fault, and the others may also be related to that fault. In the southern part of the block, east of Temporal Gulch, a larger northwest-trending fault cuts Cretaceous rocks and increases in stratigraphic displacement southeastward toward the gravel cover along Sonoita Creek. An extension of this fault east of Sonoita Creek has not been found by R. B. Raup (oral commun., 1964), who has mapped in that area.

The Big Casa Blanca Canyon fault, along the northeast margin of the block, extends from Big Casa Blanca Canyon on the east side of the Santa Rita Mountains to Florida Canyon on the west side (pl. 1). From the gravel cover in the lower reaches of Big Casa Blanca Canyon the fault strikes N. 20° W. to Gardner Canyon. The fault is better exposed south of Gardner Canyon than north of it. Between Gardner Canyon and Cave Creek the trace of the fault swings northeastward, but a short distance farther north it trends N. 40°–45° W. to the gravel cover on the west side of the range. The fault mostly consists of a single shear surface, but along several miles of its trace northwest of Cave Creek it consists of several fault planes in a sheared zone about 1,000 feet (300 m) wide. South of Gardner Canyon, it dips 40°–70° E.; north of the canyon it dips from 60° E. to 70° W. Details on the time and direction of movement along the Big Casa Blanca Canyon fault are unclear. Northwest of Cave Creek, the fault trace is approximately parallel to the trace of the Sawmill Canyon fault zone, and the two may have had a common geologic history that involved recurrent movement with some lateral and much normal displacement. Only a small sliver of volcanic rocks of the Mount Wrightson Formation, caught along the Big Casa Blanca Canyon fault near the 65° dip segment in lower Big Casa Blanca Canyon, seems to directly support a more complex history, for it is far out of stratigraphic position with respect to the Cretaceous rocks in the walls of the fault. The structural features within the Adobe Canyon block, described below, give further insight into the probable movement on this fault.

Two small folds appear along the east edge of the block near Sawmill Canyon (SE). (The designations SE and NW are used in this report to distinguish by their relative positions two canyons that have identical names and a common headwater drainage divide.) The axes of the folds trend toward the ends of small normal faults, suggesting that the folds formed by vertical flexure rather than by horizontal compression.

Dikes of the Gardner Canyon and Box Canyon swarms of late(?) Oligocene age and the quartz vein swarm of Paleocene to Oligocene age extend across the Mount Wrightson block and are inferred to have formed along systematically oriented post-Laramide tension fractures. Their strike changes progressively southeastward across the block from N. 50° E. for the Box Canyon dike swarm, subparallel to the nearby range-front fault, to N. 80°–90° E. for the quartz veins, parallel to some of the small faults in the southern part of the block. East of the mouth of Mansfield Canyon, two veins lie along such faults, the rock between them forming a small horst. Several veins and this small horst abut another northwest-trending fault east of Temporal Gulch and do not appear beyond it. Dikes of both swarms cut across the Big Casa Blanca Canyon fault, a relationship which shows it to be prelate Oligocene in age. These vein relationships to the northeast faulting suggest that all these features are contemporaneous and thus of a Paleocene to Oligocene age. The Big Casa Blanca Canyon fault was probably also active during the Late Cretaceous, as was the nearby and subparallel Sawmill Canyon fault zone.

ADOBE CANYON BLOCK

The Adobe Canyon structural block extends diagonally across the Santa Rita Mountains between the Big Casa Blanca Canyon fault and the Sawmill Canyon fault zone. The block is unique for the Santa Rita Mountains in that it is strongly folded but little faulted. It is underlain mainly by the upper part of the Bisbee Group and the entire Fort Crittenden Formation, and it also contains segments of the Box Canyon and Gardner Canyon dike swarms and a plug related to the Gardner Canyon swarm.

In general, the fold axes trend parallel to the length of the block and its bounding faults. The axes of a few of the southernmost folds, however, are gently curved, concave to the southwest. The axial planes of the folds are inclined from the vertical to steeply northeast. In cross section the folds range from nearly isoclinal, to chevron, to open flexures. Their amplitudes are as much as several thousand feet (many hundreds of meters) (pl. 3, sections *D–D′* and *E–E′* of this report, and Drewes, 1971b, section *B–B′*). The axial planes of a few of the tight folds are faulted, and to the north these faults merge with the Sawmill Canyon fault zone.

The El Pilar Tank syncline, largest of the nearly isoclincal folds, is exceptionally well exposed in the lower Adobe Canyon area. The limbs and southern end of the fold are underlain by the shale and siltstone member of the Fort Crittenden Formation, and the trough of the fold contains part of the lower red conglomerate member of the Fort Crittenden. At lower stratigraphic levels, in shaly rock, the limbs of the fold converge at only 5°–10°, whereas at higher stratigraphic levels, in the more competent conglomerate, the fold is more open. Individual beds are unbroken around the trough of the fold. To the north, the syncline merges with an anticline lying to the east of it, thereby changing both folds into a homocline.

The Bath Tub Tank anticline (pl. 3), just west of the El Pilar Tank syncline, is a slightly more open fold whose limbs converge at 10°–30° near its southeast end. Rocks in the fold are the Turney Ranch Formation and the overlying Fort Crittenden Formation. Some beds are unbroken around the crest of the anticline; in two places the crest of the anticline is faulted. Several of the unbroken beds thin at the crest toward the southwest flank of the anticline without any signs of attenuation of individual beds. Several other unsheared groups of beds high in the Turney Ranch Formation are unconformably truncated near the fold crest, and in the absence of evidence of shearing, the truncation is believed to have been caused by erosion rather than by faulting. At the northwest end of the anticline, relatively competent beds of the brown conglomerate member of the Fort Crittenden Formation are much more openly folded, and the anticline gradually loses its identity. The southeast end of this anticline and the adjacent folds are covered by gravel; beyond the east edge of the gravel no folds are reported (R. B. Raup, oral commun., 1966).

The folds west of the Bath Tub Tank anticline are of smaller amplitude than the folds near the anticline; they are of the chevron type. One end of the chevron folds and both ends of the arcuate folds are truncated by the Big Casa Blanca Canyon fault. A small fault along the trough of one small syncline merges with the larger fault at the margin of the Adobe Canyon block.

To the northwest, near Gardner Canyon (pl. 3), the folds are of the chevron or of the relatively open types and their amplitudes are small. Their axes plunge gently with about equal frequency either toward the southeast or toward the northwest, an indication that the plunges were more likely due to the compression that folded the rocks than to later tilting of the axes. The beds of the crest of one open anticline are concordant with the south end of the top of the rhyolite porphyry plug between Gardner Canyon and Cave Creek. North of Cave Creek, several additional folds of the chevron type have nearly vertical and faulted axial planes. Between Florida Canyon and Sawmill (NW) Canyon, the beds strike northwest and dip steeply either way. Stratigraphic evidence and sedimentary structural features are generally inadequate to show the position of the tops of beds; if the tops are presumed to be up, then southwest dips are more abundant than northeast dips. Apparently more folds or faults are present in these rocks than have been identified.

SAWMILL CANYON FAULT ZONE

The Sawmill Canyon fault zone separates the central from the northeastern structural units and is one of the more complex features in the Santa Rita Mountains. The fault zone is narrow to the northwest but flares out to a width of about 1½ miles (2.5 km) to the southeast (pl. 3 of this report; Drewes, 1971a, b). Paleozoic formations and the Triassic Gardner Canyon Formation make up most of the rocks within the fault zone, but some Precambrian Continental Granodiorite, Triassic Mount Wrightson Formation, Glance Conglomerate (of the Bisbee Group), and Cretaceous Fort Crittenden Formation are also included. Dynamic metamorphism of these rocks increases in intensity northwestward toward the narrow end of the fault zone. A few small intrusives of upper(?) Oligocene rhyolite porphyry cut the rocks and faults of the zone. The assemblage of rocks within the fault zone differs considerably from that of the adjacent blocks. Northeast of the fault zone the Lower Cretaceous Bisbee Group typically lies directly upon Continental Granodiorite, and southwest of the fault zone the Bisbee Group lies between the Mount Wrightson Formation and the Upper Cretaceous Fort Crittenden Formation; the Gardner Canyon Formation is absent from both the adjacent blocks, and the Paleozoic rocks are almost entirely absent from the block to the northeast but may be concealed beneath the Mesozoic rocks in the block to the southwest.

The faults along the margins of the fault zone differ from each other both in trend and in attitude. The fault along the southwest margin is relatively well exposed, dips about 80° SW., where the zone is narrow and 60° NE., where the zone is broad, and is somewhat sinuous near Gardner Canyon. The bulge in the trace of this fault north of Cave Creek resembles the eastward bend in the adjacent part of the Big Casa Blanca Canyon fault (pl. 1). The fault on the northeast side of the zone is poorly exposed but is probably nearly vertical and has a straight trace trending N. 50°–55° W. Even the few short faults that branch off this fault into the northeastern structural unit remain closely subparallel to the main fault.

Faults are abundant within the Sawmill Canyon fault zone and are especially numerous in the Paleozoic rocks (pl. 3). Most faults in the Paleozoic rocks are so closely spaced that few of the included structural blocks are sufficiently large to contain a complete formation. Indeed, some blocks are so small that their lithology is scarcely diagnostic of any particular formation. Most of the internal faults are subparallel to the trend and dip of the fault zone; thus, in plan, the included blocks form wedges or oblong areas. A few faults, however, are more gently inclined, and at least some of these may be remnants of a thrust fault. Near the center of sec. 35, T. 19 S., R. 15 E., for instance, Middle Cambrian Bolsa Quartzite is faulted onto Middle and Upper Cambrian Abrigo Formation along a surface that dips 35° E. The beds in the quartzite lie parallel to the fault, but those in the Abrigo dip steeply and, therefore, must be truncated by the fault. A few steeply dipping faults are subparallel to bedding in the adjacent blocks and separate one group of more or less contiguous formations from another; these may also be thrust faults that were tilted by a later deformation.

Folds are distinctly less abundant in the fault zone than faults, but their presence suggests that the zone is a complex feature. In the central part of the zone (SE¼ sec. 35, T. 19 S., R. 15 E., pl. 3), for instance, a broken sequence of Martin Formation (Devonian), Escabrosa Limestone (Mississippian), and Horquilla Limestone (Pennsylvanian), followed by more Escabrosa and then again by Martin, suggests that the folding preceded some faulting. Near the southeast end of the fault zone, a few small relatively tight folds and some larger open folds occur in the central of three belts of red beds of the Gardner Canyon Formation (Triassic). These folds are also faulted.

The complexity of the Sawmill Canyon fault zone by itself suggests that movement along the fault zone did not take place in a single direction nor occur as a single event. Thus, local features permitting inferences on time or direction of movement may seem to conflict with one another, or evidence permitting such inferences may be largely destroyed. The evidence of thrust faulting and of northeast-southwest-oriented compression indicated by the folds, however, is believed to be significant. Additional evidence on the directions and times of movement comes from more distant stratigraphic and structural data, reviewed below.

The stratigraphic record shows that large crustal movements occurred repeatedly across the middle of the area now occupied by the Santa Rita Mountains. Movement on the Sawmill Canyon fault zone is the most logical explanation of the stratigraphic evidence. During Triassic time, lenses of conglomerate that contained Precambrian granitoid cobbles were intercalated in the volcanics of the Mount Wrightson Formation 4½ miles (7 km) southwest of the fault zone (Drewes, 1971b, c). In order for Precambrian rock to have been exposed to erosion so soon after the retreat of the sea from which the Permian formations were deposited, a nearby block would have needed to be raised. The largest exposed body of Precambrian granitoid rock in the area today lies immediately northeast of the Sawmill Canyon fault zone, and that area is believed to have been the source of the Precambrian cobbles that were intercalated in the volcanics during the

Triassic. The total vertical movement between the blocks at this time was 1–2 miles (1.5–3 km), comprising at least the thickness of the Paleozoic cover (about 6,000 ft or 1,800 m) removed from the granitoid rocks, plus the thickness of Triassic rocks below the cobble conglomerate lenses (at least 3,000 ft (900 m), and the Triassic rocks do not appear to thin toward the fault). Later during the Triassic, in Gardner Canyon time, the area of the fault zone (or, more precisely, the area from which the rocks of the fault zone were thrust faulted during the Laramide Orogeny, as described in the second paragraph below) was a basin of deposition in which some conglomerate, derived from older Triassic volcanics, apparently to the southwest, was deposited. This apparent topographic change of the Mount Wrightson block from a high terrain to a low one may have involved reversal of movement on the fault zone.

Two large wedges of boulder conglomerate intercalated in the Temporal and Bathtub Formations of Early Cretaceous age (Drewes, 1971c) southwest of the Sawmill Canyon fault zone suggest that the block northeast of the zone was uplifted twice during this time. These bodies of conglomerate are more than 1,000 feet (300 m) thick at a distance of 1–2 miles (1.5–3 km) from the fault zone, and they wedge out 3–4 miles (5–6 km) from the fault zone. A similar occurrence of conglomerates in the Bisbee Group within both blocks adjacent to the Sawmill Canyon fault zone requires no differential relief across the zone during the late Early Cretaceous. However, during the early Late Cretaceous, thick deposits of the Fort Crittenden Formation accumulated apparently only in the area immediately southwest of the fault zone, and so upward movement of the block northeast of the fault zone may have been renewed.

The structural record from other parts of the Santa Rita Mountains provides additional clues to the timing of movement along the Sawmill Canyon fault zone. The structural features within the fault zone include thrust faults and northwest-trending folds, but in this complex structural environment there is no indication of the genetic relation or age of the faults and folds. However, similarly oriented folds, such as those of the Montosa Canyon area, already described, and others in the northern part of the mountains, to be described in the section on the northeastern structural unit, are shown to be genetically associated with thrust faults, and these thrust faults furthermore are dated as late Late Cretaceous. Therefore, the folds and thrust faults in the Sawmill Canyon fault zone are inferred to be also of late Late Cretaceous age and to have formed as a result of northeast- to southwest-oriented compression.

Finally, the abundant left-lateral tear faults, of Paleocene age, of the northeastern structural unit, to be described in the following section, are parallel to, and resemble in some ways, the Sawmill Canyon fault zone. Thrust faults that are genetically related to the tear faults typically lie along one or more horizons in the bedded rocks between the tear faults, and one such thrust fault appears in the southern part of the northeastern unit, adjacent to the Sawmill Canyon fault zone. Thus, I suspect that left-lateral tear movement took place during the Paleocene along the Sawmill Canyon fault zone, or at least on the fault along the northeast margin of the zone, at the level of the adjacent plate of Bisbee rocks. By late Oligocene time, however, movement on the fault zone had ceased, as indicated by the lack of deformation of rhyolite porphyry dikes that cut across the fault zone near Gardner Canyon and along lower Sawmill Canyon (NW) (pl. 1).

NORTHEASTERN STRUCTURAL UNIT

The northeastern structural unit extends from the Sawmill Canyon fault zone to the northern end of the Santa Rita Mountains. The southern part of the unit is underlain mainly by Precambrian rocks and Lower Cretaceous Bisbee rocks; but toward the north, metamorphosed Paleozoic and lower Mesozoic rocks appear beneath the Bisbee and some volcanics of the Upper Cretaceous Salero Formation overlie the Bisbee. In general, rocks of this structural unit dip gently to moderately steeply eastward, but they are more intensively deformed than the similarly inclined rocks of the central structural unit. Assorted small intrusive bodies of Paleocene and younger ages also underlie the area. The northeastern structural unit consists of three smaller structural blocks, the Greaterville, Rosemont, and Helvetia blocks.

GREATERVILLE BLOCK

The Greaterville block extends from the Sawmill Canyon fault zone to the Box Canyon fault zone (pl. 1). It is underlain largely by Precambrian gneiss and granodiorite porphyry and by the Lower Cretaceous Bisbee Group. A small part of the block is underlain by Middle Cambrian Bolsa Quartzite and by intrusives of Paleocene and of late(?) Oligocene ages. The rocks are abundantly faulted, and the capping sheet of Bisbee is also folded.

Most faults in this block are normal faults, and many of these trend N. 45°–70° W. A few of the faults are paired to form grabens of Bisbee rocks in the Precambrian terrane. The grabens vary in size, perhaps because they are exposed at different structural levels. The largest graben, or perhaps the one exposed at the shallowest level, is part of the Box Canyon fault zone, which is well exposed near the corral along the road through Box Canyon. The zone of Bisbee rocks at the corral and southeast of it is only about 300 feet (100 m) wide, but uphill to the northwest, the graben flares out to a width of half a mile (almost 1 km) owing to the upward divergence of dips on the bordering faults. Farther northwest across the range crest and sharply downhill, the faults converge and pinch out the graben. Farther south of Box Canyon, the Bisbee is also pinched out and the bounding faults, here single fault planes, merge with another graben-bounding pair of faults along the south fork of Box Canyon.

The graben along the south fork of Box Canyon, trending N. 70° W., either is of intermediate size or is exposed at a deeper level than that at Box Canyon. Within the graben the Bisbee is nearly upended; outside the graben it typically dips 30° SE.

The smallest graben is a sliver of Bisbee in the Continental Granodiorite on the southernmost knob of the crest of the range west of the upper part of Enzenberg Canyon (Drewes, 1971a). The graben-bounding faults merge at the end of the sliver, and a single fault extends southeastward from the graben, offsetting thrust faults that involve Bisbee rocks and merging with the Sawmill Canyon fault zone.

Although the apparent movement direction on the faults bordering the grabens is normal, some left-lateral displacement, such as is demonstrable on similarly oriented faults to the north, may also have occurred. The high-angle faults postdate thrust faults of Laramide age, described below, and are cut by a few dikes of late(?) Oligocene age; most likely they are late Paleocene structural features.

The Greaterville block is also cut by a few low-angle faults. One such fault is exposed on the north wall of Sawmill Canyon (NW), where it dips 40° northward and lies entirely within the Precambrian Continental Granodiorite.

A poorly exposed low-angle fault, thrust fault I on plate 1, is believed to underlie the Bisbee throughout the block; it extends northward into other structural blocks, where it is better exposed. In the Greaterville block, thrust fault I is exposed in a gully that crosses the basal contact of the Bisbee midway along the southeast margin of the klippe of Bisbee that lies northwest of the upper reaches of Enzenberg Canyon. In that area, a zone of fault gouge 20 feet (6 m) thick separates interbedded coarse-grained arkose and reddish-gray siltstone of the Willow Canyon Formation of the Bisbee Group from the granodiorite. Fault I was apparently cut in a drill hole put down near the north edge of the largest of the quartz latite plugs, 1 mile (1.5 km) west of Greaterville. At a depth of 1,635 feet (498 m) in this hole, Bisbee rocks are separated from granodiorite by a gouge zone about 2 feet (60 cm) thick, and the lowest 40 feet (12 m) of overlying arkose is shattered.

Thrust fault I is thought to be widespread in the Greaterville block, because many of the bedded rocks form a disharmonically deformed plate above the massive granodiorite. For instance, the rocks in the klippe northwest of upper Enzenberg Canyon form a small northeast-trending syncline that is not paralleled by the configuration of the contact beneath the bedded rocks. Some of the beds, as well as the fold axis, are truncated against the contact, and the underlying granodiorite seems to be entirely undeformed. Rocks of the thrust plate between the klippe and the main mass of the Bisbee rocks southeast of upper Enzenberg Canyon were probably deformed into a small northeastward-trending disharmonic anticline, of which the axial part has been entirely eroded away, leaving only beds of the northwestern flank of the fold in the klippe and beds of the southeastern flank of the fold in the main mass of the thrust plate.

Southeast of Enzenberg Canyon, the rocks of the Bisbee Group are warped into a large, open, northwest-trending syncline, herein referred to as the Boston syncline inasmuch as the southeast end of the syncline lies approximately along Boston Gulch (Drewes, 1971b). The axial plane of this syncline dips steeply southwest, and its axis plunges gently southeast. A string of plugs, small pods, and dikes of quartz latite porphyry, of late Paleocene age, have intruded the trough area of the Boston syncline and have metamorphosed and mineralized the host rocks (Drewes, 1970, 1971a). Beds on the northeast flank of the syncline dip 30°–40° SE., except locally along subsidiary folds, whose axial planes and axes are subparallel to those of the Boston syncline. Beds on the other flank of the Boston syncline dip steeply northeastward and include several relatively tight subsidiary chevron folds, of great length but of moderate amplitude, that also plunge gently southeastward. Three of these lesser folds are slightly overturned to the northeast, and a fourth one is inclined to the southwest. These folds are so tight that it seems unlikely that they penetrate to the structural level of the underlying massive granodiorite, and therefore the base of the folded Bisbee must be a low-angle fault between disharmonic plates.

The two fold trends that are 90° from each other in the thrust plate require two directions of movement along the thrust fault and hence two periods of movement. The alinement of the plugs along the trough of the Boston syncline, together with the intrusion of a dike similar in composition to the plugs along the axial plane of one of the tighter northwest-trending folds (Drewes, 1970, 1971b), indicates that northwest-oriented folding preceded intrusion. This folding probably took place at the same time as the similarly oriented folding in the Montosa Canyon block—during the late Late Cretaceous. The northeast-trending fold is presumed to have formed toward the end of the Paleocene at a time when the structural blocks to the north were more severely deformed.

The Greaterville block is intruded by two groups of dikes, which provide additional structural information. The older dikes are those associated with the plugs of late Paleocene age, mentioned above. The dikes are of quartz latite porphyry, are widely scattered, are variously oriented though mainly northwest-trending, and are commonly short and irregularly thick. One of these dikes intrudes the axis of a northwest-trending chevron fold, thereby indicating that the intrusion followed the folding. The younger dikes are rhyolite porphyry of late(?) Oligocene age and are part of the Box Canyon dike swarm (Drewes, 1971a, c). These dikes are loosely clustered northwest of Enzenberg Canyon, trend mostly N. 35°–40° E., and are relatively long and regularly tabular. Some of them cut several of the northwest-trending faults and the thrust fault. Others end against northwest-trending faults; some continue out of alinement across these faults, but they probably are not offset by the faults. As elsewhere, this dike swarm probably filled tension fractures. The stress system in the area seems to have changed markedly between the times the older dikes and the younger dikes were emplaced.

ROSEMONT BLOCK

The Rosemont structural block lies between the Box Canyon and the Gunsight Notch fault zones (pl. 1). Both the Gunsight Notch fault zone and the Helvetia klippe, which locally lies athwart the Gunsight Notch fault zone, will be described with the Helvetia block rather than with the Rosemont block, because of their greater similarity to structural features to the north than to those to the south. The Rosemont block is underlain by much Precambrian granodiorite and by some Paleozoic rocks, by the Lower Cretaceous Bisbee Group, and by intrusive rocks of Paleocene age. The Paleozoic rocks typically dip steeply eastward, and the Bisbee dips moderately steeply southeastward but locally dips westward. The rocks are cut by numerous faults, some of which are fairly complex. Most of the rocks in the northern part of the block are metamorphosed; and, in general, the degree of structural complexity increases as the intensity of the metamorphism increases.

The Deering Spring fault, extending from the south corner of the block at least as far north as Rosemont, is a normal fault and largely a range-front fault, along which Pliocene and Pleistocene gravel has been dropped to the east. To the south the fault follows a segment of the Box Canyon fault zone. Just north of Box Canyon, the fault is exposed in a small prospect, where it dips steeply eastward; and north of Deering Spring, the fault is marked by alined seeps. At Rosemont (pl. 4), the fault enters an intensely altered bedrock terrane in which its identity is obscured, but it is presumed to follow a steep fault between the Bisbee Group and the Paleozoic rocks, perhaps to the north edge of the block. The latest movement along this fault may be as young as Pleistocene.

Thrust faults are more abundant in the Rosemont block than they are to the south. They are identified on plate 1 and in the text by Roman numerals, in numerical order from the lowest to the highest structural position. Most of these faults are traced with confidence throughout the block, as shown on plate 4.

Thrust fault I extends nearly through the Rosemont block, where it overlies massive Continental Granodiorite and underlies bedded rocks. The fault mostly forms a single plane or narrow gouge zone; but in some places, as south of Box Canyon, it forms a pair of planes a few hundred feet apart, and in others, as along the Box Canyon road, it forms a shear zone several hundred feet (many tens of meters) thick. The bedded rocks above the fault are mostly subparallel to the fault; but in a few places, such as the southern part of the area shown on plate 4 and the area south of Box Canyon (Drewes, 1971a), they are inclined toward the fault 20°–50°. The trace of thrust fault I is fairly unbroken south of Box Canyon, but it is offset by many transverse faults north of the canyon. About 1 mile (1.5 km) north of the canyon, the thrust fault is offset by a pair of normal faults, between which Bolsa Quartzite and Abrigo Formation form a grabenlike mass. These normal faults merge southward with a steep segment of the thrust fault. The thrust fault dips mostly eastward, the dip values being low to the south and about 90° to the north. Secondary copper minerals stain the fault gouge north and west of Rosemont.

The relations along thrust fault I near the head of Wasp Canyon are similarly complex (pls. 1, 4). Bolsa Quartzite, dipping 65°–90° E., is faulted on Continental Granodiorite along an unexposed surface estimated to dip 20° E. at its north end and 60° E. at its south end. Some Abrigo lies conformably upon the Bolsa, and at the south end of the fault both formations seem to be unconformably covered by Bisbee. Because the critical junction of the fault with the contact beneath the Bisbee is unexposed, the projection of the fault southward beneath the Bisbee is conjectural. This conjectural segment of thrust fault I is commonly located to within 100 feet (30 m) on the ground; though conjectural, the slight difference in attitude of the Bisbee with respect to that of the contact at a few places supports a fault interpretation.

North of Wasp Canyon, thrust fault I is relatively well exposed. Over the first mile it dips 53°–70° E. and farther north it is nearly vertical and even slightly overturned, 85° to the west. The sheared zone in this area is 2–30 feet (0.6–9 m) thick, and between Rosemont and Helvetia it is enriched in secondary copper minerals.

Thrust fault II extends from Box Canyon almost to the Gunsight Notch fault zone (pls. 1, 4). Most of the fault underlies the Escabrosa Limestone but in other ways the fault resembles thrust fault I. To the north, thrust fault II branches: the lower branch, IIa, underlies a small plate of Horquilla Limestone and the upper branch, IIb, underlies a plate of Escabrosa, thereby bringing older rocks above younger ones. To the south, another branch of thrust fault II underlies a thin plate of Martin Formation and is well exposed along a string of prospects as a mineralized and sheared zone a few feet thick that is inclined 35°–45° E. (The limestone overlying thrust fault II in this area, west of Deering Spring, is erroneously shown on the geologic map and on section *C–C′* (Drewes, 1971a) as Horquilla Limestone instead of Escabrosa Limestone.)

Thrust fault III extends from Wasp Canyon northward at least to Rosemont and probably also reappears east of VABM Helvetia. It, too, is typically a near-bedding thrust fault, along which younger rocks, such as the Colina Limestone and Scherrer Formation, have been moved over older ones, mainly the Horquilla Formation. To the south the fault dips 40° E. but to the north it gradually steepens to about vertical.

South of the Wasp Canyon the highest thrust fault in the Rosemont block, fault IV, underlies a plate consisting largely of Glance Conglomerate. Unlike the arkosic Glance overlying fault I, this sheet of Glance is metamorphosed and consists of pebbles and cobbles, mainly of limestone set in a sandstone matrix. The Glance of this plate, moreover, dips moderately steeply westward toward fault IV and is therefore unlike most of the rocks in the thrust plates of the Rosemont block in that these rocks dip away from the faults beneath them. Thrust fault IV dips 45° E. near Box Canyon and about 10° E. near Wasp Canyon. To the south, it appears to merge with fault II; and to the north, it is cut by the Deering Spring fault and is intruded by andesitic plugs thought to be of early Tertiary age.

Faults transverse to the belt of Paleozoic rocks and to the thrust faults are abundant in the northern part of the Rosemont block. Most of these faults are nearly vertical; the larger ones strike east or east-northeast, and a few smaller ones strike northwest or northeast. Some of the transverse faults, like the fault south of the head of Wasp Canyon, are restricted to one or several thrust plates, demonstrating that the displacement on them is contemporaneous with thrusting. Others, such as the east-northeast-trending fault cut by the plug southwest of Rosemont and the east-striking transverse fault zone northwest of Rosemont, separate nonmatching sequences of Paleozoic rocks and thrust faults. Although postthrust faulting could account for the offsets, much of the movement on the transverse faults must have been contemporaneous with thrusting. The large transverse faults are probably tear faults, and they show that thrust faulting was oriented east-northeast or west-southwest.

A few faults unrelated to one of these sets of thrust and tear faults include a nearly vertical arcuate fault, concave to the northeast, near the Narragansett mine and just south of Gunsight Notch (pl. 4 of this report; Creasey and Quick, 1955) and a fault, striking about north and dipping vertically, along the west edge of a quartz monzonite stock on the road between Helvetia and Box Canyon. (See west side of pl. 4.)

The Tertiary intrusives cutting the rocks of the Rosemont block provide additional structural data that pertain to the age of thrusting. The small elliptical stock at VABM Helvetia cuts across thrust fault I, indicating that the intrusion is younger than the fault. The stock is correlated with the stocks of Helvetia farther northwest, which are isotopically dated as mid-Paleocene. Similarly, the Paleocene quartz latite porphyry plug at Rosemont and several dikes related to this plug were emplaced along thrust and tear faults; these provide a minimum age for the faults. One of the northern rhyolite dikes of the Oligocene Box Canyon swarm intrudes the transverse tear fault that is projected into the plug southwest of Rosemont. The andesite plugs at Deering Spring that are probably of early Tertiary age also cut thrust fault IV and are cut by the Deering Spring fault (pl. 1).

The structural relations between the thrust and tear faults indicate that they are not entirely synchronous, although they probably formed during one phase of deformation early in the Laramide Orogeny. Thrust fault IV truncates fault III along Wasp Canyon (pl. 4). Fault II truncates a tear fault that offsets fault IV south of Wasp Canyon, and it is therefore probably younger than fault IV. Likewise, fault I is probably younger than fault II because some transverse faults that cut fault II are cut by, or end at, fault I. The sequence of their development, then, appears to be III, IV, II, and I. These faults formed probably as the result of east to east-northeast compression during the Late Cretaceous, after Bisbee time and before the emplacement of Paleocene stocks. This deformation preceded the eastward tilting of the Rosemont block, which has contributed to the general inclination of both bedding and thrust faults.

HELVETIA BLOCK

The Helvetia block, most complex of the structural blocks, lies at the north end of the Santa Rita Mountains and northeast of the Gunsight Notch fault zone. The block is underlain largely by the same types of Precambrian, Paleozoic, and Lower Cretaceous rocks that occur in the Rosemont block. In addition, it contains some upper Upper Cretaceous Salero Formation, most of which, however, underlies that part of the block extending east of the Sahuarita quadrangle. As a whole, the rocks dip eastward, as is typical for those in the northeastern structural unit, but they dip less steeply than do the rocks south of the Gunsight Notch fault zone. The rocks are intensely faulted, and in many places they are folded, intruded, and metamorphosed.

A radiometric date from a part of the stock at the Mount Fagan Ranch (pl. 1) east of the Sahuarita quadrangle, obtained from R. F. Marvin (written commun., 1971) after publication of the geologic map of that quadrangle, shows the stock to be 73.8 ± 2.6 m.y. old. This modification of age, though adding to the intrusive history of the area, does not alter the description or interpretation of structural features presented in this report.

TEAR FAULTS

Tear faults are the most conspicuous faults in the Helvetia block, as shown on plates 1 and 4. These include the Gunsight Notch fault zone, the Sycamore Canyon fault zone, and the Johnson Ranch fault.

The Gunsight Notch fault zone strikes N. 60° W. through a notch in the crest of the range that locally is called Gunsight Notch, 1,000 feet (300 m) northeast of peak 6,118. The site of the notch is recognizable as the southern of two unmapped jeep tracks between Helvetia and Rosemont. For 1 mile (1.5 km) northwest of the notch, the fault zone consists of two to four branches, marked by slivers of Bolsa Quartzite, Pinal Schist, and Horquilla Limestone. The Bolsa slivers are recrystallized with increasing intensity toward the northwest, until they resemble quartz veins. Farther northwest, the fault zone is concealed beneath a klippe, and beyond the klippe the fault zone places Bolsa and Horquilla into contact with Continental Granodiorite (pl. 4). Judged by the habits of other tear faults, the Gunsight Notch fault flattens at relatively shallow depths, and it is believed to become the thrust fault whose remnants appear in the pediment 1 mile (1.5 km) to the northwest of the Helvetia klippe (pl. 4; inset, pl. 1). Its continuation southeast of the plexus of faults at Gunsight Notch is believed to extend across a zone of poorly exposed, diversely dipping Willow Canyon Formation and along the southwest edge of an inlier of Epitaph Dolomite.

About 1 mile (1.5 km) north of Helvetia townsite a second tear-fault zone strikes N. 65° W. and separates upper Paleozoic from Precambrian rocks (pls. 1, 4). Several slices of lower Paleozoic rocks lie along the fault zone. The fault zone is truncated to the southeast by a thrust fault and to the northwest by a stock of the Helvetia intrusives. One small aplitic dike, of the sort that intrudes the nearby stock, cuts across the fault zone (pl. 4). The tear fault probably extended northwestward to join the Gunsight Notch fault zone before the stock was emplaced.

Still another tear fault zone trends N. 60° W. about 2 miles north of Helvetia townsite. Slices of Bolsa, Abrigo, and Escabrosa are dragged along this zone, and the Bolsa adjacent to the zone shows a left-lateral displacement of about 2,000 feet (600 m). The tear fault zone is truncated by a thrust fault to the southeast and extends into the Continental Granodiorite to the northwest, roughly midway between two stocks of the Helvetia intrusives. Farther northwest it is covered by pediment gravel.

A fourth tear fault is inferred to trend N. 50° W. a short distance south of Johnson Ranch (pls. 1, 4), because northeast of an elongate granodiorite stock that intrudes the tear fault the rocks are upper Paleozoic formations that dip steeply northeast, whereas to the southwest of the stock the rocks are lower Paleozoic formations that dip moderately to the southeast. This juxtaposition is best explained by inferring a fault whose attitude and movement direction resemble those of the other tear faults of this block. To the southeast of the stock, a thrust plate of Horquilla Limestone overlies the trace of the inferred tear fault and presumably truncated the fault before the fault was intruded by the stock.

Half a mile (about 1 km) north-northwest of Gunsight Notch, several short N. 40° W.-trending left-lateral tear faults merge with thrust faults (pl. 4). The dips of the southeast ends of the tear faults are steep, but at the other ends of three tear faults, the dips flatten and the strikes veer northward, whereby these three faults become thrust faults that separate plates of Paleozoic formations from plates of Precambrian rock. The northeasternmost of these three tear faults, which remains steep, separates Pennsylvanian and Permian rocks to the northeast from Precambrian to Pennsylvanian rocks to the southwest. It truncates one thrust fault zone in its northeastern block and abuts the thrust fault that merges with the southwesternmost tear fault.

478-028 O - 73 - 3

About 1½ miles (2.5 km) north-northeast of VABM Helvetia the Sycamore Ridge fault trends N. 60°–65° W. from just beyond the east edge of the Sahuarita quadrangle to the thrust fault last mentioned above, thrust fault C. (See inset map, pl. 1.) Deflection of beds near the fault and displacement of beds across it indicate that it has a left-lateral offset of about 7,000 feet (2,200 m).

The Sycamore Canyon tear fault zone strikes N. 45° W. from beyond the east margin of the quadrangle to a point about 1 mile (1.5 km) southeast of the Johnson Ranch, where it swings northward and flattens to become a thrust fault. This tear fault zone separates a southwestern sequence of a few Bisbee and many pre-Bisbee rocks in several thrust plates from a northeastern sequence consisting entirely of Bisbee. A sliver of Salero Formation of late Late Cretaceous age is caught along a thrust fault related to the Sycamore Canyon fault zone. Slices of Concha Limestone and Bisbee Group are dragged along the fault zone, and an elongate stock and dikes of Paleocene quartz latite porphyry have intruded segments of the zone. The rocks across the tear fault were offset left-laterally at least 8,000 feet (2,500 m) between late Late Cretaceous and late Paleocene time.

The Johnson Ranch fault is another tear fault that trends N. 45°–85° W.; it extends from 1 mile (1.5 km) east of the ranch to the ranch (inset, pl. 1). It is truncated to the east by a thrust fault and probably extends beneath pediment gravel northwest of the ranch beyond the stock that presumably intrudes it. Although the fault is rarely exposed, it is thought to be a major structural feature, inasmuch as it separates a thick thrust plate of Permian rocks to the southwest from many thin plates of assorted Paleozoic and Mesozoic rocks to the northwest.

THRUST FAULTS

Thrust faults are almost as abundant as the tear faults in the Helvetia block (pls. 1, 4). Many of them lie subparallel to bedding, but others strike across bedding. Because of the uncertainties of correlating faults across the Gunsight Notch fault zone, most thrust faults of the Helvetia block are designated by letters rather than by the Roman numerals used in the Rosemont block. Only fault I of the Rosemont block is thought to extend into the Helvetia block, although there is no evidence that its segments were formed as a coherent element at a uniform rate. Because of similar difficulties in correlating thrust faults across the Johnson Ranch fault, lowercase letters are used for the faults to the north, except for fault G, and uppercase letters are used for those to the south.

Typically, the contact between the massive Precambrian granodiorite and the bedded Cambrian rocks is the site of a thrust fault. In the Rosemont block, this is the widespread thrust fault I; in the Helvetia block, however, there are several such horizons, the granodiorite having been thrust imbricately upon the plates of Cambrian rocks. On the west flank of the two high knobs between Shamrod Spring and Johnson Ranch, the rocks adjacent to the second lowest imbricate fault most closely resemble those next to fault I south of Gunsight Notch, and so these faults are tentatively correlated. In places, the basal conglomeratic beds of the Cambrian Bolsa Quartzite are present; but, in others, the entire Bolsa is missing, and the Abrigo is in fault contact with the Continental Granodiorite. Fault I may have extended north of the Johnson Ranch tear fault before the emplacement of Paleocene stocks there, inasmuch as the roof pendants and inclusions in the stocks lie roughly in the proper stratigraphic and structural position to correlate with their less severely intruded counterparts to the south.

Thrust fault A separates Bolsa Quartzite from Continental Granodiorite on hill 3,802 in the pediment area northwest of Helvetia townsite (inset map, pl. 1; pl. 4). Its extension to the south of the hill is inferred, in part from the presence of a minor thrust fault believed to be subsidiary to fault A, and in part from the habits of similar faults 1½ miles (2.5 km) north and east of Helvetia townsite. On hill 3,802 the Bolsa dips more steeply eastward than does the contact beneath it, and this relationship confirms a thrust-faulted basal contact more than any evidence that can be found along the poorly exposed contact itself. The subsidiary thrust fault separates truncated Martin Formation from massive Escabrosa Limestone on a knoll about 1 mile (1.5 km) south of hill 3,802.

Another unlettered thrust fault is inferred to lie east of hill 3,802 and the knoll capped by Escabrosa on the basis that a concealed contact must be present between the Paleozoic rocks overlying fault A to the west and Continental Granodiorite, in part intruded by a Paleocene stock, to the east. To the south, this unlettered fault is believed to merge with the Gunsight Notch fault zone northwest of the Helvetia klippe and to be intruded by the Paleocene stock. That this concealed and intruded fault is a thrust fault rather than a normal fault is inferred solely from the style of faulting common in the Helvetia block, especially in such places as east of the Helvetia klippe.

Thrust fault B dips gently to moderately steeply eastward between the Martin Formation and the Escabrosa Limestone, from near Shamrod Spring to a point 1¼ miles (2 km) to the northeast (pls. 1, 4). Most of the beds adjacent to the southwestern part of the fault are parallel to each other, but in two places beds above the fault are warped into small west-northwest-striking folds that are disharmonically truncated against the fault. Toward the northeast, thrust fault B splits into two branches; the lower one, B_1, truncates a tear fault zone in the underlying plate and is truncated by the elongate strock of granodiorite. The upper branch fault, B_2, brings a thin sheet of relatively older Martin and other formations onto relatively younger Horquilla of a lower thrust slice, and to the northeast it probably is truncated by the end of the elongated stock.

A minor unlettered thrust fault east of the southern part of fault B and half a mile east of Shamrod Spring separates the Earp Formation from the overlying Epitaph Dolomite. The Colina Limestone is absent between the Earp and Epitaph, and some beds beneath the fault are truncated by the fault. The minor thrust is truncated by fault C to the east and by a tear fault to the southwest.

Thrust fault C extends from near Gunsight Notch almost to the south fork of Sycamore Canyon (pls. 1, 4). Most of the fault dips moderately steeply eastward and truncates beds above as well as below it. Near the south end of fault C, about three-fourths mile (1.2 km) northwest of Gunsight Notch (pl. 4), small slices of lower Paleozoic formations are thrust onto the Continental Granodiorite and probably onto an edge of the Gunsight Notch fault zone. Half a mile (less than 1 km) northwest of the Leader shaft (pl. 4), strongly contorted pods of flow-laminated gypsum lie in the Epitaph Dolomite close beneath the thrust fault. Still farther north, a block of moderately steeply southeast-inclined Permian rocks is thrust over upended to overturned north- to northwest-striking Horquilla Limestone. At its north end, fault C is truncated by the Sycamore Canyon fault zone and is intruded by a body of Paleocene quartz latite porphyry.

Near the Leader shaft, thrust fault D brings a plate of Precambrian Continental Granodiorite over a plate of lower Paleozoic rocks (pls. 1, 4). Near the shaft, fault D merges with a tear fault that truncates thrust fault C; and half a mile (less than 1 km) north of the shaft, faults D and C merge.

Three additional minor unlettered thrust faults follow bedding planes in the rocks east of the Leader shaft. Two of them lie along the basal and top contacts of the Bolsa Quartzite, which is almost sheared out southward where the thrust faults merge with a tear fault. These two minor faults are truncated about half a mile (less than 1 km) north of the shaft by a tear fault. The third minor fault follows a plane of lithologic contrast above a gypsiferous zone within the Epitaph Dolomite and is truncated by tear faults at both ends.

Thrust fault E underlies two small klippen of Scherrer quartzite and Concha Limestone, respectively, about ¾ mile (1.2 km) and 1¼ miles (2 km) north of the Leader shaft. Fault E is anomalous in that it dips westward rather than eastward and in that it appears to be cut by fault C rather than by tear faults. The similarity of these klippen suggests that they may be remnants of a single plate.

Fault F forms the contact between the Willow Canyon Formation of the Bisbee Group and the Rainvalley Formation of the Naco Group east of Sycamore Ridge, half a mile (1 km) northeast of Gunsight Notch, and also 1 mile (1.5 km) northwest of the ridge (pl. 4). This fault is probably a bedding-plane thrust fault much like the abundant faults nearby, but it could be a normal fault. The north end of fault F is truncated by the Sycamore Canyon fault zone, the central part is offset southeastward about 1½ miles (2.5 km) on the Sycamore Ridge tear fault, and the southern part is cut by the east-trending normal(?) fault running through Gunsight Notch.

Thrust fault G, southeast of Johnson Ranch, is inferred to follow the unconformity separating a klippe of Triassic and Jurassic sedimentary rocks from underlying Permian rocks (pl. 1). The fault may extend beneath a smaller klippe of highly metamorphosed Triassic(?) rocks at the edge of the pediment cover southwest of the ranch (pl. 4). Fault G is truncated by the Sycamore Canyon fault zone southeast of the ranch and by fault B_2 to the south-southeast; it may reappear among the many fault slices north of Sycamore Canyon. A sheared contact has been seen along the southwest margin of the main klippe near the National Forest boundary line (pl. 4); but, elsewhere, evidence for thrust faulting is indirect, because the rock is strongly attenuated and recrystallized. Extensive truncation of the rocks at the base of the upper plate, however, indicates shearing along the contact rather than simply local onlapping. Furthermore, slightly disharmonic folding of the upper plate with respect to the lower plate, as indicated by a lack of alinement of the axes of the synclines in the two plates, also suggests movement along the contact.

Thrust fault H underlies the Helvetia klippe, which forms a roughly polygonal area, 1¼ miles (2 km) long and more than ½ mile wide (about 1 km), immediately north of Helvetia townsite. Fault H is exceptionally well exposed because of the resistance to weathering of the overlying rocks and because of the abundance of prospects and mines in the mineralized and sheared rocks along the fault. The trace of the fault is roughly horizontal around the west flank of Peach Hill (about one-fourth mile NW. of Helvetia townsite), but overall it rises gently to the east. Fault H dips inward toward the center of the klippe, the dips being about 40° along the west side, 5°–10° along the north and south sides, and 10°–30° along the east side. Drill-hole data from the southeast side of Peach Hill (Heyman, 1958) show the lowest part of the fault to lie 160–420 feet (50–130 m) beneath the surface, the range of depth reflecting the topography. Thus, the fault surface is like a slightly asymmetrical saucer, concave side up. A zone of sheared rock and gouge 1–3 feet (30–90 cm) thick commonly lies along the fault.

The rocks of the Helvetia klippe consist of a little Bisbee and parts of all the Paleozoic formations except the Escabrosa, Colina, and Rainvalley. The rocks are considerably disrupted by subsidiary thrust faults to the west and by many high-angle faults throughout the plate. The older Paleozoic rocks are restricted to the west, and the younger ones lie, generally in rising succession, toward the east. The klippe rests on two granodiorite to quartz monzonite stocks of late Paleocene age, as well as on Precambrian granodiorite, and it is believed to be intruded by a quartz latite porphyry plug, also of late Paleocene age. Heyman (1958) and Michel (1959), however, interpreted the quartz latite porphyry to be part of the klippe, a view not favored here because of the absence of a shear plane from the east side of the plug and the possibility that locally the plug was emplaced along thrust fault H in an irregular manner—as such plugs were elsewhere—to produce the particular relations cited by Heyman and Michel in support of their interpretation.

Fault H can be closely dated as late Paleocene by a combination of geologic and isotopic data. The stocks on which the klippe rests are dated by the potassium-argon method; the stock to the south is 53.5 $\pm$1.6 m.y. old (Drewes, 1972a) and that to the north is 53.9 $\pm$2.0 m.y. old (R. F. Marvin, written commun., 1970). The plug that is inferred to intrude the klippe is dated by similar isotopic methods as about 56 m.y. old (Drewes and Finnell, 1968), and nearly identical ages have been obtained on other nearby plugs of quartz latite porphyry (Drewes, 1970, 1972a). The difference in ages between these two groups of intrusives is here regarded as insignificant, and the age of the thrust faulting is accepted as about 55 m.y. Should the difference in ages be significant, then the geologic relations of the plug would need to be reappraised, and the age of the thrust fault would then be younger than about 54 m.y.; no upper limit would be available except through association with similar structural features nearby that are unequivocally intruded by other plugs of quartz latite porphyry.

The thrust faults northeast of the Johnson Ranch tear fault differ more in scale than in style from those of the main part of the Helvetia block. The thrust faults in both areas are closely related to tear faults and include many younger-over-older faults, as well as some older-over-younger ones. However, the thrust faults are much closer together northeast of the ranch than they are to the south, and the intervening plates are much thinner. These thrust faults are described below in three groups, distinguished from each other by diverse rock types or by structural features in their upper plates. Individual faults are labeled in lowercase letters a through h to indicate a general lack of correlation with the thrust faults to the south; only fault G is inferred to extend into the area northeast of the ranch. No fault is designated c to avoid confusion with the label of fault C.

Thrust faults of the lower group, a through d, are overlain mainly by plates of Permian formations that dip gently to moderately southeastward. Fault a, however, separates pre-Permian rocks from an overlying plate of Bisbee, and it is unique among the northeastern faults in that it is intruded by stocks of granodiorite-quartz monzonite and of quartz diorite presumed to be of Paleocene age. Fault b cuts across these stocks and also across fault a, and therefore is younger than fault a; the overlying thrust faults are presumed also to be younger than the stocks, for fault d cuts b. Fault d probably extends southward from the main segments of plates of Permian rocks to subordinate segments of plates largely of Cretaceous rocks, but this part of the fault may have been reactivated as a part of fault f of the upper group.

Fault G, of the middle group, is distinctive in that it is overlain by a plate of upended north-trending phyllitic rock correlated with the Gardner Canyon(?) Formation. The strong similarity of the rocks and a comparable steepness of the attitudes above and below this fault with those at the north end of the klippe of Gardner Canyon Formation half a mile south of the Johnson Ranch suggests that the intervening thrust fault is an extension of G. Fault G truncates the north end of d, but if the correlation of G is valid, then this fault movement represents local rejuvenation along an older structure, elaborated on in the section on the Helvetian phase of the Laramide Orogeny.

Thrust faults of the upper group, e through h, are overlain mainly by plates of Glance Conglomerate and Willow Canyon Formation, of the Bisbee Group of Early Cretaceous age, but the plates include a little older and a little younger rock. The plate overlying g, for instance, consists partly of the Bolsa Quartzite of Cambrian age and partly of the Salero Formation of late Late Cretaceous age. Small dikes and plugs of quartz latite porphyry, correlated with the intrusives of Greaterville of late Paleocene age, intrude the upper group of thrust faults.

Some of the structural features associated with the rocks of the upper group of thrust faults differ from those related to the lower groups of thrust faults. The plates above faults e and g are remarkably thin in relation to their extent, and the rocks of the plates strike east-northeast and dip steeply south-southeast, about at right angles to the attitudes of the rocks overlying fault G. The rocks above fault h are folded along northwest-trending axes; these folds are progressively tighter and more strongly overturned to the northeast near the thrust faults. The south end of fault h merges with the Sycamore Canyon fault zone. The thrust faults are cut by (or merge abruptly with) a complex northeast-trending fault south of hill 4,407; and these thrust faults, as well as some of the lower ones, are also cut by another complex but northwest-trending fault north of the hill.

The direction of movement of the upper plates of most of the thrust faults of the Helvetia block relative to the lower plates is inferred to be northwest; that of a few thrust faults may be northeast. A general northwesterly direction of transport of many thrust plates is suggested by the northward and westward imbrication or southward and eastward pinching out of many of the minor thrust plates, such as those near the Leader shaft and some of those northeast of Johnson Ranch. The strike of the tear faults that merge with thrust faults indicates even more precisely that many of the thrust plates moved either northwest or southeast. The direction of offset on the beds across these tear faults indicates not only left-lateral movement on the faults, but suggests that the upper plates of the imbricated thrusts moved northwestward relative to the lower ones. A few thrust plates probably moved northeastward, perhaps at an earlier time, as indicated by the orientation of a few tear faults and by the trend evidence of the folds in the Helvetia block, described in the following section on folds.

Many of the thrust faults were active during late Paleocene time; some were probably active during the late Late Cretaceous, and a few may have been active during both of these times. Fault H, for example, is dated directly as late Paleocene because it truncates granodiorite stocks of late Paleocene age and is thought to be intruded by a quartz latite porphyry plug of about the same age. Faults A and d are likewise late Paleocene because they also cut the upper Paleocene granodiorite stocks, and the northwest-trending tear faults into which they merge are intruded by quartz latite porphyry plugs of approximately the same age. The other thrust faults associated with the many tear faults of similar trend are, by analogy, also believed to be late Paleocene. This late Paleocene faulting occurred during what will be described in the last section of this text as the Helvetian phase of the Laramide Orogeny.

Thrust fault G was probably active during the Late Cretaceous. This interpretation is based on the probable genetic association of fault G with one of the northwest-trending folds, others of which in the Montosa Canyon area are associated with thrust faults of Late Cretaceous (Salero) age. Clearly, the age of the thrust faulting throughout the area is closely related to the development of other structural features and so the events of this time of deformation will be reviewed more fully toward the end of this report.

FOLDS

Folds are less abundant than faults in the Helvetia block, but provide much of the information about stress systems in the block.

Northeast of the Sycamore Canyon tear fault zone, the Bisbee Group of the upper plate of thrust fault h is warped into a series of folds whose axes strike N. 55°–75° W. (pl. 4). The southern folds of this series are more open, more closely spaced, and of smaller amplitude than the northern folds. Folds in the more shaly Apache Canyon Formation are disharmonic to those in the more massive rocks of the underlying Willow Canyon Formation. Fold axes plunge gently to moderately steeply southeast, virtually paralleling the dip of the youngest rocks along the east flank of the northeastern structural unit. Some fold axes are truncated by thrust fault h or by the tear-fault zone. Although the axial planes of most folds are nearly vertical, the axial plane of the northernmost fold dips southwestward, and toward fault h the fold is slightly overturned to the northeast.

The Triassic rocks that overlie the main segment of thrust fault G are warped into a syncline much like the folds in the Bisbee. The fold axis is slightly arcuate, concave to the southwest; it strikes N. 40°–50° W. and is truncated by fault G. The axial plane dips steeply southwest.

Several folds are also present in the Paleozoic rocks (pls. 1, 5). The Horquilla Limestone three-fourths mile (1.2 km) northeast of Helvetia townsite forms a steep-limbed anticline, whose axis strikes N. 70° W. Horquilla and Escabrosa Limestones are folded into another anticline on the hill 2 miles (3 km) northwest of Helvetia, where the fold axis strikes N. 60° W.; the fold is slightly overturned to the northeast and plunges to the southeast. Presumably this fold is also truncated by the tear and thrust faults bounding the plate of Paleozoic rocks. Lastly, the much-faulted Permian rocks south of Johnson Ranch are synclinally folded around a northwest-trending and steeply southwest-dipping axial plane.

The uniform orientation of all the fold axes suggests that the folds were formed together in one structural environment. Compressive stress was clearly oriented northeast-southwest, and it probably was directed northeastward, as judged from the dominance of southwest-inclined axial planes. The folds were formed after the deposition of the Bisbee rocks of late Early Cretaceous age and before the intrusion of the granodiorite-quartz monzonite stocks in the late Paleocene. Indeed, as indicated by the unfolded condition of the unconformably overlying Salero Formation of that part of the Sycamore Canyon area lying just east of the area of plate 4, folding occurred before the end of Salero (late Late Cretaceous) time. Comparison with folds in other parts of the Santa Rita Mountains and association with other structural features, reviewed below, permit a further restriction of the time of folding to the late Late Cretaceous.

DIKES

Dikes are shorter and less systematically distributed in the Helvetia block than in the blocks farther south, and so provide relatively few clues to the structure of the area. Several dikes or apophyses of quartz latite porphyry extend along faults, such as the Sycamore Canyon fault zone, the east-trending fault near Gunsight Notch, and some of the faults northeast of Johnson Ranch. Several dioritic dikes intrude the folded Bisbee northeast of the Sycamore Canyon fault zone, and andesitic to dioritic dikes cut across the faults and stocks northeast of Johnson Ranch. A dike of Oligocene rhyolite porphyry strikes N. 80° W. across the granodioritic rocks of the pediment north of Helvetia, and another short dike of this kind lies along a tear fault east of the longer dike.

RANGE-FRONT FAULTS

Normal faults that separate gravel from bedrock lie along some of the mountain flanks (pl. 1). Some of these faults, such as the Elephant Head and the Patagonia faults, are contacts between gravel and bedrock or are confined to gravel, whereas others, such as the Deering Spring and the San Cayetano faults, extend into the bedrock for some distance. The faults that extend into bedrock have already been described with the slightly older structural features of the mountain areas; the others are described in this section. This gradation in types and ages of faults from very young ones in gravel to older ones in bedrock suggests that, in a tectonically active area, the range-front aspect of faults is a transitory feature, one which may be modified in a short span of geologic time as a result of erosion and of a shift in the loci of faulting.

The Elephant Head fault (pl. 1) is the longest range-front fault. It extends northeastward, more or less continuously, from near Yoas Mountain to near the village of Corona de Tucson. Where the fault separates gravel from bedrock, it forms a single fault plane or narrow fault zone; but where it extends into gravel it commonly forms an en echelon set of faults. Near Elephant Head, a silicified zone or vein complex lies along the fault, as do a few small slivers of Triassic Mount Wrightson Formation and of Paleozoic rocks. Where it crosses the Madera Canyon and Sycamore Canyon fans, the fault is marked by subtle scarps, as much as 18 feet (5.5 m) high. Pediment gravel and a soil of mid-Pleistocene age (Drewes, 1971a) are offset, northwest side down, along some of the scarps. The fault is also marked by alined seeps, relatively luxuriant vegetation, and concentrations of caliche in the gravel. A branch of the fault is exposed between gravel and bedrock near the mouth of Sawmill Canyon (NW). Unpublished gravity data permit the extension of this branch fault westward and northward from the mouth of the canyon, as inferred on plate 1.

The Patagonia fault lies along the foot of the northwest flank of the Patagonia Mountains, as shown in the southeast corner of plate 1. South of Aztec Gulch the fault separates gravel of Pliocene and Pleistocene age from Cretaceous or older rocks, but younger terrace gravels or soils are not demonstrably offset. Dips on the fault between Aztec Gulch and Flux Canyon are 60°–80° NW. Southwest of Flux Canyon, the fault is covered, but a southwestward extension is suggested by the fact that the gravel near the projected fault commonly dips or strikes toward the mountain front and by the fact that the gravel adjacent to the foot of the high mountain front is finer grained than that away from the mountains. This distribution of coarse and fine gravel indicates that the gravels were deposited in a topographic environment different from the present one and that most likely the gravel was then faulted into its present position at the foot of a high mountain. North of Aztec Gulch, the fault is inferred to extend into the Pliocene and Pleistocene gravel, but it is covered by younger terrace gravels; it is last recognized in the bluffs along the road 1–2 miles (2–3 km) east of Patagonia.

The range-front faults are young, but some of the faults may have been active several times and as long ago as the Tertiary. The San Cayetano fault, for instance, was active at various times in the Tertiary but seems not to have been active thereafter. The only identifiable movement on the Patagonia fault is dated as

Pliocene or early Pleistocene, postdating gravel deposition. However, the abundance of coarse angular detritus derived from the footwall rocks north of Aztec Gulch (pl. 1) in the faulted gravel suggests that a steep mountain front was present before the recorded faulting occurred, and the existence of such a mountain front implies that there was some earlier faulting. The slivers of Paleozoic and Triassic rocks along the Elephant Head fault near Elephant Head suggest that movement on that fault may also have been complex.

Without additional data on the rocks and structural features now concealed beneath gravels, the development of the Elephant Head and Patagonia faults is difficult to analyze. However, their northeast trend suggests that they were formed either as a result of continued tensional stresses, beginning as early as the close of the Paleocene and recorded by the northeast-trending veins emplaced during the time interval between the Paleocene and Oligocene (Drewes, 1972a) and dike swarms of Oligocene age, or as a result of younger stresses that were sufficiently similarly oriented that the old fracture system was reactivated. The youngest movement, during the late Pleistocene, need only reflect compaction of the gravels.

STRUCTURAL DEVELOPMENT

The rocks of the Santa Rita Mountains were deformed many times in response to stresses of varied orientation and intensity. During the recorded part of the Precambrian and Paleozoic Eras there was a little early orogenic activity and much epeirogenic activity, but during the Mesozoic and Cenozoic Eras tectonic activity increased in frequency and intensity. The strongest tectonic imprint was that of the Laramide Orogeny, which locally is closely dated as Late Cretaceous and Paleocene; it was a complex multiphased group of tectonic, plutonic, and volcanic events. The structural development of the Santa Rita Mountains is described in this section and is summarized in figure 2 in terms of pre-Laramide, Laramide, and post-Laramide events.

PRE-LARAMIDE DEFORMATION

The structural development occurring before the Laramide Orogeny remains the least well understood; much, however, has been learned about the Mesozoic events.

The oldest rocks of the area, those of the Pinal Schist, are bedded rocks that were deeply buried, foliated, and folded before, or perhaps partly as the result of, the emplacement of the Continental Granodiorite during the Precambrian. The composition of this rock suggests that it is the older of the two kinds of Precambrian granitoid rock of southern Arizona recognized by Silver (1969). Its radiometric age, of about 1,450 m.y. (Precambrian Y), probably is not reliable enough to distinguish a 1,650-m.y. event from a 1,450-m.y. one. Wilson (1939, p. 1161) has referred to the older tectonic event, occurring through much of Arizona, as the Mazatzal Revolution (fig. 2). Evidence from areas only a few miles to the north indicates that these ancient rocks were strongly uplifted and deeply eroded before Precambrian Z time.

During the Precambrian Z time and again during the Paleozoic, structural activity in the area of the Santa Rita Mountains was restricted largely to epeirogenic movements. Before Middle Cambrian time, the raising of the area and perhaps its gentle northward tilting permitted erosion of the Precambrian Apache Group rocks; so only the lower part of that group appears a few miles north of the Santa Rita Mountains, and no part of the group appears in the Santa Rita Mountains. In Middle Cambrian time, the area was inundated by the sea. Other marine invasions followed during parts of Devonian, Mississippian, and Pennsylvanian through mid-Permian times. Toward the end of the Permian, the area was uplifted once more, and a continental environment prevailed thereafter, with a single brief exception.

During later pre-Laramide time, vertical crustal movements were more localized and stronger than the epeirogenic movements of earlier times. The locations of uplifted areas are deduced largely from the sedimentary record. The raised areas are inferred to be upfaulted rather than upwarped if an uplifted area and the detritus shed from it are separated by a fault of suitable kind and amount of throw.

The cobble conglomerate of Precambrian granitoid rocks intercalated in the middle of the volcanic rocks of the Mount Wrightson Formation at a horizon near which a 220-m.y. radiometric age was obtained indicates major and rapid uplift suggestive of faulting. During the time between about the mid-Permian and the mid-Triassic, a nearby area was raised sufficiently for erosion to remove about 1 mile (1.5 km) of Paleozoic cover and for Precambrian granitoid rocks to be exposed to erosion. Furthermore, the area was raised sufficiently to have enabled the resulting detritus to be transported into the middle of a volcanic pile that was at least 8,500 feet (2,500 m) thick. The kinds of Precambrian rocks occurring as cobbles are like the Precambrian rocks that crop out about 5 miles (8 km) northeast of the cobble conglomerate and are not like the rocks found in the other nearby Precambrian outcrops. By itself, an uplift of this magnitude—some 1–2 miles (2–3 km) operative in a distance of 4 miles (6.5 km)—is regarded as a strong sign of fault uplift

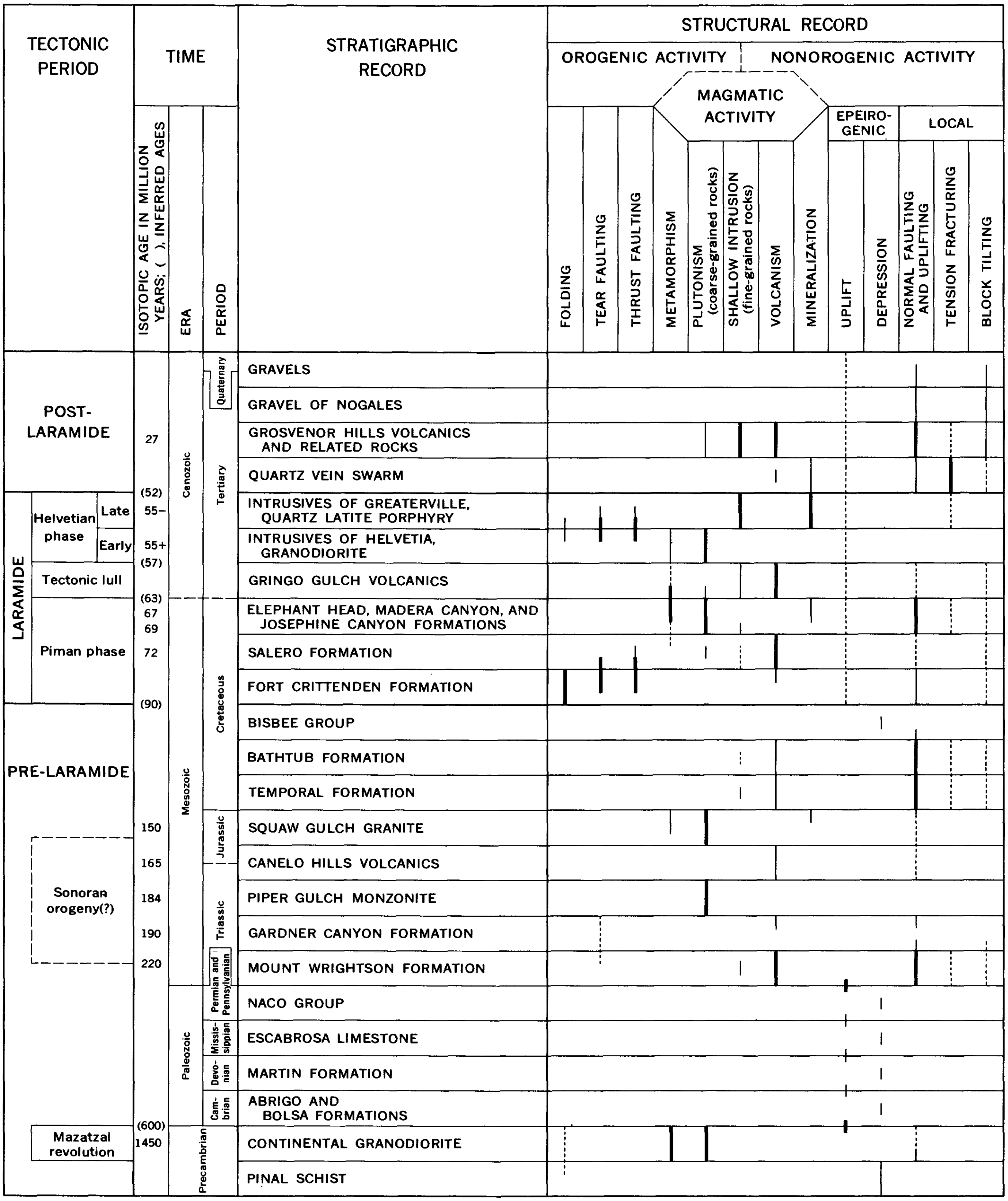

FIGURE 2.—Summary of the tectonic record of the Santa Rita Mountains. Bars indicate record of abundant activity, lines indicate record of little activity, and dashed lines indicate uncertain record.

rather than of upwarp. This inference is strengthened by the occurrence of the Sawmill Canyon fault zone between the conglomerate to the southwest and the Precambrian terrane to the northeast. The northeast side of the fault zone is thus believed to have been faulted up many thousands of feet (several thousand meters) shortly before, or during, Mount Wrightson Formation (Triassic) time. The thick part of the prism of volcanics of the Mount Wrightson Formation may have been deposited in a northwest-trending fault trough (Drewes, 1971c) that was bounded to the northeast by the Sawmill Canyon fault zone.

By the end of Triassic time, other crustal movements that may have been faulting occurred along the Sawmill Canyon fault zone. During Gardner Canyon Formation time, parts of the Sawmill Canyon fault zone and the area to the northeast were receiving deposits, including conglomerate, from Precambrian granitoid sources as well as Triassic volcanic sources. Most likely, the source of the volcanic clasts was southwest of the fault zone, for the area northeast of it supplied the Precambrian granitoid detritus. Furthermore, the Gardner Canyon rocks of the Fish Canyon area contain a few large masses of Paleozoic limestone, resembling the exotic blocks (described by R. B. Raup in Simons and others, 1966) inferred to have slid into the lower Mesozoic red beds of the Canelo Hills. These limestone masses probably were derived from the southwest, inasmuch as most of the Paleozoic rocks had been eroded from the area to the northeast by Mount Wrightson time. The conglomerate and the slide blocks suggest appreciable local relief and indicate that the relief was distributed differently from the postulated relief earlier in the Triassic. A reversal of throw on the Sawmill Canyon fault zone would explain the evidence.

The Santa Rita fault zone was also probably active during the Triassic, inasmuch as some masses of Mount Wrightson Formation are upended along the zone, whereas Late(?) Triassic and Jurassic plutons, whose emplacement is believed to be controlled by the fault zone, are themselves unfaulted.

The several early Mesozoic disturbances and plutonic events may be distant effects of the Sonoran Orogeny reported a few hundred miles (about 1,000 km) to the south (Fries, 1962).

Near the end of the Jurassic, the southwestern structural unit and at least part of the central unit were uplifted and deeply eroded, as is indicated by the pronounced unconformity between the lower Lower Cretaceous Temporal Formation and the Jurassic Squaw Gulch Granite. This uplift could have been the result of doming; nevertheless, in view of the evidence of repeated faulting in the area, both before and after this time, it is reasonable to suspect that faulting was also involved in the Late Jurassic uplift.

During early Early Cretaceous (pre-Bisbee) time, the northeastern structural unit was twice uplifted along the Sawmill Canyon fault zone, and wedges of fanglomerate were intercalated in the Temporal and Bathtub Formations in the central structural unit. That the deformation took place near the fault zone is indicated by the combined evidence of the coarse clast size of the fanglomerate near the fault zone and of the abrupt wedging out of the thick fanglomerate masses to the southwest away from the fault zone.

The unconformity between the Bathtub and the overlying Bisbee Group and the lenticularity of the Glance Conglomerate at the base of the Bisbee suggest that local uplift continued into, or was renewed during, the late Early Cretaceous. During mid-Bisbee time, however, the area remained relatively stable and was lowered epeirogenically just enough to allow encroachment of a short-lived shallow arm of a continental sea and the deposition of the thin oyster-bearing limestone beds of the Apache Canyon and Shellenberger Canyon Formations.

LARAMIDE OROGENY

The concentrated tectonic, plutonic, and volcanic activity that occurred during the Late Cretaceous and early Tertiary in the Cordilleran region is referred to as the Laramide Orogeny. In southeastern Arizona abundant evidence shows that this orogeny was complex and of varied duration and intensity from range to range.

In the Santa Rita Mountains, the orogeny lasted from the early Late Cretaceous through the Paleocene, or roughly from about 90 to 52 m.y. ago (Drewes, 1969b). The intensity of the orogenic activity varied throughout this period, and evidence at the north end of the mountains indicates that the direction of compression changed about 90° during a midorogenic tectonic lull. The early orogenic phase, referred to as the Piman phase, lasted nearly to the close of the Cretaceous, about 63 m.y. ago (Gill and Cobban, 1966, fig. 2). Tectonic activity was relatively strong and widespread during the Piman phase. The lull in tectonic activity lasted several million years, and it was followed by a more localized, weaker, and shorter lived orogenic phase, referred to as the Helvetian phase.

PIMAN PHASE

In the Santa Rita Mountains, the deformation attributed to the Piman phase of the Laramide Orogeny began at the end of the Early Cretaceous, increased gradually through the Late Cretaceous, culminated with major faulting about 75 m.y. ago, and drew to a close with the emplacement of several large plutons 69–65 m.y. ago. An unconformity between the Turney Ranch Formation (at the top of the Bisbee Group) and the overlying Fort Crittenden Formation is the earliest evidence of a disturbance. The dominantly fine grained clastic deposits of the Turney Ranch are succeeded upward by the dominantly coarse grained rocks of the Fort Crittenden Formation, which consists of a basal conglomerate, a local lens of shale, much cobble conglomerate, and a thick capping body of coarse sedimentary breccia. Some folding may have accompanied deposition of the Fort Crittenden. For example, the systematic thinning and lapping out of the basal conglomerate and several of the overlying units of this formation southwestward on the Turney Ranch Formation around the crest of the Bath Tub Tank anticline suggests that folding of this anticline began early in Fort Crittenden time. Folding continued only until the beginning of deposition of the overlying Salero Formation, because the Salero is unfolded, except for local drag folds, and in the northern end of the mountains it lies unconformably across folded Bisbee. Deformation is also known to have occurred during the same period in nearby areas. For instance, in the northwestern part of the Huachuca Mountains, Fort Crittenden rocks unconformably overlie thrust-faulted rocks as young as the Bisbee, as shown on the geologic map by P. T. Hayes (in Hayes and Raup, 1968). The evidence so far accumulated, then, indicates that the interval between Bisbee and Salero times, which is represented in part by the Fort Crittenden Formation, was one of repeated compression and uplift.

The onset of the Laramide is not precisely dated in the Santa Rita Mountains. However, Hayes (1970) showed that over a broad region in the southwestern United States and northern Mexico, a hiatus commonly separates Turonian from Coniacian beds, a horizon which Gill and Cobban (1966, table 2) dated as about 87 m.y. and which is almost certainly no older than about 92 m.y. In the San Juan Basin of northwestern New Mexico, Dane (1960, p. 53–55) indicated that rocks of Niobrara age (Coniacian) rest unconformably upon rocks of Carlile age (Turonian). Similarly, in western Texas (West Texas Geol. Soc., 1959, p. 37) a disconformity separates the Austin Chalk from the Eagle Ford Shale, also at this horizon. Thus, regional evidence indicates that the Laramide Orogeny probably began about 90 m.y. ago in the Santa Rita area.

The persistent northwest trend of the early Laramide folds suggests that they were formed in response to compressive stress oriented in a northeast-southwest direction. In the Santa Rita Mountains, such folds occur in the Montosa Canyon area on the west flank of the mountains, in the Adobe Canyon-Greaterville area on the east flank, and in the Sycamore Canyon area at the north end of the mountains. Folds that trend differently either are local drag folds or are younger than the Laramide folds. All of the few overturned folds in the area are overturned to the northeast. In many other folds, axial planes dip steeply southwestward but a few dip steeply northeastward, and some are vertical. In general, the tilting of the folds as a result of younger deformation decreased the inclination of axial planes only about 10°, an amount sufficiently small that the direction of the inclination was rarely changed. Where the axial planes of a group of folds are diversely inclined, these inclinations are probably the result of relatively weak stresses applied to rocks that had an inhomogeneous fabric, rather than of strong stresses directed in diverse ways. Altogether, the evidence suggests that at least most of the folds were formed by northeastward-directed, rather than southwestward-directed, stress, but the evidence is not overwhelming.

The stress that produced the folds probably also caused the many thrust faults that mark the climax of the Piman phase. The folds above thrust faults G and h (pls. 1, 4), for example, are restricted to the upper plates of these faults. Likewise, the folds near Greaterville must be disharmonic folds in a plate thrust over the Precambrian rocks. The overturned fold northwest of the Helvetia klippe (pl. 1) is also restricted to the Paleozoic rocks of a thrust plate overlying fault A and lying north of the Gunsight Notch tear fault. The folds in the Paleozoic rocks adjacent to the Montosa tear fault (pl. 2) likewise seem to be genetically related to that tear fault, and hence to the thrust faults which also end at the tear fault.

A few thrust faults, such as I and B, are datable only as older than the Paleocene intrusive rocks and, of these, at least I was active during the Piman phase. Faults II, III, and possibly IV are assigned to the Piman phase because of their general structural similarity to fault I.

Most, or all, of the east- to northeast-trending tear faults were active during the Piman phase. The time of movement on the Montosa tear fault is dated directly as late Late Cretaceous (see section on Montosa Canyon block). Other east- to northeast-striking tear faults are dated indirectly through their genetic association with thrust faults or folds of the Piman phase. For example, the short tear fault south of the head of Wasp Canyon ends against one Piman phase thrust fault, II, and is truncated by another, fault IV. The structural discordance across many of the east-northeast-trending faults west and northwest of Rosemont suggests that tear faulting was contemporaneous with Piman phase thrusting along faults I to IV. The short northeast-trending tear fault northeast of Johnson Ranch is associated with Piman-phase thrust faults and has a similar orientation to other Piman-phase tear faults; it may also have been active during the Piman phase.

The probable movement direction of the upper plates of the Piman-phase thrust faults was northeastward. A northeast or southwest transport direction is persistently indicated by the orientation of the tear faults associated with the thrusts. Axial planes of most asymmetrical folds and of all overturned folds dip southwest, suggesting a northeastward-directed stress. The southwestward concave traces of the fold axes west of Adobe Canyon are also consistent with an inferred northeast direction of transport. The direction of drag beneath the Montosa fault, however, indicates that at least the final movement of the upper plate was to the southwest.

The relatively uniform direction of Piman-phase deformation is consistent with the hypothesis that a single more or less coherent thrust plate moved across the area.

Magmatic activity increased toward the end of the Piman phase. The earliest activity was volcanic, but plutonic activity followed shortly thereafter. The earliest volcanic activity is recorded by the rhyolitic tuff member near the top of the Fort Crittenden Formation. More abundant volcanism is shown by the Salero Formation, which consists of an earlier pile of dacite and a later pile of rhyodacite, dated at 72 m.y. The first of the plutonic rocks, the Corona stock, was emplaced in the north end of the Santa Rita Mountains about 74 m.y. ago, almost concurrently with the rhyodacite volcanism of the Salero Formation. Shortly thereafter, plutons of Josephine Canyon Diorite, Madera Canyon Granodiorite, and Elephant Head Quartz Monzonite were emplaced, approximately along the Santa Rita fault scar. The main phases of the plutons have been dated at 67–69 m.y.; one of their younger phases is about 65 m.y. old (Drewes, 1971b).

The close association of northeast-directed thrust faults, tear faults, and folds with the exotic block and welded-tuff members of the Salero Formation and with the quartz monzonite and diorite plutons suggests the following structural development in the Montosa Canyon area (pl. 2): (1) During the late Late Cretaceous an extensive overthrust plate moved northeastward on the Montosa thrust fault, and similar movement may have occurred on the Agua Caliente thrust fault before the intrusion of the Elephant Head Quartz Monzonite. The relatively incompetent and not too deeply buried layered rocks of the upper plate were folded and tear faulted. (2) Almost concurrently with (1), some dacite lava was extruded onto part of the thrust plate to the northwest of the area of plate 2, (Drewes, 1971b), and other dacite magma was intruded beneath it southeast of the Montosa tear fault. (3) That part of the thrust plate overlying the dacite intrusive foundered into the magma to form the exotic blocks. The entire mass flowed southwestward, downhill, and away from the core of the ancestral Santa Rita Mountains, beneath which more magma was rising. The unroofed dacitic magma flowed as a breccia sheet, cool enough to be sheared against the remaining part of the thrust plate but locally remaining hot enough to permit volcaniclastic material to be injected into border zones of some of the exotic blocks. The remaining thrust plate also moved a short distance southwestward in response to the effects of gravity and perhaps of drag of the adjacent volcanic mass. (4) After, at most, only a brief pause, and perhaps as a direct result of the abrupt drop in pressure caused by the rupturing of the caprock above the original dacite intrusive and the subsequent flowage away from a location above the magma chambers, much rhyodacite tuff was extruded from a presumed second chamber; it generally flowed southwestward and was welded. Locally, it flowed against a scarp formed by the Montosa tear fault, and over a wide area it flowed onto a hilly granite terrane. (5) Less than 4 m.y. later, magmatic activity resumed, apparently from both chambers. Emplacement of quartz diorite and granodiorite plutons was followed by emplacement of quartz monzonite, and the plutons were emplaced at levels adjacent to, and slightly above, their earlier dacite and rhyodacite volcanic counterparts. The roof and wall-rocks of the plutons were widely propylitized and were locally hornfelsed.

MID-LARAMIDE QUIESCENT TIME

During the middle of the Laramide Orogeny, an interval of tectonic quiescence, lasting from about 63 to 57 m.y. ago, separated the Piman from the Helvetian phase. Stratigraphic records of this tectonic lull are few and the rocks of this interval are inadequately dated, but circumstantial evidence supports this interpretation. The direction of compression changed from the northeast-southwest direction of the Piman phase to the northwest-southeast direction of the Helvetian phase. This change in direction required an intervening time free of horizontally directed compression. It may have been, but need not have been, a time of tension, yet in effect it should have favored the development of tensional structural features and the emplacement of intrusives typical of a tensional environment, such as the Cottonwood Canyon dike swarm (Drewes, 1971b, 1972a).

The chief stratigraphic record of the mid-Laramide quiescent phase is provided by the Gringo Gulch Volcanics, of Paleocene(?) age. Four miles west of Patagonia these rocks lie unconformably on a stock of upper Upper Cretaceous Josephine Canyon Diorite, and 1 mile (1.5 km) southwest of Patagonia they apparently are intruded by a plug of late(?) Paleocene hornblende dacite porphyry. Between these localities they are cut by a swarm of lower Tertiary quartz veins and intruded by an Oligocene rhyolite dike. In general, the Gringo Gulch Volcanics are less altered than the Salero and older formations; but locally they are silicified, mineralized, and otherwise altered in a manner like that of the rocks surrounding some intrusives of the Helvetian phase; thus, their age assignment to the early(?) Paleocene is reasonable.

The area in which the Gringo Gulch Volcanics were deposited must have been high, for in a short time (after the emplacement of the late phase of the stock 65 m.y. ago and before the intrusion of the plug 55–60 m.y. ago), the top of a stock of Josephine Canyon Diorite was exposed and then covered by the volcanics. Apparently the stock was emplaced close enough to the surface that only a minimum amount of erosion was required to expose it. A shallow emplacement is also suggested by the intrusion of the stock into the Salero Formation, which is only a few million years older than the diorite. The grain size of the diorite, finer than that of the other Laramide plutonic rocks, further substantiates shallow emplacement of the diorite.

HELVETIAN PHASE

During late Paleocene time, some of the rocks of the Santa Rita Mountains were faulted in response to compressive stress of the Helvetian phase. This stress was oriented in a northwest-southeast direction. Where this deformation occurred in previously deformed rocks, some favorably oriented segments of older faults were reactivated. Late movement on these fault segments was consequently radically different from early movement, which was typically directed toward the northeast. Most evidence of the Helvetian phase of deformation comes from the northeastern structural unit, in which two groups of dated intrusive rocks are closely associated with the deformation. Relations of structural features to these intrusives show that, locally at least, the Helvetian phase can be divided into an early and a late subphase.

Structural features of the early Helvetian subphase include tear faults and thrust faults, which are especially abundant in the Helvetia block of the northeastern structural unit. The Gunsight Notch tear fault, the tear fault at Shamrod Spring, and the tear fault half a mile south of Johnson Ranch (pls. 1, 4) cut structural features of the Piman phase and are intruded by stocks of the Helvetia area of late(?) Paleocene age. The association of the tear fault 1 mile (1.5 km) north of Shamrod Spring and the Johnson Ranch fault with other faults of this set also indicates that these two faults are probably early Helvetian faults. The tear faults, nevertheless, were not completely synchronous inasmuch as thrust fault B cuts some of them and is itself cut by other tear faults. Thrust faults A, B, and other unnumbered smaller ones were active during the early Helvetian, for they either merge with these tear faults without extending beyond them, or they abut them. The stratigraphic offset along the tear faults and the direction of shingling of small thrust fault slices between faults B_1 and B_2 suggest that the blocks northeast of the tears moved left-laterally northwestward relative to those southwest of the tears. This movement direction is nearly parallel to the trend of the Piman-phase folds, and thus must be genetically unrelated to them.

Structural features of early Helvetian age also include thrust fault a, for the fault is cut by a stock of the Helvetia intrusives east of Johnson Ranch and ends against the Johnson Ranch tear fault. Thrust fault I north of the Gunsight Notch fault zone may have been reactivated during early Helvetian time, for it also abuts two of the northwest-trending tear faults and is offset by a third. That fault I was not simply truncated by the tear faults and transported within the plate beneath thrust fault B cannot be demonstrated in the Helvetia area, but to the south at Enzenberg Canyon the disharmonic northeast-trending fold in the klippe of Bisbee rocks above fault I suggests that northwest-oriented compressive stresses were active there.

Faults of the late Helvetian subphase truncate the early Helvetian structural features or truncate the stocks of the Helvetia area, of late Paleocene age; and they are intruded by quartz latite porphyry plugs and dikes, also of late Paleocene age. (The Late Cretaceous age of the northernmost of these stocks does not alter these interpretations.) Thrust fault H beneath the Helvetia klippe is a typical younger feature. It cuts a stock of the Helvetia intrusives and is faulted onto the Gunsight Notch tear fault. Similarly, fault C lies across part of this tear fault zone, as well as across the tear fault at Shamrod Spring. By association, the tear faults that end against fault C on the east, the thrust faults D and E, and assorted minor ones between faults C and F are also late Helvetian. North of Johnson Ranch, fault b, resting on a stock of the Helvetia intrusives and cutting across fault a, may also be a late Helvetian feature. Fault d, which cuts fault b and merges with the Sycamore Canyon fault zone, was also active at this time, although it seems that a segment of d followed the older thrust fault f. Fault d and the Sycamore Canyon fault zone may be the youngest faults of the late Helvetia, inasmuch as the quartz latite porphyry plug that intrudes the fault zone is itself sheared. Here again, because the nearby fold axes are subparallel to the Sycamore Canyon tear fault, the folds must have been formed under different stresses than the tear fault.

Structural features of Helvetian age also occur in the Greaterville and Rosemont blocks, but they are more tenuously dated in these blocks than they are in the Helvetia block, mainly because Paleocene intrusive bodies are fewer and less critically situated. Some of the small east- to northeast-trending faults that cut thrust fault I and the overlying thrust faults were probably reactivated during the Helvetian phase and after the Piman-phase tear faulting that produced the structural discordance across them. Helvetian-phase movement is suggested by the combined evidence on two of the transverse faults: the transverse fault through Gunsight Notch offsets the Helvetian-age Gunsight Notch fault zone, and the transverse fault southwest of Rosemont is intruded by a plug of quartz latite porphyry, of late Paleocene age. In addition, inasmuch as many transverse faults offset thrust fault I, they are at least younger than some Piman deformation. The following circumstantial evidence that the segment of fault I in the Rosemont block was also reactivated is additional support for the inference that the transverse faults were reactivated during or after the Helvetian.

The segment of thrust fault I in the Greaterville block (pl. 1) also was probably reactivated during the Helvetian phase. The orientation of the stress field inferred in the Helvetia block during this time apparently extended into the Greaterville block, for the disharmonic fold in the klippe northwest of upper Enzenberg Canyon, trends northeastward, at right angles to the nearby fold axes of Piman age. If the interpretation of the late development of the northeast-trending fold is accepted, then, through analogy with the Helvetian-age structures of the Helvetia block, the plate above fault I was thrust faulted northwestward and was bounded on the southwest by a tear fault, presumably a combination of the northwest-trending fault at the head of Enzenberg Canyon and the fault along the northeast edge of the Sawmill Canyon zone itself. If this interpretation of Helvetian-age movement is accepted for the Greaterville block segment of fault I, as it has already been for the Helvetia block segment of that fault, then it is possible that the intervening Rosemont segment of fault I was also reactivated. The movement on this segment of fault I is pictured as independent of the movement in the adjacent blocks because of left-lateral slip along the Box Canyon and Gunsight Notch fault zones. The Helvetian-age deformation of the northeastern structural unit thus makes a consistent pattern of northwestward shifting of the overlying and northeastward-lying plates.

The faults associated with the grabens in the Rosemont and Greaterville blocks are more difficult to date; perhaps the normal displacement that formed the grabens is associated with the relaxation of Piman compressive stress during the mid-Laramide quiescent time, and the fault planes were reactivated during the Helvetian when thrust fault I was rejuvenated.

No evidence of deformation specifically of the Helvetian phase of the Laramide Orogeny has been recognized south of the Sawmill Canyon fault zone. However, some of the movement on the Salero fault zone, and perhaps also on other faults, could be of this age.

The emplacement of many of the intrusive rocks of Paleocene age shows the influence of structural controls, although some of the variations in their habit seems to reflect chemical differences as well (Harald Drewes, unpub. data). Most of the stocks of the Helvetia area are elliptical and appear to lack structural controls; only the stock south of the Johnson Ranch is elongate in the zone of a northwest-trending fault and the northernmost stock is somewhat irregular in plan (and has been shown to be older and not associated with the Helvetia stocks as originally mapped). Contrasting markedly with the Helvetia stocks, the intrusives of Greaterville are strongly controlled by the thrust faults and tear faults in the northeastern structural unit. Most of the Greaterville plugs and dikes are younger than the faults, but one plug is sheared by the latest movement on a northwest-trending tear fault. Nevertheless, the intrusives are probably late orogenic, rather than postorogenic bodies, for very little time elapsed between faulting and intrusion, as shown by the near contemporaneity of the stocks and the plugs (54–56 m.y. old). Another group of intrusives of Paleocene age, the Cottonwood Canyon dike swarm, also show signs of structural control. The fractures into which the western group of these dikes were injected are subparallel to many of the high-angle structures within the allochthonous Montosa Canyon block to the west, whereas the eastern group of these dikes lie in fractures subparallel to those later intruded by the Gardner Canyon dike swarm and the quartz vein swarm to the east. The Cottonwood Canyon swarm may simply be the first group of dikes to intrude an incompletely developed post-Piman set of tension fractures, or this dike swarm may reflect a deeper structural zone concealed by the Salero Formation and Josephine Canyon Diorite.

The intrusives of Greaterville are commonly associated with base- and noble-metal mineralization, described by Schrader (1915), Creasey and Quick (1955), and Drewes (1970, 1972b). Inasmuch as the faults associated with these intrusives are largely thrust faults and tear faults merging with thrust faults, all relatively shallow features, the ducts of the intrusives themselves may have been the chief controls of mineralizing fluids, which however spread widely along the faults near the surface. Some of the northwest-trending faults, such as the Sawmill Canyon fault zone and the graben-bounding faults, may be older, deeper faults that also controlled the passage of mineralizing fluids.

POST-LARAMIDE DEFORMATION

Post-Laramide deformation recorded in the Santa Rita Mountains consists of faulting and related drag folding that resulted from tensional stresses (or the relaxation of compression). Although a few older major faults were reactivated, most faulting was relatively shallow, generally being confined to the Grosvenor Hills volcanic field and the edges of sedimentary basins. Many faults thus follow trends, chiefly northeast to east, that differ from those of the older faults. Relatively early in post-Laramide time, quartz veins were deposited in a set of tension fractures mainly in the Salero and Mount Wrightson structural blocks. The vein swarm is oriented easterly to east-northeasterly, approximately at right angles to the trends of the Santa Rita fault scar and the large Laramide stocks. Minor normal faulting also occurred on some of these fractures and movement on at least the southern part of the Salero fault may be this young.

During the late Oligocene, magmatic activity was renewed, particularly in the southwestern part of the mountains (Drewes, 1972a). Granodiorite magma was emplaced at depths of a few thousand feet (about 1,000 m) in the San Cayetano block and may also underlie the Grosvenor Hills block. Large amounts of magma reached the surface of at least the Grosvenor Hills block. Concurrently with the volcanism, and probably as a result of it, the roof area of the magma source foundered slightly along the San Cayetano and Hangmans faults. Toward the end of the time of outpouring of rhyodacitic tuffs, agglomerates, and lavas, some of the magma worked its way upward in the fractured rocks above the magma chambers to form two swarms of west-northwest-trending dikes, one in each of the structural blocks. Several dikes reached the level of the poorly consolidated rocks at the base of the volcanic pile and bulged out into laccoliths. Abundant small faults were formed as a result of collapse of the volcanics around the laccoliths.

The northeast-trending tension fractures exerted their influence well to the north of the quartz vein swarm. Rhyolite dike swarms were intruded along the fractures in the central and northern part of the mountains during late Oligocene time. Several range-front faults, probably mainly of late Tertiary age, seem to have used northeast-trending fractures. Movement on the Elephant Head fault, along the northwest flank of the Santa Rita Mountains, raised the Santa Ritas and tilted them gently southeastward. Similar movement on the Patagonia fault raised the northwestern part of the Patagonia Mountains. As a result of this late, gentle tilting of the Santa Rita Mountains, deeper levels of the quartz vein swarm are exposed to the north, whereas along Sonoita Creek to the south shallow levels of the veins are still preserved (Drewes, 1972a, b).

During the late Tertiary, movement along the San Cayetano and Hangmans faults was renewed, further offsetting the Grosvenor Hills Volcanics and tilting the gravel of Nogales that unconformably caps the volcanics. More movement during the Pliocene and Pleistocene is recorded along the faults on the northwest or north flanks of the Patagonia, Santa Rita, and San Cayetano Mountains, where basin-fill gravel is tilted and locally is also gently folded. Similarly young movement is recorded on the Deering Spring fault. The youngest movement, however, is restricted to the alluvial fans along the northwest flank of the Santa Rita Mountains, where gravels of late Pleistocene age, bearing a soil probably formed during the Sangamon Interglaciation, are faulted down toward the basin.

REFERENCES CITED

Anthony, J. W., 1951, Geology of the Montosa-Cottonwood Canyons area, Santa Cruz County, Arizona: Tucson, Ariz., Arizona Univ. M.S. thesis.

Cooper, J. R., 1970, Preliminary geologic map of the Twin Buttes quadrangle, Pima County, Arizona: U.S. Geol. Survey open-file report.

Creasey, S. C., 1967, Geologic map of the Benson quadrangle, Cochise and Pima Counties, Arizona: U.S. Geol. Survey Misc. Geol. Inv. Map I–470.

Creasey, S. C., and Quick, G. L., 1955, Copper deposits of part of Helvetia mining district, Pima County, Arizona: U.S. Geol. Survey Bull. 1027–F, p. 301–323 [1956].

Dane, C. H., 1960, The boundary between rocks of Carlile and Niobrara age in San Juan Basin, New Mexico and Colorado: Am. Jour. Sci., v. 258–A (Bradley volume), p. 46–56.

Drewes, Harald, 1969a, New and revised stratigraphic names in the Santa Rita Mountains of southeastern Arizona: U.S. Geol. Survey Bull. 1274–C, 15 p.

——— 1969b, The Laramide orogeny of Arizona southeast of Tucson, *in* Abstracts for 1968: Geol. Soc. America Spec. Paper 121, p. 501–502.

——— 1970, Structure control of geochemical anomalies in the Greaterville mining district, southeast of Tucson, Arizona: U.S. Geol. Survey Bull. 1312–A, 49 p.

——— 1971a, Geologic map of the Sahuarita quadrangle, southeast of Tucson, Pima County, Arizona: U.S. Geol. Survey Misc. Geol. Inv. Map I–613.

———1971b, Geologic map of the Mount Wrightson quadrangle, southeast of Tucson, Santa Cruz and Pima Counties, Arizona: U.S. Geol. Survey Misc. Geol. Inv. Map I–614.

——— 1971c, Mesozoic stratigraphy of the Santa Rita Mountains, southeast of Tucson, Arizona: U.S. Geol. Survey Prof. Paper 658–C, 81 p.

——— 1972a, Cenozoic rocks of the Santa Rita Mountains, southeast of Tucson, Arizona: U.S. Geol. Survey Prof. Paper 746 (in press).

——— 1972b, Geochemical reconnaissance of the Santa Rita Mountains, southeast of Tucson, Arizona: U.S. Geol. Survey Bull. 1365 (in press).

Drewes, Harald, and Finnell, T. L. (leaders), 1968, Mesozoic stratigraphy and Laramide tectonics of part of the Santa Rita and Empire Mountains southeast of Tucson, Arizona, Field Trip 2 *in* Titley, S. R., ed., Southern Arizona Geol. Soc. Guidebook 3—Geol. Soc. America Cordilleran Sec. 64th Ann. Mtg., Tucson, 1968: p. 315–324.

Fries, Carl, Jr., 1962, Reseña de la Geología del Estado de Sonora, con Enfasis en el Paleozoico: Asoc. Mexicana Geólogos Petroleros Bol., v. 14, nos. 11–12, p. 257–273.

Gill, J. R., and Cobban, W. A., 1966, Regional unconformity in Late Cretaceous, Wyoming, *in* Geological Survey research 1966: U. S. Geol. Survey Prof. Paper 550–B, p. B20–B27.

Hayes, P. T., 1970, Cretaceous paleogeography of southeastern Arizona and adjacent areas: U.S. Geol. Survey Prof. Paper 658–B, 42 p.

Hayes, P. T., and Landis, E. R., 1961, Lower member of Mural limestone of Early Cretaceous age, Bisbee quadrangle, Arizona, *in* Short papers in the geologic and hydrologic sciences: U.S. Geol. Survey Prof. Paper 424–B, p. B125–B127.

——— 1964, Geologic map of the southern part of the Mule Mountains, Cochise County, Arizona: U.S. Geol. Survey Misc. Geol. Inv. Map I–418.

Hayes, P. T., and Raup, R. B., 1968, Geologic map of the Huachuca and Mustang Mountains, southeastern Arizona: U.S. Geol. Survey Misc. Geol. Inv. Map I–509.

Heatwole, D. A., 1966, Geology of the Box Canyon area, Santa Rita Mountains, Pima County, Arizona: Tucson, Ariz., Arizona Univ. unpub. M.S. thesis, 70 p.

Heyman, A. M., 1958, Geology of the Peach-Elgin copper deposit, Helvetia district, Arizona: Tucson, Ariz., Arizona Univ. unpub. M.S. thesis, 66 p.

Lutton, R. J., 1958, Some structural features in southern Arizona: Tucson, Ariz., Arizona Univ. unpub. M.S. thesis, 138 p.

Michel, F. A., Jr., 1959, Geology of the King mine, Helvetia, Arizona: Tucson, Ariz., Arizona Univ. unpub. M.S. thesis, 59 p.

Schrader, F. C., 1915, Mineral deposits of the Santa Rita and Patagonia Mountains, Arizona, with contributions by J. M. Hill: U.S. Geol. Survey Bull. 582, 373 p.

Silver, L. T., 1969, Precambrian batholiths of Arizona, *in* Abstracts for 1968: Geol. Soc. America Spec. Paper 121, p. 558–559.

Simons, F. S., 1972, Geologic map and sections of the Nogales and Lochiel quadrangles, Santa Cruz County, Arizona: U.S. Geol. Survey Misc. Geol. Inv. Map I–762 (in press).

Simons, F. S., Raup, R. B., Hayes, P. T., and Drewes, Harald, 1966, Exotic blocks and coarse breccias in Mesozoic volcanic rocks of southeastern Arizona, *in* Geological Survey research 1966: U.S. Geol. Survey Prof. Paper 550–D, p. D12–D22.

West Texas Geological Society (Cannon, R. L., and others, leaders), 1959, Geology of the Val Verde Basin and field trip guidebook, Nov. 5–8, 1959: 118 p.

Wilson, E. D., 1939, Pre-Cambrian Mazatzal revolution in central Arizona: Geol. Soc. America Bull., v. 50, no. 7, p. 1113–1163.

U.S. GOVERNMENT PRINTING OFFICE : 1973 O—478–028