Geologic Map and Report for the Cocoraque Butte 7.5' Quadrangle, Pima County, Arizona

by

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Digital Geologic Map 6

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INTRODUCTION

The rocks exposed in this study area represent the eastern-most exposures of the Roskruge Mountains, themselves part of a long chain of low ridges and hills extending as far north as the Silverbell Mountains, and as far south as the Coyote Mountains. This part of the Roskruge Mountains contains rocks that can be grouped into three major subdivisions as follows: (1) a sequence of steeply tilted and folded sedimentary and volcanic rocks containing andesite, rhyolite, and both fluvial and eolian sandstones, (2) a thick pile of Cretaceous rhyodacitic welded ash-flow tuff—here containing only the Tuff of Sharp Peak, and (3) much younger middle Tertiary volcanic and sedimentary rocks. A small granitic pluton intrudes rocks of subdivision 1 but it is not entirely clear how it relates to subdivision 2 rocks.

The younger Tertiary rocks are only slightly tilted, and overlie moderately to steeply tilted welded ash-flow tuffs. However, both of these sequences are everywhere separated from subdivision 1 rocks by the Recortado Well Fault. Therefore, the relative age of the steeply tilted rocks is uncertain, although exposures of similar rocks to the west (Ferguson et al., 2000) suggest that the sequence is older than subdivision 2 and 3 rocks. Furthermore, sequence 1 strata include quartz arenite of suspected eolian origin that is probably correlative with a regional suite of Jurassic wind-blown sand recognized in southern Arizona (Bilideau and Keith, 1986; Tosdal et al., 1989). Subdivision 1 rocks are overlain unconformably (and apparently conformably as well) by the Unit of Tunnel Well—a volcanogenic deposit of uncertain origin (map unit KJtw). It is not certain whether rocks exposed south of Tunnel Well below the Tertiary rocks on Recortado Mountain (map unit Kt) are also the Unit of Tunnel or are younger.

The older sedimentary and volcanic rocks of Subdivision 1 were folded and tilted at least in part before they were overlain by the Unit of Tunnel Well (map unit Ktw). This unit and the older rocks were intruded by the Granodiorite of Cocoraque Butte. Two disparate K-Ar ages of about 70 and 110 Ma (Bikerman, 1967) indicate the pluton intruded either in the middle or late Cretaceous. Petrologic similarities between the plutonic rock and the andesite (map unit KJa, suspected to be Jurassic), however, suggest the pluton may be older. If the Tuff of Sharp Peak (subdivision 2 rocks) at one time overlay the older subdivision 1 rocks, this relationship has since been obscured by erosion and/or burial. The Granodiorite of Cocoraque Butte is cut by the Recortado Well Fault, showing that faulting occurred along this major structure sometime after crystallization of the pluton. The details will be discussed in the sections below.

The best access to the southern part of the map area is from the road heading north from Highway 86, about 2 miles west of Three Points. The northern part of the map area is best reached by driving west on Mile Wide Road until it makes a right-angle turn to the north. Turn left and a good dirt road takes you as far as Cocoraque Ranch. All roads are gated and locked at the boundary of the Tohono O'Odham Indian reservation. Fieldwork was carried out between February and April 2000.

PREVIOUS WORK

Wilson and others (1960) created a geologic map of Pima and Santa Cruz Counties. Bikerman (1965, 1967) examined the rocks of the Roskruge Mountains in a detailed study of the geochemistry and geochronology of the area. He distinguished between the three major episodes of volcanic activity and reported K-Ar dates for many of the rocks. Keith (1976) made reconnaissance geologic maps of the San Vicente and Cocoraque Butte 15' quadrangles. Pearthree and others (1988) made a geologic map of Quaternary and upper Tertiary deposits in the Tucson 1° x 2° quadrangle. To the north, Ferguson and others (1999a) mapped the Sawtooth Mountains and the north end of the West Silver Bell Mountains and Ferguson and others (1999b) made a geologic map of the Samaniego Hills. Ferguson and others (2000) mapped the San Pedro and southern half of the La Tortuga Butte quadrangles to the west.

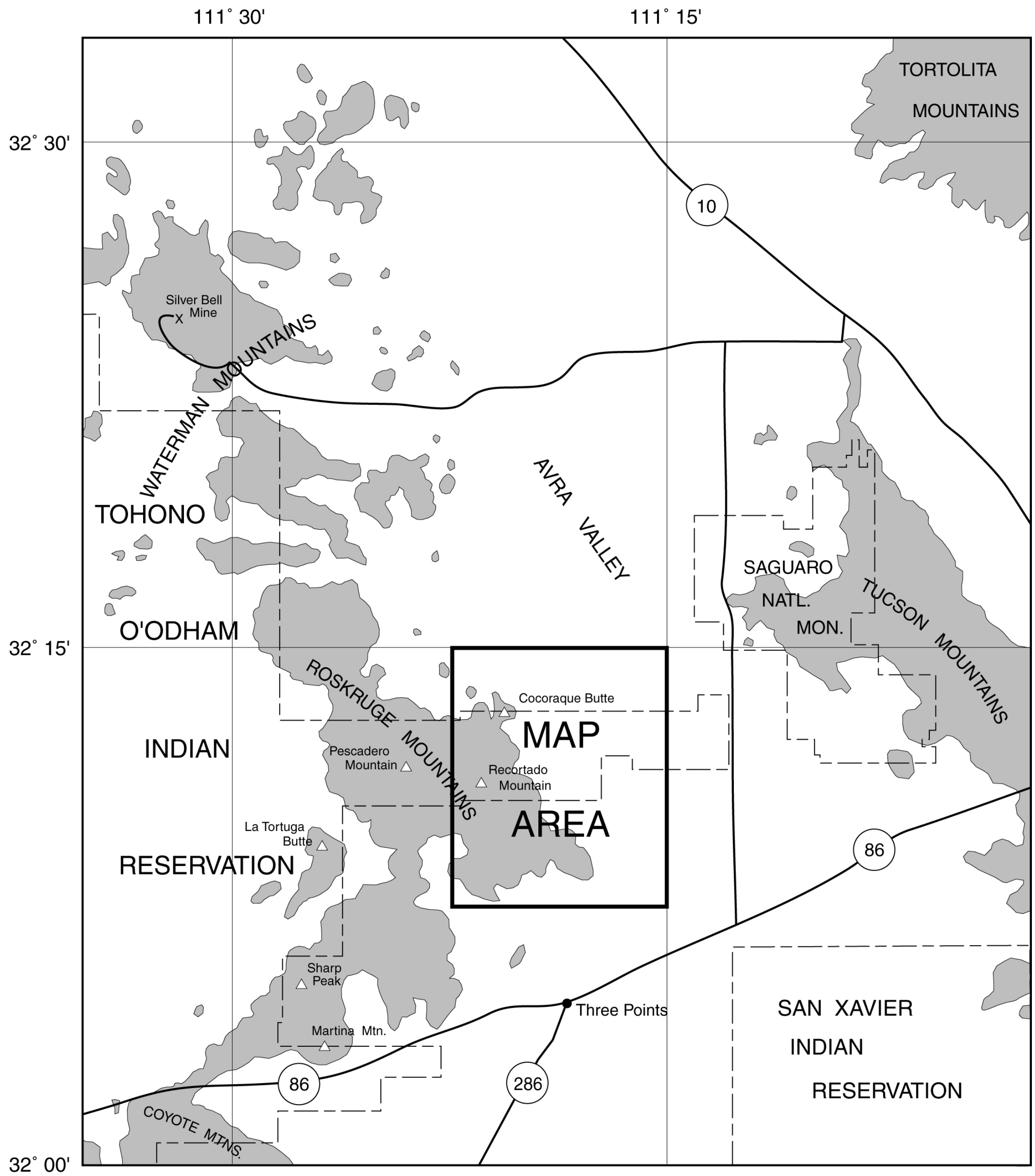

Figure 1. Location map for the Cocoraque Butte 7.5' quadrangle.

MESOZOIC ROCKS

Sedimentary and volcanic sequence east of the Recortado Well Fault

An interesting sequence of interbedded sedimentary and felsic to intermediate volcanic rocks is exposed east of the Recortado Well Fault. From the center of the range northward the rocks have been extensively intruded by the Granodiorite of Cocoraque Butte (Bikerman, 1967), but a thick sequence is exposed directly east of Recortado Well. To the southeast, a large outcrop area of andesite overlies dominantly fine-grained siliceous sedimentary rocks. The area between these two regions has been mostly consumed by the intrusion and Mesozoic strata of the two regions are only in contact in the southern part of section 33, T. 14 S., R. 10 E. and the northern part of section 4, T. 15 S., R. 10 E. This contact zone is complex and not well exposed. The andesite appears to both overlie and locally intrude the older rocks. Bikerman (1967) obtained a K-Ar age of 111.0 ± 2.4 Ma from rocks he thought were andesite in section 33, T. 14 S., R. 10 E. However, mapping during this study has shown that these rocks are actually the Granodiorite of Cocoraque Butte. Although this age is not inconsistent with an older mid-Cretaceous age for the sedimentary and volcanic rocks, it conflicts with the younger K-Ar age of about 70 Ma (Bikerman, 1967).

The visible bottom of the sequence to the north is andesite breccia (map unit KJax). This breccia is poorly exposed and at first glance the rock mineralogically resembles the neighboring granodiorite. However, very locally, interbeds of dark, iron-oxide-rich sandstones show this rock to be supracrustal. The breccia may be autoclastic flow breccias associated with older andesite lava flows or debris flows derived from a nearby andesitic source.

Overlying the andesite breccia is clean, eolian sandstone/quartzite (map unit KJe). It contains moderately sorted to well sorted, subrounded to well rounded quartz grains. The lowermost 10 cm or so is impure sandstone containing some detritus from the underlying unit, but overall the contact is very sharp. Low-angle cross bedding and thin iron-oxide laminations are visible locally, but in general primary sedimentary structures are not widely visible. This unit commonly forms light gray, resistant outcrops shedding angular fragments. In the northeast corner of section 4, T. 15 S., R. 10 E. the sandstone is apparently intruded by andesite. Contacts are almost everywhere mantled by obscuring debris shed from the sandstone, but the irregularly shaped contacts surrounded by andesite suggest intrusive contacts. This relationship is better exposed to the southeast, in the northwest corner of section 11, T. 15 S., R. 10 E., where bedding in sandstone is truncated by intruding andesite.

Overlying the eolian sandstone is a crystal-poor rhyolite lava (map unit KJr). The rhyolite is generally light tan and contains about 5-10% phenocrysts of K-feldspar 1-2 mm long and less abundant quartz. The rock commonly exhibits strong flow-banding approximately parallel to bedding in the overlying sedimentary rocks. Joints follow the flow-banding and the rock commonly weathers into near-vertical plates. Locally, this unit contains abundant subspherical to irregularly shaped blobs 5-2 mm wide of white, coarse-grained quartz. These blobs may be recrystallized spherulites. The unit contains at least two separate flows, and possibly more. The two flows are separated by thin- to medium-bedded arkosic sandstone a few tens of centimeters to 2-3 meters thick (mapped only where thickest).

Apparently, dark green mafic sills (map unit KJm) intrude along the contact between the eolian sandstone and the rhyolite. This dark green rock contains abundant 1-2 mm dark red to dark green pseudomorphs after pyroxene and olivine, in a dark green aphanitic matrix. The unit pinches and swells along the contact over distances of tens of meters. The rock crumbles readily and is not well exposed, but neither vesicles nor breccia were seen. This evidence suggests the rock was not a lava flow but a sill.

Resting on the rhyolite is a sequence of thin- to medium-bedded, well sorted, fine- to medium-grained arkosic sandstones (map unit KJs). Locally, this unit contains beds of fine to coarse gravel with rounded pebbles of gray quartzite, but is typically characterized by fine- to coarse-grained sandstone containing grains of quartz and pink K-feldspar. Up-direction indicators are very rare. Very low-angle cross-beds are commonly ambiguous and contradictory. Two exposures of higher-angle cross-bedding in gullies east of Recortado Well clearly show that the up-direction is to the southwest. Also east and southeast of Recortado Well a thin, 1-2 meter-thick tuff containing quartz and K-feldspar phenocrysts is locally interbedded with the sandstone (map unit KJts). Not all exposures of the tuff were large enough to map. A few exposures in gullies reveal dark purple siltstone beds a few tens of centimeters thick interbedded with sandstone.

Interbedded within the sandstone sequence are discrete beds of breccia containing angular rhyolite clasts surrounded by a sandy matrix (map unit KJrx). While a single bed southeast of Recortado Well, north of Recortado Well the bed merges into several separate beds showing gradational boundaries with the sandstone. These breccia beds probably represent material being shed from the top or sides of a nearby rhyolite flow/dome.

Massive, non-bedded conglomerate overlies the sandstone (map unit KJc). The conglomerate is moderately to poorly sorted and contains subangular to well rounded clasts almost exclusively of the underlying sandstone with rare quartzite. The poorly sorted, nonbedded nature of the unit suggests the material was shed off of a relatively nearby topographic high in the underlying sandstone. This implies local uplift possibly related to tectonic activity at the time. However, the presence of at least some well rounded clasts indicates some of the material was transported greater distances.

Overlying and intruding the older rocks is dark brown to maroon andesite (map unit KJa). The unit contains massive flows, zones of monolithic andesite breccia, and minor interbedded lenses of welded tuff (map unit KJta). In the center of the map area the andesite appears to rest conformably on the conglomerate. However, to the southeast the andesite overlies siltstone (map unit KJss), but nowhere are the conglomerate and siltstone in contact. Either the siltstone pinches out northward and abruptly changes to coarse conglomerate (which is unlikely) or the siltstone really rest on top of the andesite. No reliable up-indicators were seen in the siltstone. Also, andesite detritus is found in the beds of siltstone within about 1-2 meters of the contact, suggesting the siltstone really is on top. Toward the southeast end of the range, in the northwest corner of section 11, T. 15 S., R. 10 E., andesite clearly intrudes eolian sandstone (map unit KJe).

The siltstone unit (map unit KJss) is a heterogeneous unit consisting of concoidally breaking massive siltstone, fine-grained arkosic sandstone, volcaniclastic sandstone, and probably minor andesite flows (?) or slightly reworked volcanic material. Its most prominent feature is the massive, nonbedded siltstone. The rock is very dark gray to almost black with light gray to green reduction spots. In thin-section the matrix appears to be both muscovite and apatite (?). Bedding in the unit dips to the southwest and because this attitude is similar to bedding in the sandstone (map unit KJs) the up-direction was inferred to be towards the southwest as well. As stated in the previous paragraph, though, the up direction may in fact be to the northeast. However, without any additional structural or sedimentological information the up-direction in this unit is uncertain.

In the southern part of section 33, T. 14 S., R. 10 E., rhyolite (map unit KJr) appears to directly overlie the tuff of Sharp Peak. The Recortado Well Fault projects through the area but was not visible. Instead, the tuff of Sharp Peak appears to crop-out on the east side of the fault. Either this rock was misidentified, or this is a critical contact. Work by Ferguson and others (2000) to the west indicates that the tuff of Sharp Peak is younger than the rhyolite.

Age and correlation of the sedimentary and volcanic sequence east of the Recortado Well Fault

Bikerman (1967) originally assigned a mid-Cretaceous age to this sequence based on a ~110 Ma K-Ar date taken from what he thought was andesite about 4 miles southeast of Cocoraque Butte. The sample, however, was actually taken from an exposure of the Granodiorite of Cocoraque Butte (see map). If the date for the pluton is reliable then the sedimentary and volcanic sequence is probably of mid-Cretaceous age or younger.

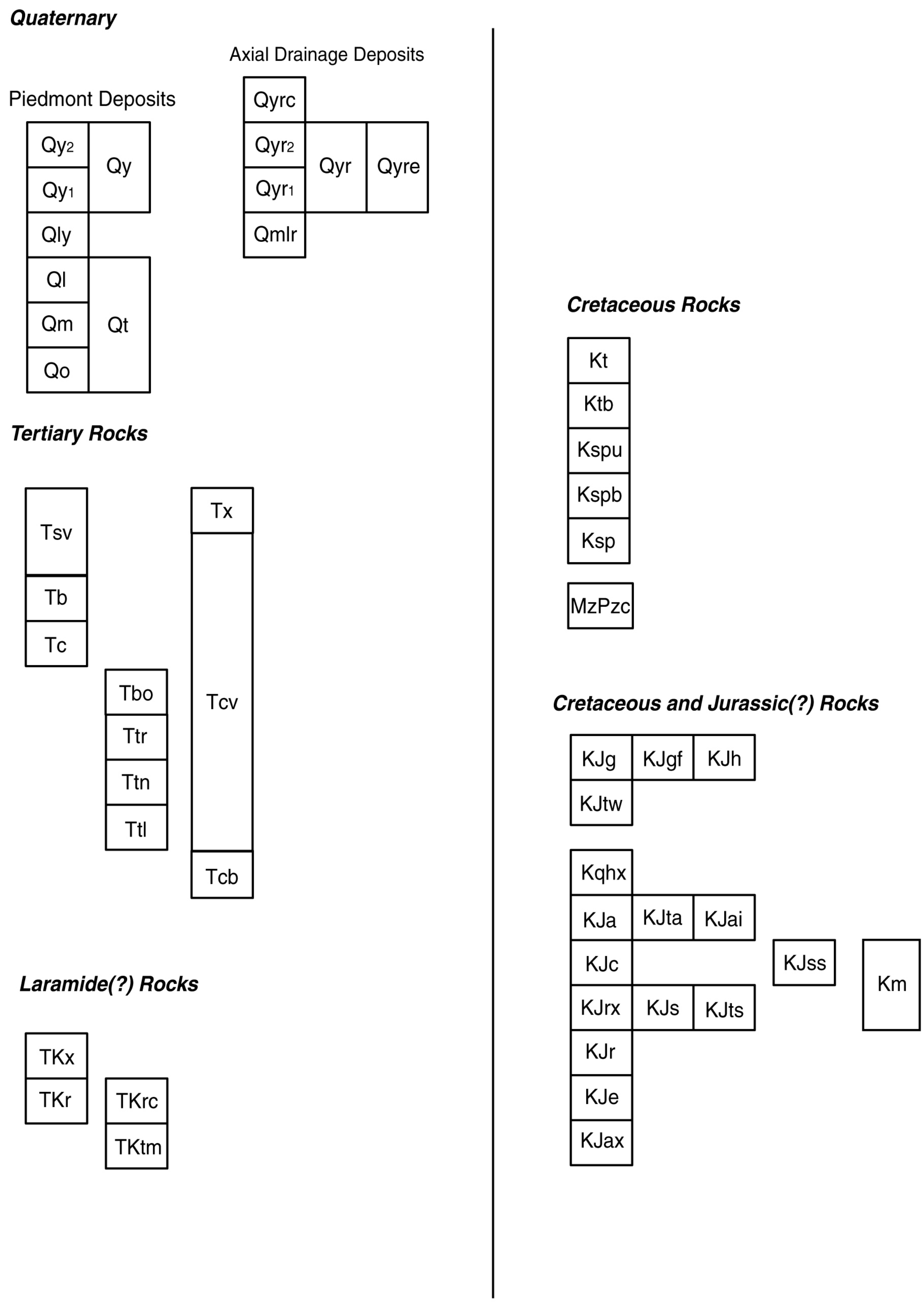

Figure 2. Corrrelation diagram for the Cocoraque Butte quadrangle.

However, the association of thick eolian sandstone with volcanic rocks is more consistent with Lower (?) Jurassic formations (Bilodeau and Keith, 1986; Tosdal et al., 1989).

Heindl (1965) defined a sequence of Mesozoic formations in the Comobabi and Roskruge Mountains. The oldest is the Nolia Volcanic Formation, named for good exposures of the unit near the town of Nolia in the southern Comobabi Mountains. The Nolia is composed of brick-red, maroon, and black andesite flows locally intruded by, and/or overlying quartz monzonite. This formation may be equivalent to the andesite breccia (map unit KJax) which is intruded by the Cocoraque Butte pluton. Heindl states that the formation in the Comobabi Mountains may be as much as 7000 feet thick and thin laterally to only a few hundred feet thick. This description is similar to the map pattern of andesite (map unit KJa), which is very thick in the south and very thin in the north, albeit truncated by the Recorado Well Fault. However, map unit KJa both intrudes and overlies rocks stratigraphically above the andesite breccia, and therefore both andesitic rocks in the Cocoraque Butte quadrangle cannot at the same time be equivalent to the Nolia Volcanic Formation.

Heindl (1965) defined the Cocoraque Formation as a sequence of gray-green arkose and graywacke, gray quartzite, red and gray mottle mudstone, and pebble conglomerate beds. It overlies the Nolia Volcanic Formation based on the presence of andesitic and felsic clasts within the Cocoraque Formation that he assumed eroded from the Nolia. As described, the Cocoraque Formation of Heindl is equivalent to map units KJss through KJe (see map legend). Heindl (1965) reported that a few fossil dinosaur fragments have been found in arkosic beds on the southwest side of the Comobabi Mountains. The fossils are probably late Mesozoic (Jurassic or Cretaceous) in age, though no other information about them is known. Tentatively correlating these rocks with the Amole arkose in the Tucson Mountains to the east (Bryant and Kinnison, 1954), Heindl suggests that the Cocoraque Formation is probably Lower Cretaceous in age. Heindl points out that the formation south of Cocoraque Ranch is intruded by fine-grained porphyritic andesite dikes, however no andesite dikes were seen during this study. He may have been referring to the numerous basalt dikes on the west side of the map. He also stated that the arkosic rocks commonly become flinty and hornfelsic closer to the Cocoraque pluton. This description sounds similar to the very localized fine-grained margin of the pluton itself (map unit KJgf).

Overlying the Cocoraque Formation Heindl defined the Roadside Formation as a sequence of mostly volcanic conglomerate and andesitic flows and breccias. His type locality is near the Roadside Mine just north of the Coyote Mountains, where it is dark purplish gray to olive drab and characteristically contains abundant angular, purplish andesitic fragments. This description sounds similar to the andesite intruding and overlying the sedimentary rocks southeast of Cocoraque Butte (map unit KJa).

Directly east of Recortado Mountain, mature, well-sorted quartz arenite of probable eolian origin overlies andesite breccia (map unit KJax) and is overlain by rhyolite and interbedded fine- to medium-grained arkosic sandstones. Bilodeau and Keith (1986) noted the association of eolian sandstones with early Jurassic rhyolitic to andesitic rocks in southern Arizona. They stated that these rocks are best exposed in five widely separated localities: (1) within the Mount Wrightson Formation in the Santa Rita Mountains, (2) within the Ox Frame Volcanics of the Sierrita Mountains, (3) within the Ali Molina Formation in the Boboquivari Mountains, (4) within the Sil Nakya Formation of the Sil Nakya Hills, and (5) within the Cobre Ridge tuff and other unnamed volcanic units in the small mountain ranges around Arivaca, northwest of Nogales. West of the study area, in the Sil Nakya Hills, Heindl (1965) originally interpreted the Sil Nakya Formation to be equivalent to the Roskruge Rhyolite in the Roskruge Mountains. His interpretation was based on his observation that the welded tuffs in both units are lithologically similar. Since the Roskruge Rhyolite (the "Viopuli red ignimbrite" and "immediately overlying dense welded tuff") was dated at about 74 and 71 Ma (Damon, 1964), Heindl surmised that the Sil Nakya Formation was also late Cretaceous in age. However, Wright and others (1981) determined a mean Pb-Pb-zircon age of 188 Ma from welded tuff in the Sil

Nakya Formation, placing it in the early Jurassic. This age is similar to the mean Pb-Pb age they determined for the Ali Molina Formation (quartz porphyry) of 191 Ma, with an upper concordia intercept of 194 Ma.

Bilodeau and Keith (1986) concluded that the clean, cross-bedded, Jurassic eolian sandstones in southern Arizona can be directly correlated with the Aztec and Navajo Sandstones in the eastern Mojave Desert and on the Colorado Plateau, respectively (see their correlation chart, figure 10, p. 699). If the older volcanic and sedimentary sequence in the Cocoraque Butte quadrangle is indeed early Jurassic, then, as Bilodeau and Keith (1986) suggested, the eolian sandstone (map unit KJe) may be the southern end of the Jurassic sand sheet blowing southward from what is now the Colorado Plateau up onto the Jurassic magmatic arc that existed.

Granodiorite of Cocoraque Butte

The granodiorite of Cocoraque Butte (dated at 70.30 ± 1.40 Ma, Bikerman, 1967) is a predominantly fine- to medium-grained pluton. It is exposed in a N-NW-trending belt through the center of the map area. The grain-size and fabric are generally consistent, although locally there are small pods several meters across that are coarser-grained. One such pod is exposed in the road immediately east of the Santa Rita Well. The freshest exposure is on the lone hill in the northeast corner of section 8, T. 14 S., R. 10 E. This hill was also the coarsest-grained exposure found. The mafic minerals in this pluton consist mostly of biotite, but locally tabular, black crystals of hornblende are conspicuous. These hornblende crystals are commonly much larger than the other crystals in the rock—up to 2 cm long, suggesting they may be xenocrysts.

South and southwest of Cocoraque Butte small zones several meters across near the edge of the pluton are very fine-grained and dark gray to purple. These zones are probably areas of the pluton that cooled quickly at its margin. They are not common and were only mapped in one small area about 1 mile west of Cocoraque Butte.

The pluton intrudes the older, tilted and folded sequence of sedimentary and volcanic rocks, as well as the apparently undeformed Unit of Tunnel Well (map unit Ktw) that overlies the older rocks. South of Cocoraque Butte, the contact between the granodiorite and the sandstone (map unit KJs) was at first difficult to locate. The grain-size and texture of the two rocks are very similar. However, the absence of mafic minerals and presence of thin iron-oxide laminae in the sandstones provide distinguishing features. Also, the sandstone tends to weather into small rounded blocks, whereas the granodiorite weathers into small angular blocks. Likewise, the contact between granodiorite and andesite in the south-central part of the study area is also difficult to recognize. The textures and mineralogy of these two rocks are very similar, but pervasive near-vertical jointing and the absence of fragmental texture can generally distinguish the granodiorite.

The Recortado Well Fault cuts the granodiorite about 1-2 miles southeast of Recortado Well. Here the granitic rock is pervasively fractured and the fracture surfaces are stained with fine-grained red hematite. Exposures of the fault contact are rather poor. The best is in the northwest corner of section 33, T. 14 S., R. 10 E.

The Tuff of Sharp Peak

The Tuff of Sharp Peak (map unit Ksp) dominates the higher relief areas of this part of the Roskruge Mountains. In the map area this unit was divided into (1) a lower, welded, main member, (2) a middle bedded tuff member (map unit Kspb), and (3) an upper welded member (map unit Kspu). All three units are crystal-rich rocks characteristically containing 20-25% phenocrysts of quartz and sanidine. On weathered surfaces, quartz phenocrysts weather out in relief and are generally a diagnostic feature for identification. Bikerman (1967) reported several K-Ar biotite ages that range from about 70.4 to 74.2 Ma. The reported error bars of these ages overlap the age of the Granodiorite of Cocoraque Butte. Bikerman (1967) called this rock a quartz latite. In the classification system of Stekeisen (1976) the chemical composition of quartz latite and granodiorite are not too different. Although the plutonic rock is more basic than the volcanic rocks, it is possible that the Cocoraque Butte pluton may have been the source magma for the Tuff of Sharp Peak.

In most outcrops the Tuff of Sharp Peak displays a weak to moderately welded eutaxitic foliation. The foliation is defined by flattened light gray pumice fragments 1-2 cm long. There are large areas where pumice fragments are difficult to recognize or absent, particularly on the west side of section 33, T. 14 S., R. 10 E., and here no eutaxitic foliation was visible. On the steep, west-facing slope in section 32, T. 14 S., R. 10 E., weak layering is defined by slight color differences, possibly related to degree of welding. In general, though, neither bedding nor flow breaks were seen in the lower nor upper welded members.

The base of the Tuff of Sharp Peak is not seen in the study area. The thick, main member of the Tuff of Sharp Peak (map unit Ksp) is overlain by a sequence of bedded tuffs (map unit Kspb). The bedded tuffs have the same mineralogy as the main member, but are typically lighter in color and probably represent air-fall deposits. These beds are in turn overlain by a second welded ash-flow tuff (map unit Kspu) which also has the same mineralogy as the lower members. Contacts between the bedded tuffs and the welded tuffs are sharp.

From hand-sample analyses in the field only, the abundance of phenocrysts appears to decrease upward in the main member. The abundance of phenocrysts increases at the base of the middle, bedded member, and then decreases upward in a similar fashion. The same pattern seems to repeat in the upper welded tuff member.

Unit of Tunnel Well

This dark green unit contains abundant small subhedral crystals of feldspar and rare quartz, both less than 1 mm across, in a green fine-grained matrix. The unit contains abundant angular to well-rounded clasts of andesite up to ~30 cm wide and is mostly matrix-supported. Bedding is indistinct from a distance and commonly invisible up-close. Only locally is bedding visible, defined by light and dark layers of similar composition. North of Tunnel Well what look like crude columnar joints cut perpendicular to what resembles weak eutaxitic foliation. It is not clear if this is a fragmental volcanic rock such as a tuff or if it is a volcanogenic conglomerate. Locally, the unit contains well-rounded cobbles of gray-green andesite and resembles a conglomerate. However, the abundance of feldspar crystals and paucity of quartz in the matrix suggests this is a tuff. The almost complete absence of any clast type other than andesite indicates the unit had a common source in an andesitic terrain. It is possible that the unit was deposited as debris flows or lahars, or even as partially reworked tuff. More work needs to be done to unravel the rock's history. This unit is distinct from the other units in the area and, for convenience, is here named the Unit of Tunnel Well for good exposures at and north of Tunnel Well in section 18, T. 14 S., R. 10 E.

This unit clearly overlies sandstone (map unit KJs) east of Tunnel Well. The sandstone has been folded into synclines and anticlines, but the unit does not appear to be folded. The contact between the two units in the north trends back and forth in a sawtooth pattern. Locally the contact here is clearly depositional, but it is possible that some of the northeast-striking contacts may be faults. But of course, the contacts are all obscured by rubble from the more resistant sandstone. Southeast of Tunnel Well the contact changes direction from northeast to southeast. Curiously, instead of cross-cutting bedding in the sandstone, the unit apparently conformably overlies the conglomerate (map unit KJc). The contact between map units Ktw and KJc is steep and is parallel to the underlying contact between map units KJc and KJs. No evidence for faulting was seen along the upper contact.

How can the Unit of Tunnel Well both conformably overlie the older rocks and at the same time cross-cut bedding in the older rocks? There are at least three possibilities: (1) the Unit of Tunnel Well was deposited both prior to and during tilting and/or folding in the older rocks. If this was the case then the Unit of Tunnel Well may represent syntectonic debris flows shed from newly created topographic highs. The unit covered the top of the older sequence while the older rocks were relatively undeformed and then subsequently filled-in the low areas as the older sequence tilted more steeply. The last, only slightly tilted deposits of the Unit of Tunnel Well then surrounded the now steeply tilted older rocks; (2) The rocks conformably overlying the conglomerate (map unit KJc) were misidentified and are really andesite (map unit KJa) which rests conformably on conglomerate farther to the southeast. Since the Unit of Tunnel Well contains abundant fragments of andesite, the two units appear very similar; (3) The contact between the Unit of Tunnel Well and the conglomerate is really a fault contact. This is the least favorable of the alternatives. No brecciation nor mineralization was seen along the contact. Also, the strike and dip of the contact very closely matches that of the contact between the underlying conglomerate and sandstone, as well as bedding in the sandstone. Faults do not normally follow bedding, but instead cut across bedding.

Tuff northwest of Recortado Mountain

Immediately northwest of Recortado Mountain the middle, bedded member of the Tuff of Sharp Peak (map unit Kspb) appears to be overlain and truncated by a fine-grained, green- to tan-colored welded tuff (map unit Kt). This tuff is weakly welded and contains abundant angular to subrounded fragments of andesite in a green, fine-grained matrix. It contains abundant small subhedral phenocrysts of feldspar, minor dark opaque minerals, and rare quartz, all less than 1 mm across.

South of Tunnel Well, the rock contains abundant green clots up to about 1 cm wide that may be altered pumice. Here, eutaxitic foliation is more easily seen. The lower contact appears to cut across bedding in the bedded tuffs (map unit Kspb). This relationship is the basis for defining this tuff as younger than the Tuff of Sharp Peak. This definition is probably valid since varying dips of eutaxitic foliation in the Tuff of Sharp Peak suggest Ksp be also folded to some degree. However, immediately southeast of Tunnel Well a crystal-rich, quartz- and sanidine-bearing welded tuff overlies this unit. The welded tuff resembles the Tuff of Sharp Peak. If it is the Tuff of Sharp Peak then map unit Kt and the Tuff of Sharp Peak erupted penecontemporaneously.

The younger age of this unit is also based on the assumption that the contact between the bedded tuffs of the Tuff of Sharp Peak (map unit Kspb) and map unit Kt is depositional. To the south, in the southwest ¼ of section 19, T. 14 S., R. 10 E., siltstone and sandstone (map unit Tcv) butt up against what appears to be a high-angle contact between Tcv and Ktw. This contact may be a fault or buttress unconformity (as explained below). It also projects along the contact between the bedded tuffs and map unit Kt, suggesting this contact may be a fault. Because of these uncertainties the proposed age-relationship between the Tuff of Sharp Peak and map unit Kt should be viewed with caution.

It should be noted that this tuff (map unit Kt) and the Unit of Tunnel Well are mineralogically and texturally similar. They were first mapped as the same unit but only later separated to alleviate contradictions between observed age-relationships north and south of the Recortado Well Fault. It is possible that the two units are the same, but more work needs to be done to make that determination.

TERTIARY VOLCANISM AND SEDIMENTATION

The Tuff of Recortado Mountain

Flow-breaks and bedding in non-welded tuff below Recortado Mountain

Below Recortado Mountain is a very conspicuous sequence of light yellow, bedded, lithic tuffs (map unit Ttl). Within the unit, several flow breaks are visible. They are defined both by unconformities and by changes in clast compositions. These flow breaks were not mapped individually, but at a larger scale a more detailed study might show some interesting relationships. Some sequences of beds contain almost exclusively clasts of maroon, nearly aphyric rhyolite (this particular rhyolite unit is not exposed in the map area but clasts are very abundant in Ttl). Large brecciated piles of this rhyolite several meters locally across occur at the base of the sequence and may represent large blocks ejected from the vent. Other sequences of beds contain almost solely clasts of the Tuff of Sharp Peak, while other beds contain a mix of clasts and even include rare clasts of quartzite, rhyolite (map unit TKr), and equigranular, medium-grained biotite granite.

The unconformities within the bedded lithic tuffs are defined by sets of gently to moderately sloping bedding separated from the upper and lower sets by curving erosional surfaces. The effect from a distance is that of large-scale trough cross-bedding. These features are particularly well exposed in the center of section 30, T. 14 S., R. 10 E., in the deeper gullies. The variation in dips between bedding sets is greater than that shown on the map. Some variations just could not be shown over such small distances.

Bikerman (1967) reported a sanidine K-Ar age of 12.96 ± 0.40 Ma for the southernmost exposures of this unit in the northeast corner of section 6, T. 15 N., R. 10 E. This age is very similar to that of the overlying Tuff of Recortado Mountain. Although the bedded tuffs contain phenocrysts of sanidine and quartz, their abundance is much less than those in the welded tuff. Even so, their close ages, as well as their close special proximity, suggest these two tuffs were related to the same pulse of volcanism.

Welded Tuff of Recortado Mountain

The welded part of the Tuff of Recortado Mountain is quite a distinctive rock. The lower part (5-10 meters or so) is a strongly welded, dark gray to almost black vitrophyre, and many zones farther up in the section appear at least locally vitric. The rock forms a prominent dark-colored cliff bordering a relatively flat mesa tilting gently about 5° to the southeast. From a distance and on aerial photographs layering can be seen in this unit. Although this layering may represent flow breaks, at the outcrop there does not seem to be much mineralogical variation between the different layers. Nor are there distinctive non-welded horizons. In any case, the separate layers could probably be mapped individually with more work.

The tuff is very lithic-rich and characteristically contains angular, poorly sorted clasts of light gray, flow-banded crystal-poor rhyolite. The tuff contains about 5-10% subhedral clear sanidine 1-2mm, possibly quartz, and rare biotite, all in a yellow-orange to black matrix. Black where vitric. Compacted pumice fragments are black near the base and brown above. In thin-section the rock contains abundant euhedral and broken fragments of K-feldspar (probably sanidine). Dark spots are green-pleochroic pyroxene (?) altering to and surrounded by a rim of fine-grained opaque minerals (hematite?). Some pyroxene phenocrysts are nearly euhedral. The wavy matrix is very fine-grained to glassy and is nearly isotropic. Bikerman (1967) reported two K-Ar sanidine ages of 12.93 ± 0.60 and 14.25 ± 0.50 Ma from this unit.

The main mass of the tuff of Recortado Mountain is at Recortado Mountain where it forms a gently dipping plateau. Another, smaller exposure 1.5-2 miles directly south shows that the tuff was deposited within preexisting valleys in the tuff of Sharp Peak. On the west side of Recortado Mountain the welded tuff is exposed at lower topographic levels. Since there are no visible faults between the mesa and the lower exposures, the lithic tuff (map unit Ttl) appears to have been locally eroded prior to deposition of the welded tuff.

Down-slope from the northern part of the mesa is a curious exposure of welded tuff. It locally displays near-vertical eutaxitic foliation and the rock itself appears to both intrude and be included in the lithic tiff. The outcrops are irregularly shaped and almost resemble dikes. Does this exposure represent some type of fissure vent for the tuff of Recortado Mountain? It does not make sense that it would be a block foundering in the underlying lithic tuff since the lithic tuff was probably already lithified prior to deposition of the welded tuff.

About 1 mile southwest of Recortado Mountain, where the "R" is in "Roskruge" on the map, the younger sandstone and conglomerate unit (map unit Tsv) appears to contain clasts of the tuff of Recortado Mountain. Contrary to this, however, the tuff also appears to overlie the sedimentary deposits. This evidence is contradictory. The clasts or the in-place rock was either misidentified or volcanism was active during sedimentation. Pumice fragments are abundant throughout the thin- to medium-bedded sandstones in the upper part of the sedimentary deposits. They may be reworked but their freshness and consistent size-range suggests they may have been incorporated directly from air-fall deposition rather than erosion of an older unit.

Intrusive dike-like band of tuff west of Recortado Mountain.

Down-slope from the west side of Recortado Mountain a dike-like band of tuff cross-cuts the yellow lithic tuff (map unit Ttl). Exposures are good, but limited. At first glance this band resembles a fault cutting through the lithic tuff. Upon closer examination, however, beds in the lithic tuff do not appear offset. The band is 1-2 meters wide and cuts nearly vertically across the bedding in the tuff. Within about 10 cm or so from the contacts the margins of the band exhibit near-vertical layering. The layering bends around protrusions in the wall of the contact. The tuff itself is crystal-poor, and contains abundant pebble-size clasts of the Tuff of Sharp Peak.

What exactly is this band? It is younger than the part of the lithic tuff it cuts through. It is possible that it was a feeder vent to shallow deposits of the lithic tuff. The band strikes nearly north-south and projects towards the high-angle contact between the tuff (map unit Kt) and younger sedimentary deposits (map unit Tcv) less than 0.5 miles to the north. This band may be a younger expression of a buried structural feature of some sort, such as a fissure vent along the structural margin of a caldera. Or it may be coincidental that the band and the high-angle contact happen to line-up.

Tertiary volcanic depression?

Poorly to moderately consolidated siltstone, sandstone, and conglomerate (map units Tsv and Tcv) fill the small valley directly west of Recortado Mountain. These deposits may be equivalent but were mapped as different units for two reasons: (1) Tcv clearly underlies the bedded lithic tuff (map unit Ttl) and the Tuff of Recortado Mountain (map unit Ttr), whereas Tsv is not overlain by these tuffs (except for the possible locality discussed above), and (2) Tcv contains mostly clasts of map units Ksp, Ktw, and TKr, whereas Tsv contains clasts of all local rock types including map units Tbo, Ttl, and Ttr.

As mentioned above map unit Tsv appears to contain clasts of the Tuff of Recortado Mountain and at the same time may be overlain by the tuff in one area. Compounding the confusion, not only does Tsv contain clasts of basalt (probably map unit Tbo) but also it is cut by basalt dikes that appear identical to map unit Tbo. Again, either the clasts were misidentified or extrusion of the volcanic rocks occurred before and after sedimentation. More detailed petrographic and/or geochemical work needs to be done to clarify the sequence of events.

In the west side of section 19, T. 14 S., R. 10 E., these sedimentary rocks overlie megabreccia (map unit Kx). The megabreccia contains large, poorly sorted, jumbled blocks of welded tuff (probably map unit Ksp), and the contact truncates the contact between the welded and bedded members of the Tuff of Sharp Peak. These blocks did not travel far and likely slid down a nearby, steep escarpment. The contact on the east side of the outcrops is very sharp and seems to truncate eutaxitic foliation in the tuff (map unit Kt). The contact projects up-section where the overlying map unit Tcv is in steep contact with the tuff. Another mega- and mesobreccia unit (map unit Tx) truncates this contact and in turn overlies map unit Tcv. The contact was mapped as depositional and may be a buttress unconformity along a steep fault scarp. Or the contact may actually be a fault. In either case the contact is sharp, truncates contacts and foliation, and is steep.

The fact that the steep contact, the breccia units, the sedimentary units, and the Tuff of Recortado Mountain all crop-out in the same relatively restricted area in a low-lying paleovalley within the Tuff of Sharp Peak suggests they all may be related to the same volcano-tectonic depression. There may be a small caldera buried beneath these deposits in this valley. Two other rhyolite lavas were also erupted into this small area (map units TKrc and TKr) and are exposed nowhere else. Also, the uppermost part of map unit Tcv where it is exposed beneath the overlying breccia (map unit Tx) is composed almost entirely of fine-grained silt and poorly consolidated siltstone. This is evidence for quiet water deposition, possibly in a small playa that filled the volcanic depression.

Basalts

At least two different basalts are exposed in the study area: an older crystal-rich basalt (map unit Tbo) and a younger crystal-poor basalt (map unit Tb). The older basalt contains two varieties: a rock containing abundant large subhedral plagioclase phenocrysts and a rock containing only very few plagioclase phenocrysts. Both varieties of the older basalt characteristically contain xenoliths. The xenoliths are black, glassy pyroxene (and spinel?), dark green, glassy pyroxene, and pebbles to cobbles composed of coarse-grained plagioclase and pyroxene. In thin-section the coarse-grained xenoliths contain plagioclase, clinopyroxene, clots of opaque minerals, and possibly minor K-feldspar. The feldspars are anhedral to subhedral and the spaces between them are filled with poikalitic clinopyroxene. Apatite is abundant and occurs as long laths and hexagonal cross-sections. The north side of the circular outcrop of older basalt west of Recortado Mountain contains abundant xenoliths. The margins between the xenoliths and the lava are commonly quite planar and locally the grain-size of the xenoliths decreases into the basalt. The gradational character of some of the margins suggests the xenoliths may be parts of the basalt magma chamber that crystallized at depth and were then brought to the surface.

The younger basalts (map unit Tb) all contain tiny red, altered olivine and/or pyroxene phenocrysts in an aphanitic matrix. These fine-grained lavas contain no xenoliths but commonly contain vesicles filled with zeolites or carbonate, and form dark, talus mantled hills. The younger basalts crop-out only in the southern part of the study area where they unconformably overlie the Tuff of Sharp Peak and the Tuff of Recortado Mountain. Locally, the flows overlie a thin conglomerate (map unit Tc) containing abundant subrounded clasts of the Tuff of Sharp Peak. Bikerman (1967) reported a K-Ar whole-rock age on this unit at the southern margin of the map area of 14.74 ± 2.41 Ma. He also reported another date on what he called the Brawley Wash Basalt, exposed to the south of the study area, of 10.99 ± 1.30 Ma. Bikerman separated the two basalts based on a much lower initial $^{87}Sr/^{86}Sr$ value for the later. These younger basalts form a thick sequence of flows that make up dark-colored hills that from a distance look like broken-up fault blocks slightly tilted to the southwest. Because bedding was only suggestive and not definitive, no attitudes were placed on the map for this unit.

The older basalts (map unit Tbo) are mineralogically identical to the basaltic dikes. Both contain variable amounts of large pyroxene phenocrysts and both contain xenoliths. Bikerman (1967) reported a K-Ar whole-rock age on the long basalt dike N-NW of Tunnel Well of 9.86 ± 1.70 Ma. This age is slightly younger than the younger basalts (map unit Tb) to the south. Map unit Tbo, in general, appears more weathered and does not form the fresh, varnished outcrops that map unit Tb does. The abundance of mafic xenoliths suggests that map unit Tbo came from deeper in the crust or upper mantle than map unit Tb, without being contaminated by more felsic material. Hence map unit Tbo may be more primitive lavas that underwent the least amount of fractionation, whereas the basalts to the south probably underwent more extensive fractionation and may have erupted later. Really, though, without more accurate constraints the relative age of the two basalts remains uncertain.

The occurrence of the crystal-rich basalts (map unit Tbo) and dikes only in the same area as the Tuff of Recortado Mountain and associated volcanic and sedimentary rocks suggests a connection. Bikerman (1967) pointed out that the calculated original volume of the Tuff of Recortado Mountain is very small—only about 0.15 cubic kilometers. He surmised that this must be one of the smallest ash flows to show a basal vitrophyre. For such a small ash flow tuff it must have been very hot. Was that heat generated at deeper crustal levels in a differentiating magma chamber and brought to the surface quickly? Bikerman (1967) used index of refraction curves from Mathews (1951) to determine minimum silica content of the vitric part of the tuff between 60 and 65%--relatively low for a tuff so rich in sanidine. The presence of pyroxene crystals with altered rims indicates the magma was generated at deeper levels and brought to the surface before it could undergo any solid-state phase changes.

So the Tuff of Recortado Mountain was apparently erupted from deeper crustal levels and so was the crystal-rich basalt. Their occurrence together may not be a coincidence. The eruption of the tuff may have created a weaker conduit for later eruption of deep-seated basaltic lava.

STRUCTURE

Rocks in the Cocoraque Butte quadrangle were deformed during at least four separate deformational events: (1) folding and tilting of the older sequence of sedimentary and volcanic rocks, (2) northeast-striking faulting of the same older sequence, (3) intrusion of the granodiorite of Cocoraque Butte and tilting of the late Cretaceous/Laramide volcanic rocks, and (4) faulting and tilting of the younger basaltic lavas. There may be a fifth episode, depending on whether or not the shallow 5° southeast dip of the Tuff of Recortado Mountain is primary.

Folding

During the first episode the sandstone (map unit KJs) north of Recortado Mountain was folded into northwest-trending synclines and anticlines. The orientation of the folds is consistent with northeast-directed compression during the Laramide Orogeny. However, the younger ash flow tuffs to the west of the study area have reported K-Ar ages of between about 76 and 67 Ma and the Cocoraque Butte pluton has a reported age of 70.30 ± 1.40 Ma (all dates are from Bikerman, 1967). These ages fall within the Laramide Orogeny, but the rocks do not appear folded. About 1 mile southeast of Recortado Well reversal of dips of the foliation within the Tuff of Sharp Peak suggests the tuff may be deformed here into a broad anticline. If so, the fold is not very strong and not very extensive. No other folds were seen in any of these Laramide-age rocks. Therefore, the folding in the older sequence occurred sometime before eruption of the Tuff of Sharp Peak between about 76 and 67 Ma.

Older Faulting

During the second episode an older set of northeast-striking, high-angle normal (?) faults cut the older sedimentary and volcanic sequence. Offsets are less than 5-10 meters southeast of Recortado Well. North-northeast of Recortado Well actual displacement is unknown but there is an apparent right-lateral displacement of over 400 meters. Only one outcrop in the southwest corner of section 21, T. 14 N., R. 10 E., revealed that that fault dips ~60° north. The way the other faults project over the topography suggests they all dip to the north-northwest. The fault north of Recortado Well cuts and displaces the earlier-formed folds of episode 1.

Recortado Well Fault

During the third episode the northwest-striking Recortado Well Fault was active. Nowhere could a definitive attitude be measured on the fault and, hence, its sense is uncertain. By the way it wraps across the landscape it may dip to the northeast. This is at odds with the apparent down-to-the-southwest displacement of the younger Tuff of Sharp Peak down against the older rocks. The relative movement on the fault is uncertain. Unfortunately, the two different sequences of rocks on either side of the fault are everywhere only in fault-contact. Hence, their exact stratigraphic relationships are uncertain as well.

The Recortado Well Fault is named for Recortado Well in the southwest corner of section 20, T. 14 S., R. 10 E., through which the fault projects. It slices northwest-southeast across the bedrock in the map area. Exposures are almost everywhere covered by alluvium. In the south-central part of the bedrock area the fault curves to nearly an east-west orientation and splits into two faults—one striking east, the other continuing southeast. The east-striking normal fault dips to the north and it is not clear whether or not it is related to the second episode of deformation. Where these two faults intersect the bedrock has been altered and mostly replaced by dark hematite and quartz, such that the original rock type is unidentifiable. The rock there was given its own label (map unit Kqhx).

To the north near Recortado Well the fault is very difficult to follow. It is mostly buried by alluvium but even the bedrock outcrops are ambiguous. The andesite (map unit KJa), which overlies conglomerate (map unit KJc) to the south, suddenly pinches out just southeast of the well. At the same place, an unnamed tuff (map unit KJta), thought to be the same one interbedded with sandstone (map unit KJs), suddenly swells to take the andesite's place. It seems logical to place the trace of the fault along the previous trend between units KJta and Ksp. There is another fault to the northwest with the same strike (south of Tunnel Well), which dips at a shallow angle to southwest. If this fault and the Recortado Well Fault are one and the same, then that is a strong argument for the Recortado Well Fault dipping southwest. As stated earlier the Unit of Tunnel Well cross-cuts bedding and folding in the sandstone unit, but north of Recortado Well the contact strikes northwest and is very linear. It seems strange that the Unit of Tunnel Well should overlie the sandstone concordant to bedding when it cuts across the bedding farther north. It is possible this contact represents the trace of the Recortado Well Fault. The problem with this is that the conglomerate layer perfectly follows the proposed fault without changing thickness over an appreciable distance, meaning the fault would have cut very nearly parallel to bedding, which would be unusual. Another possibility is that the Unit of Tunnel Well is only partly deformed, as described above. Older portions of the tuff overlying the conglomerate near Recortado Well may be tilted and younger portions of the unit may bury the fault.

The problem posed by the Recortado Well Fault is the age of the Unit of Tunnel Well with respect to the Tuff of Sharp Peak is unknown. It is unlikely that the Tuff of Sharp peak is older. That would invoke extreme differential erosion north of the Recortado Well Fault to remove all of the Tuff of Sharp Peak prior to deposition of the Unit of Tunnel Well there, but leave a thick section south of the fault. In that case the older sequence on the northeast side of the Recortado Well Fault may have been topographically much higher before Sharp-Peak-time and did not receive great thicknesses of the Tuff of Sharp Peak. In that case the Recortado Well Fault might have been something resembling a caldera structural margin. If the Tuff of Sharp Peak is younger than the Unit of Tunnel Well, all of the Tuff of Sharp Peak still had to have been removed everywhere on the north side of the Recortado Well Fault. Why there is no Tuff of Sharp Peak north of the Fault is unclear.

MINERALIZATION

The north-dipping fault in the southwest corner of section 21, T. 14 S., R. 10 E., displaces clean eolian sandstone (map unit KJe) against itself. The fault zone is 1-3 meters wide and forms a light-colored, resistant ridge. The fault zone contains several discrete, anastomosing fracture zones that are partially filled and cemented by fine-grained silica. The silica locally contains abundant hematite and stains some of the outcrops rusty red.

In the northeast corner of section 32 the southeast-striking fault displaces the Tuff of Sharp Peak against itself. White quartz veins and fine-grained silica extensively permeate the fault zone near the "A" in Mountains on the map.

At and near the intersection of the two faults in the northeast corner of section 4, T. 15 S., R. 10 E., the rocks are extensively mineralized with quartz and hematite. Along both fault traces, and in the altered area labeled as map unit Kqhx, the original rock is unrecognizable. Instead, the rock is dark purple brecciated quartz, containing abundant fine-grained and specular hematite. The quartz is locally coarse but is mostly granular, with grains 2-3 mm across. Hematite is pervasive throughout the quartz as well as fills fractures and coats surfaces. In small voids up to about 5 mm long, long euhedral needles of quartz have grown outward into the voids. Some smaller voids are rectangular in shape and may be moulds of sulfide minerals (pyrite?).

The fault zone that extends eastward from this location through the andesite (map unit KJa) is locally filled with brecciated quartz and hematite. The fault zone forms a resistant, rusty red-colored ridge locally up to 4-5 meters thick. Good exposures are found along the wash in the northeast corner of section 3, T. 15 S., R. 10 E.

REFERENCES

Bikerman, Michael, 1965, Geological and Geochemical studies of the Roskruge Mountains, Pima County, Arizona: Tucson, University of Arizona unpub. Ph.D. dissertation, 112 p.

Bikerman, Michael, 1967, Isotopic studies in the Roskruge Mountains, Pima County, Arizona: Geological Society of America Bulletin, v. 78, p. 1029-1030.

Bilodeau, W.L., and Keith, S.B., 1986, Lower Jurassic Navajo-Aztec-equivalent sandstones in southern Arizona and their pale geographic significance: The American Association of Petroleum Geologists Bulletin, v. 70, No. 6, p. 690-701.

Bryant D.L., and Kinnison, J.E., 1954, Lower Cretaceous age of the Amole arkose, Tucson Mountains, Arizona, (abs.): Geological Society of America Bulletin, v. 65, no. 12, pt. 2, p. 1235.

Damon, P.E., and Bikerman, Michael, 1963, K-Ar dating of volcanic and orogenic events in the Tucson Mountains, Arizona (abs.): Geological Society of America Rocky Mountain Section 16th Annual Meeting, Albuquerque, New Mexico.

Damon, P.E., 1964,Summary of research accomplishments in Correlation and chronology of ore deposits and volcanic rocks: Tucson, University of Arizona Geochronology Lab, June 1, 1964, p. 4-28.

Damon, P.E., and Bikerman, Michael, 1964, Potassium-argon dating of post-Laramide plutonic and volcanic rocks within the Basin and Range province of southeastern Arizona and adjacent areas: Arizona Geological Society Digest, v. 7, p. 64-78.

Ferguson, C.A., Gilbert, W.G., Klawon, J.E., and Pearthree, P.A., 1999a, Geologic map of the Sawtooth Mountains and the north end of the West Silver Bell Mountains, Pinal and Pima Counties, southern Arizona: Arizona Geological Survey Open-File Report 99-16, 25 p., scale 1:24,000.

Ferguson, C.A., Gilbert, W.G., Orr, T.R., Spencer, J.E., Richard, S.M., and Pearthree, P.A., 1999b, Geologic map of the Samaniego Hills, Pinal and Pima Counties, southern Arizona: Arizona Geological Survey Open-File Report 99-17, 15 p., scale 1:24,000.

Ferguson, C.A., Gilbert, W.G, and Biggs, T.H., 2000, Geology of the southern Roskruge Mountains including he San Pedro and southern half of the La Tortuga Butte 7.5' quadrangles, Pima County, Arizona: Arizona Geological Survey Open-File Report (in press).

Gelderman, F.W., 1972, Soil Survey of the Tucson-Avra Valley area, Arizona: U.S. Dept. of Agriculture Soil Conservation Service.

Keith, W.J., 1976, Reconnaissance geologic map of the San Vicente and Cocoraque Butte 15' quadrangles, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF-769, 1 sheet, scale 1:62,500.

Lipman, P.W., 1993, Geologic map of the Tucson Mountains caldera, southern Arizona: U.S. Geological Survey Miscellaneous Investigation Series Map I-2205, 2 sheets, scale 1:24,000.

Pearthree, P.A., McKittrick, M.A., Jackson, G.W., and Demsey, K.A., 1988, Geologic map of Quaternary and upper Tertiary deposits, Tucson 1° x 2° quadrangle, Arizona: Arizona Geological Survey open-File report 88-21, 1 sheet, scale 1:250,000.

Phillips, M.P., 1976, Geology of Tumamoc Hill, Sentinel Peak and vicinity, Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 83 p., 1 sheet, scale 1:3,600.

Richard, S.M., Spencer, J.E., Ferguson, C.A., and Youberg, Anne, 2000, Geologic map of the Waterman Mountains and northern Roskruge Mountains, Pima County, Arizona: Arizona Geological Survey Open-File Report (in press).

Sawyer, D.A., 1996, Geologic map of the Silver Bell and west Silver Bell Mountains, southern Arizona, U.S. Geological Survey Open-File Report 96-006, 21 p., 1 sheet, scale 1:48,000.

Tosdal, R.M., Haxel, G.B., and Wright, J.E., 1989, Jurassic geology of the Sonoran Desert region, southern Arizona, southeastern California, and northernmost Sonora; construction of a continental-margin magmatic arc, in Jenny, J.P., and Reynolds, S.J., Geologic evolution of Arizona: Arizona Geological Society Digest 17, p. 397-434.

Wilson, E.D., Moore, R.T., and O'Haire, R.T., 1960, Geologic map of Pima and Santa Cruz Counties, Arizona: Arizona Bureau of Mines, 1 sheet, scale 1:375,000 [now available as Arizona Geological Survey Map M-3-8].

Wright, J.E., Haxel, G., and May, D.J., 1981, Early Jurassic uranium-lead isotopic ages fro Mesozoic supracrustal sequences, Papago Indian Reservation, southern Arizona (abs.): Geological Society of America Abstracts with Programs, v. 13, p. 115.

UNIT DESCRIPTIONS
FOR THE COCORAQUE BUTTE QUADRANGLE
AZGS OFR-00-08

Quaternary Surficial Deposits

Piedmont Deposits

Qy_2 **Modern alluvium (< 100 yr).** Unconsolidated sand and gravel in active stream channels. Deposits consist of stratified, poorly to moderate sorted sands, gravels, pebbles, cobbles, and boulders. These deposits are highly porous and permeable. Soils are generally absent.

Qy_1 **Holocene alluvial deposits (< 10 ka).** Unconsolidated sand to small boulders reaching sizes up to 25 cm in diameter upstream but smaller and fewer downstream. Larger clasts are metamorphic rocks and medium-grained granites. Smaller clasts are subangular granitic grus. Qy deposits are characterized by stratified, poorly to moderately sorted sands, gravels, and cobbles frequently mantled by sandy loam sediment. On this surface the main channel commonly diverges into braided channels. Locally exhibits bar and swale topography, the bars being typically more vegetated. Soil development is relatively weak with only slight texturally or structurally modified B horizons and slight calcification (Stage I). Some of the older Qy soils may contain weakly developed argillic horizons. Because surface soils are not indurated with clay or calcium carbonate, these surfaces have relatively high permeability and porosity.

Qy **Holocene alluvial deposits, undivided.**

Qly **Holocene and Late Pleistocene alluvial deposits, undivided.**

Ql **Late Pleistocene alluvial deposits (10 to 250 ka).** Moderately sorted clast-supported sandstones and conglomerates. Ql surfaces are moderately incised by stream channels but still contain constructional, relatively flat interfluvial surfaces. Ql soils typically have moderately clay-rich tan to red-brown argillic horizons. These soils contain much pedogenic clay and some calcium carbonate, resulting in relatively low infiltration rates. Thus these surfaces favor plants that draw moisture from near the surface. Ql soils typically have Stage II calcium carbonate development. These surfaces are commonly slightly darker than Qm deposits in the region because the older soils generally contain more, lighter-colored carbonate closer to the surface.

Qm **Middle Pleistocene alluvial deposits (250 to 750 ka).** The deposits are moderately consolidated and locally weakly indurated by carbonate. Argillic horizons are strongly developed where original depositional surfaces are well preserved.

Qt **Talus (Tertiary).** These deposits contain moderately sorted to poorly sorted angular clasts of basalt. Clasts commonly exhibit dark varnish. The top 10-30 cm is generally loose material, but below that Stage III caliche laminae form a strongly cemented horizon. Forms sloping aprons around hills capped by younger basalt (map unit Tb).

Qo **Early Pleistocene alluvial deposits (750 ka to 2 Ma).** A high-standing, preserved surface on the west-central border of the map area contains abundant subangular to subrounded pebbles to boulders of Ksp and TKr. Stage III caliche laminae are visible along some edges of the deposits. About 1.5 miles southeast of Cocoraque Butte Qo deposits form lower, more subdued topography. The surface is smooth compared to younger deposits and is mostly covered with subrounded pebble-size clasts. Cobbles and boulders up to ~40 cm are widely spaced but very abundant on the dissected edges of the unit. Small chips of carbonate become more abundant toward the apex of the fan (southward). Surface clasts are mostly Ksp, with less abundant KJs, KJg, KJa, and TKr (whose only known source is rather far away). This surface exhibits a loose pavement and weak to moderate varnish. Qo soils are characterized by a relatively thin argillic horizon.

Axial Drainage Deposits

Sediment deposited by Brawley Wash covers the eastern part of the map area. Surfaces consist of channels, young stream terraces that compose the geologic floodplain, and older relict floodplain deposits that date to the Pleistocene. Deposits are primarily sand and finer, with minor gravel, and channels are generally quite small and discontinuous. Much of the area covered by axial stream deposits has been altered by agricultural activity. In these areas, deposits are subdivided into Holocene and Pleistocene units based on soils information obtained from a soil survey of this area (Gelderman, 1972).

Qyrc **Modern river channel deposits (< 100 years).** This unit consists of river channel deposits of Brawley Wash. They are composed primarily of sand and gravel, with finer sediment along the channel banks. Deposits are typically poorly sorted and have well preserved planar beds and cross-bedding. There is no soil development in these deposits. Along the parts of Brawley Wash, modern channels are entrenched up to several meters below adjacent young terraces. The current entrenched channel configuration began to evolve with the development of arroyos in the late 1800's, and is continuing to evolve through this century. Channels are extremely flood prone and are subject to deep, high velocity in moderate to large flow events. Channel banks formed in weakly consolidated Holocene deposit and are subject to severe lateral erosion during floods.

Qyr$_2$ **Late Holocene floodplain deposits (< ca. 4 ka).** Generally fine-grained deposits on the active floodplain of Brawley Wash. Deposits generally consist of sand, silt, and clay, with local gravel concentrations in small channels and fans. Shallow, small, discontinuous channels are common; many of them are linear, suggesting that channels developed along roads or wagon tracks. Soil development is minimal, consisting of brown A horizons and carbonate filaments (weak stage I calcic horizons); surface colors are brown to grayish brown. Vegetation typically is creosote and low grass and shrubs, with local concentrations of mesquite, acacia, and palo verde trees along channels. Variegated surface color depends mainly on vegetation density, dark brown color along channels and where vegetated, brown where more sparsely vegetated. These areas are prone to inundation in floods and may be subject to intense erosion along existing small channels.

Qyr$_1$ **Holocene terrace deposits (< 10 ka).** Deposits associated with low terraces of Brawley Wash. Typically, they are flat surfaces that are on the fringes of and less than 1 m above the active floodplain, but small channels exist in some places within this unit. Deposits are generally fine-grained, but locally surfaces have weak, discontinuous gravel lags composed of mixed lithologies. Soil development is weak, with cambic horizons and carbonate filaments (stage I calcic horizons). Surface color typically is light brown, and surface clasts have no varnish. Very limited low (0.5 m high), heavily bioturbated coppice dunes are associated with creosote bushes. Portions of the Qy$_1$r surfaces may be inundated in the largest floods.

Qyre **Holocene stream terrace deposits and eolian deposits (< 10 ka).** Mixed young river terrace deposits and eolian deposits. Landforms consist of low coppice dunes and intervening flat surfaces with minimal gravel lags and no pavement development, less than 1 m above adjacent floodplains. Drainage networks typically are discontinuous and channels are very small. Low coppice dunes are abundant. Soil development is weak, with cambic horizons and carbonate filaments (stage I calcic horizons). Surface color typically is light brown. Vegetation is sparse; desert shrubs are relatively concentrated in dunes and along small channels. The preservation of eolian deposits indicates that these areas have not been subject to substantial flooding recently.

Qyr **Holocene stream deposits, undivided (<10 ka).** Holocene deposits underlying areas that have been impacted by intensive agricultural activity, generally irrigated fields. In these areas, it is not possible to subdivide Holocene deposits.

Qmlr **Middle to late Pleistocene stream terrace deposits (~10 to 500 ka).** Relict late or middle Pleistocene river terrace deposits on the basin floor. Deposits are dominated by clay, sand and silt, with some fine gravel. Soil development is moderate to strong, with reddish brown clay loam to clay argillic horizons and soft carbonate nodules and whitening of calcic horizons (stage II to III calcic horizons). Reddish brown surfaces are typically fairly flat and slightly elevated above the adjacent floodplain. In areas that have been cultivated, topographic differences between Pleistocene and Holocene surfaces are generally undetectable. In these areas, Qmlr deposits are distinguished from Holocene deposits based on soil survey mapping (Gelderman, 1972).

Tertiary Rocks

Tsv **Sandstone and conglomerate (Tertiary).** Thin- to medium-bedded, interbedded sandstone and conglomerate. Nearly horizontally bedded. This unit contains moderately sorted to well sorted, subangular to subrounded clasts of every local volcanic rock type, including map units Ttr, Tbc, KJr, and TKr. It is mostly covered by a thin mantle of colluvium but there are some excellent exposures in the area located at the number “25” in section 25, T. 14 N., R. 9 E. Basalt dikes cut these deposits. Moderately to strongly consolidated with carbonate cement. Most clasts are pebble-size and smaller. The upper part of this unit contains alternating beds of fine-grained sandstone and sandy layers containing yellow pumice and mustard-colored clasts of what resemble the tuff of map unit Ttr.

Tb **Younger basalt (Tertiary).** These dark gray lavas contain tiny red phenocrysts <1 mm of subhedral to euhedral olivine and/or pyroxene completely altered to red opaques, and larger 1-2 mm, dark green pyroxene. The matrix is mostly aphanitic but commonly contains tiny plagioclase microlites. In thin-section the slightly larger phenocrysts are subhedral clinopyroxene and lath-shaped red opaques. Most of the section is felty laths of plagioclase, tiny opaque minerals, and small clinopyroxene crystals. Clinopyroxene crystals commonly occur in clumps. Fresh surfaces are dark bluish gray. The rock is commonly covered with a dark varnish. Thick, laminar Stage III caliche is common a few inches below the surface on the talus aprons surrounding the outcrops. On several hills, particularly the hill farthest to the southwest, fracture faces are coated with ropey, light gray to clear botryoidal chalcedony. Locally, fractures are coated with caliche. Bikerman (1967) reported a K-Ar whole-rock age on this unit at the southern margin of the map area of 14.74 ± 2.41 Ma. He also reported another date on what he called the Brawley Wash Basalt, exposed to the south of the study area, of 10.99 ± 1.30 Ma.

Tc **Conglomerate (Tertiary).** These deposits contain poorly sorted, subangular to subrounded pebbles to small boulders of the tuff of Sharp Peak (map unit Ksp). The largest clasts are up to ~50 cm across. The unit is exposed in two small outcrops beneath basalt (map unit Tb) in the southwest part of the map. The northernmost outcrop is better exposed and reveals a matrix of volcanic-lithic sand. Here the unit is also overlain by a thinly bedded, pumice-rich basaltic sandstone/tuff 2 meters thick.

Tbo **Older basalt (Tertiary).** This basalt contains phenocrysts of large, translucent anhedral to euhedral plagioclase 5-10 mm and anhedral to subhedral black pyroxene (?) up to 15 mm and commonly broken and glassy. Matrix is microcrystalline to aphanitic. In thin-section the rock contains phenocrysts of plagioclase, clinopyroxene, and probably orthopyroxene. Plagioclase crystals are anhedral to subhedral and the rims are zoned. Opaque minerals appear at least partially altered to red opaque minerals (hematite?). Pyroxenes are anhedral to nearly euhedral and commonly contain opaques and are locally twinned. The matrix is intergrown, fine-grained plagioclase crystals and smaller, disseminated pyroxene and opaque crystals. Locally, the rock contains large, round black and dark green pyroxene xenocrysts and rounded xenoliths composed of intergrown coarse plagioclase and pyroxene. Fresh surfaces are dark gray. Weathered surfaces are tan and commonly varnished. Locally, small vesicles 1-2 mm across are filled with white minerals. The rather circular exposure of this rock contains abundant xenocrysts and xenoliths (zeolites?), but is also similar to the younger basalt (map unit Tb) because it contains smaller, less abundant plagioclase. Its relationship to both of these basalt units is not clear. Bikerman (1967) reported a K-Ar whole-rock age on the long basalt dike N-NW of Tunnel Well of 9.86 ± 1.70 Ma.

Ttr **Tuff of Recortado Mountain (Tertiary).** Crystal-rich, yellow-brown to black welded tuff. This unit contains about 5-10% subhedral clear sanidine (1-2mm), possibly quartz, and rare biotite, all in a yellow-orange to black matrix. Black where vitric. Compacted pumice fragments are brown. In thin-section the rock contains abundant euhedral and broken fragments of K-feldspar (probably sanidine). Dark spots are green-pleochroic pyroxene (?) altering to and surrounded by a rim of fine-grained opaque minerals (hematite?). Some pyroxene phenocrysts are nearly euhedral. The wavy matrix is very fine-grained to glassy and is nearly isotropic. In outcrop the rock contains very abundant, poorly sorted, angular, light gray clasts of crystal-poor, flow-banded rhyolite. Weathers dark brown to dark gray and commonly varnished. Caps Recortado Mountain and resembles basalt from a distance. Some areas are not very dense and the rock breaks easily. Typically, though, this tuff is very densely welded and difficult to break. Bikerman (1967) reported three K-Ar sanidine ages of 12. 93 ± 0.60, 12.96 ± 0.40, and 14.25 ± 0.50 Ma from this unit.

Ttn **Nonwelded base of the Tuff of Recortado Mountain (Tertiary).** This crystal-rich tuff is mineralogically the same as the overlying tuff, but is not welded. It crumbles easily and becomes more competent as it grades upward into welded tuff over a distance of about 3 meters. Exposed only to the west of Recortado Mountain at the base of the round hill of basalt (map unit Tbo).

Ttl **Lithic tuff (Tertiary).** This yellow, crystal-poor lithic ash-fall tuff contains <2% subhedral quartz and sanidine 1-2 mm wide and abundant yellow pumice. It is composed of separate bedded intervals characterized locally by particular clast types. Most exposures in the south contain mostly subangular to subrounded pebbles to cobbles of the Tuff of Sharp Peak (map unit Ksp). In exposures to the west and northwest clasts of maroon, crystal-poor, flow-banded rhyolite form pebbles to giant blocks 5 meters or more across at the base of the unit (this rhyolite is nowhere exposed in outcrop). High in the section clasts of the Tuff of Sharp peak (map unit Ksp) locally comprise more than 50% of the tuff and form a dark armor on the surface. Most deposits are thin- to thick-bedded, are clast-supported to weakly matrix supported, and locally show weak graded bedding. In the south the tuff contains rare lithic fragments of medium-grained granite and light gray quartzite.

Tx **Breccia (late Tertiary).** This poorly sorted unit contains angular to subrounded pebbles to small boulders of ash-flow tuff (probably Ktw and Ksp), all in a reddish brown sandy matrix. It is exposed only in one small outcrop about 0.5 miles northwest of Recortado Mountain where it cross-cuts a rather steep contact between the sedimentary deposits (map unit Tcv) and the lower breccia unit (map unit Ttx). Relationship to other rocks is uncertain.

Tcv **Conglomerate, sandstone, and siltstone (Tertiary).** Exposures are poor, and mostly mantled by a cobble lag. Deposits lower in the unit appear to be mostly conglomerate containing pebbles to small boulders of map units Ksp, TKr, and Ktw, all in a reddish brown sandy matrix. Thin- to medium-bedded where visible and nearly flat-lying. Upwards in the unit, below Tx, these deposits are mostly friable, reddish brown, fine-grained sandstone and siltstone. The entire unit appears to fine upward. Intruded by basalt dikes. This unit may be equivalent to map unit Tsv.

Tcb **Conglomerate with basalt clasts (Tertiary).** This unit is a nonbedded, poorly sorted conglomerate composed exclusively of basalt clasts. The clasts are angular to rounded and range from pebbles to boulders surrounded by a very fine-grained red silty matrix. Some small clasts are broken hornblende xenocrysts. Locally, the deposits are overlain by map units Tsv and Ttr. Relationships to other units are unclear.

Laramide Rocks (?)

TKh **Hypabyssal rock? (Tertiary or Cretaceous).** This rock mineralogically closely resembles the Cocoraque Butte granodiorite, except that it locally exhibits a fragmental texture. In thin-section the rock contains very abundant (over ~70%) phenocrysts of mostly anhedral K-feldspar, and less abundant plagioclase, rare quartz, and minor biotite and/or muscovite and opaques. The matrix is granular fine-grained quartz to nearly glassy. Clots of opaques commonly occur together with aggregates of a fine-grained mineral exhibiting high relief and low to medium birefringence (probably apatite). The rock weathers and erodes similar to the Cocoraque Butte granodiorite. This unit is exposed only on one small hill near the northwest corner of the map area.

TKx **Breccia, southern exposure (Tertiary or Cretaceous).** This breccia unit contains poorly sorted angular blocks of rhyolite (map unit KJr), quartzite (map unit KJe), and what looks like clasts of the mafic sill (map unit KJm). It appears to overlie andesite (map unit KJa) and is intruded by the Granodiorite of Cocoraque Butte. Exposed only near the west side of the large andesite mass on the north side of the Recortado Well Fault.

TKr **Rhyolite (Tertiary or Cretaceous).** This felsic lava contains ~5% subhedral quartz and sanidine as large as 3 mm, but commonly 1 mm across, all in a bluish gray aphanitic matrix. Small lithophysae a few millimeters to about 1-1.5 cm long are commonly lined with euhedral quartz crystals several millimeters long. The rock breaks easily into platy slabs. Exhibits minor varnish. Overlies and may intrude the Tuff of Sharp Peak (map unit Ksp) on west-central edge of study area. In thin-section the rock contains anhedral to euhedral K-feldspar phenocrysts. Many are twinned. Wavy laminae visible in hand-sample are composed of tiny feldspar laths arranged with their long axes mostly parallel to the laminations. In crossed-polarized light many crystals go extinct together in zones that, together, resemble a larger, intergrown crystalline texture, with each zone containing hundreds of laths. More opaque areas have moderate to high birefringence and resemble very fine-grained carbonate. Tiny dark spots are probably opaque minerals.

TKrc **Crystal-rich rhyolite (Tertiary or Cretaceous).** This crystal-rich felsic lava contains abundant, large subhedral to euhedral, equant sanidine phenocrysts 1-5 mm wide, in a tan to dark maroon aphanitic matrix. The rock is exposed on the west-central side of the map where it overlies a crystal-poor ash-flow tuff (map unit TKtm) and is overlain by sediments (map unit Tcv) and yellow lithic tuff (map unit Ttl). Most of the outcrop shows steeply north-dipping, east-west flow-banding. The northern part of the exposure is bluish gray and vitric, grading into yellow, crumbly, devitrified zones. Fresher pieces are found as clasts within the overlying lithic tuff.

TKtm **Tan, crystal-poor ash-flow tuff (Tertiary or Cretaceous).** This rather crystal poor, gray ash-flow tuff contains ~5% subhedral phenocrysts of rather clear feldspar (sanidine?) <1 mm to 2 mm in a tan to gray aphanitic matrix. Light gray pumice fragments are up to 2 cm across. Low density and crumbles easily. Bedding is indistinct, but exposures are very poor. This rock is overlain by crystal-rich rhyolite (map unit TKrc) on the west-central side of the map. Ferguson and others (2000) mapped similar rocks to the west in the La Tortuga Butte quadrangle where he subdivided them into an upper crystal-poor tuff (their map unit KJxpu) and a generic crystal-poor tuff (their map unit KJxp). They also observed small conspicuous quartz phenocrysts, so the rocks may or may not correlate. Map unit TKtm may correlate with one or both of two, thin outflow sheets of crystal-poor, lithophysal, welded tuffs in the western Tucson Mountains (map units Jt and Jlt of Lipman, 1993), and/or a thin crystal-poor welded tuff in the easternmost Tucson Mountains mapped as the Mission Road Tuff (Phillips, 1976). The tuff may also correlate with a thin tuff or sequence of tuffs mapped by Sawyer (1996) in the southwestern Silverbell Mountains (his unit Mzr), or a thin tuff (KJxp outcrop isolated by alluvium) in the southeastern Silverbell Mountains (Richard et al., 2000).

Cretaceous Rocks

Tuff of Sharp Peak

Kspu **Upper member of the Tuff of Sharp Peak (Cretaceous).** This rock is very similar to the main unit of the Tuff of Sharp Peak (map unit Ksp), but contains a smaller percentage of phenocrysts, ~5%. Contains subhedral phenocrysts of quartz and light gray feldspar 1-2 mm wide. The rock also contains abundant, poorly sorted, angular sand- to large pebble-size clasts of fine-grained felsic volcanic rocks. Pumice is not abundant. In the south the unit commonly weathers a slightly lighter shade of pink or tan than Ksp. On the east side of section 4, T. 15 S., R. 10 E., thin bedding is folded and contorted, resembling flow-banding in a lava.

Kspb **Bedded tuff (Cretaceous).** This light gray to tan bedded tuff contains abundant, subhedral, clear quartz ~1 mm wide, and less abundant subhedral light gray to clear sanidine 1-2 mm. Contains a few small andesite and felsic volcanic pebbles and light gray to tan pumice. Thin- to medium-bedded. Overlies the main unit of the Tuff of Sharp Peak (map unit Ksp). Phenocrysts decrease in abundance upward. In the south the unit contains non-bedded intervals that resemble ash-flow tuffs.

Ksp **Main member of the Tuff of Sharp Peak (Cretaceous).** Welded ash-flow tuff. Moderate to strong welding is defined by flattened pumice clasts 1-2 cm long. Pumice is locally difficult to see. Contains 10-15% subhedral clear quartz 1-2 mm and locally up to 4 mm across, and 5-10% anhedral to subhedral pink K-feldspar 1-2 mm long, all in a pinkish tan to brown aphanitic matrix. In thin-section the rock contains euhedral and broken fragments of K-feldspar. Many K-feldspar crystals show pervasive, thin, wavy, darker lamellae of unknown origin. These crystals are cross-cut by abundant microfractures filled with fine-grained muscovite. K-feldspar crystals without lamellae do not contain these fractures. The wavy matrix is nearly isotropic. In outcrop the abundance of crystals decreases up-section, and then increases again in the base of the overlying bedded tuff section (map unit Kspb). Quartz commonly stands out in relief on weathered surfaces and is useful for identifying this unit. Mostly the rock breaks into angular blocks. Where there is a strong eutaxitic foliation it breaks into platy slabs and blocks. In the northeast corner of section 4, T. 15 S., R. 10 E., the rock is vitric and dark gray-brown. Locally, in sections 32 and 33, T. 14 S., R 10 E., the rock is not foliated. May be equivalent to the Cat Mountain Tuff to the east in the Tucson Mountains (Bikerman and Damon, 1966).

Cretaceous and/or Jurassic (??) Rocks

KJg **Granodiorite of Cocoraque Butte (Cretaceous or Jurassic).** Named by Bikerman (1967). Mostly fine-grained to medium-grained granodiorite. Contains phenocrysts of subhedral to euhedral light gray feldspar, clear-gray quartz, about 5-10% anhedral biotite, and locally minor black hornblende. Feldspars are easier to see on weathered surfaces. All crystals are typically 1-2 mm across. Locally, K-feldspar crystals are as large as 8 mm wide, but that size is rare. In thin-section most of the section is intergrown K-feldspar crystals. Larger, subhedral laths are surrounded by smaller, more equant K-feldspar phenocrysts, and the remaining space was filled by anhedral, locally poikalitic feldspar. Biotite is minor and heavily corroded. Large K-feldspar crystals and poikalitic feldspars show only minor serricitic (?) alteration, but the intermediate-size feldspar crystals show more. Rare quartz. Opaque minerals are common. The freshest exposure is the lone hill in the northeast corner of section 8, T. 14 S., R. 10 E. This hill is also the coarsest-grained exposure. Locally, this unit contains large, conspicuous, black subhedral to euhedral hornblende crystals up to 2 cm long. A few rare crystals seen had hexagonal cross-sections and terminating ends. The rock erodes into steep slopes shedding small angular blocks. Rarely spheroidal. Bikerman (1967) reported a K-Ar biotite age of 70.30 ± 1.40 Ma for this rock.

KJgf **Border phase of the Granodiorite of Cocoraque Butte? (Cretaceous or Jurassic).** This fine-grained, dark green rock contains a microcrystalline matrix of plagioclase microlites and slightly larger, unidentified phenocrysts up to 1 mm that may be altered mafic minerals. Epidote is common. This rock occurs in only a few small areas near the contact between the Cocoraque Butte granodiorite (map unit KJg) and sandstone (map unit KJs), but was mapped only in one spot about 1 mile W-SW of Cocoraque Butte.

KJtw **Unit of Tunnel Well (Cretaceous or Jurassic).** This dark green unit contains abundant small subhedral crystals of feldspar and rare quartz, both less than 1 mm across, in a green fine-grained matrix. The unit contains abundant angular to well-rounded clasts of andesite up to ~30 cm wide and is mostly matrix-supported. In the wash immediately downstream from Tunnel Well, layers of slightly different color and possibly interbedded sand define bedding. On the higher hills weak bedding can be seen from a distance but is nearly invisible up close. Exposures approximately north of Tunnel Well overlie folded exposures of sandstone, but does not itself appear to be folded. The contact locally cuts across bedding in the bedded tuff member of the Tuff of Sharp Peak on the west side of section 19, T. 14 S., R. 10 E. In a thin-section taken northeast of Tunnel Well the rock contains anhedral quartz and K-feldspar phenocrysts, and irregularly shaped areas of high birefringence and low relief that appear to be either muscovite or carbonate (?). The matrix is mostly glassy. Opaque minerals are common. It is not entirely clear if this unit is strictly volcanic or sedimentary in origin. It may represent volcanogenic debris avalanches or lahars shed from a close-by source of andesite.

KJt **Welded tuff (Cretaceous or Jurassic).** In exposures south of Tunnel Well this green unit contains abundant small subhedral crystals of feldspar and rare quartz, both less than 1 mm across, in a green fine-grained matrix—very similar to map unit Ktw. The rock contains abundant green clots up to about 1 cm wide that may be altered pumice. Here, eutaxitic foliation is more easily seen. In a thin-section from south of Tunnel Well, just below the northwest point of Recortado Mountain the rock contains anhedral quartz and K-feldspar and minor opaques. In plane polarized light the texture of partially compressed glass shards is well displayed. The matrix is glassy and the K-feldspar phenocrysts are extensively serricitized. It may be that the rocks north and south of Tunnel Well (map units KJtw and Kt) are the same unit, but they were mapped as different units to satisfy structural and stratigraphic requirements as discussed in the text.

KJtb **Bedded tuff of map unit Kt (Cretaceous or Jurassic).** These thin- to medium-bedded tuffs posses the same mineralogy as map unit Kt. They form light gray-colored exposures on the northwest side of Recortado Mountain.

KJx **Breccia (Cretaceous or Jurassic).** This unit is composed of poorly sorted blocks of ash-flow tuff. Blocks range in size from cobbles to tens of meters across. At first glance the unit superficially resembles an in-place ash-flow tuff, but upon closer examination eutaxitic foliation in adjacent blocks is arranged randomly. Also, adjacent blocks are commonly slightly different colors, from shades of tan and yellow to light pink and maroon. Many tuff clasts contain ~5% phenocrysts of feldspar and quartz—notable fewer than found in the Tuff of Sharp Peak, but more than in Ktw. Their source is uncertain; may be from upper-most crystal-poor zone in the Tuff of Sharp Peak (not exposed nearby).

Sedimentary and volcanic sequence east of the Recortado Well Fault

Kqhx **Quartz-hematite breccia (Cretaceous or Jurassic).** The protolith of this rock is uncertain. It has been extensively replaced by dark red hematite and white quartz. The quartz is extensively brecciated, the fractures permeated by hematite. The quartz is granular and composed of crystals up to 2-3 mm across. Long euhedral needles of quartz commonly line voids. Some smaller voids are rectangular and may be molds of sulfides (pyrite?) altered to hematite and dissolved. Locally, the quartz-hematite breccia is strongly cemented by silica and projects upward as resistant knobs. This alteration occurs adjacent to the large northwest-striking fault in the northeast corner of section 4, T. 15 S., R. 10 E. The timing of alteration with respect to faulting is not clear, although brecciation and silica infiltration of the quartz suggests at least some syn-faulting mineralization.

KJa **Andesite (Cretaceous or Jurassic).** This dark purple to gray, crystal-rich, porphyritic rock contains 40-50% light gray, anhedral to subhedral plagioclase 2-4 mm across in a nearly aphanitic dark brown to maroon matrix. Locally, spaced dark spots and laths ~2 mm wide may be altered amphibole. Locally the unit consists of monolithic breccia containing only angular and subangular andesite clasts. The breccia was not mapped separately and may represent autoclastic flow-breccia. This unit forms dark maroon hills in the south central part of the study area. Overlies siltstone (map unit KJss). Locally, this rock intrudes eolian sandstone (map unit KJe). Southeast of the Recortado Well Fault andesite flows overlie conglomerate (map unit KJc). Locally, the unit contains lenses of light gray weakly welded tuff (map unit KJta).

KJta **Ash-flow tuff (Cretaceous or Jurassic).** This light gray rock contains 2-5% phenocrysts of fresh, subhedral quartz and sanidine in a light gray matrix. Poorly sorted subangular clasts of andesite and felsic aphyric volcanic (?) rocks are abundant. A planar fabric is best seen from a few meters away. Up-close, the fabric is defined by slightly darker areas and lenticular cavities that may have been pumice. On a fresh surface no pumice is visible. The rock is interbedded with andesite flows (map unit KJa). Rocks of this unit are difficult to break. In thin-section this rock contains anhedral to subhedral phenocrysts of K-feldspar, some broken, quartz, and abundant apatite (?) that occurs as large crystals and clots of crystals. The rock also contains minor fine-grained clasts of fine-grained sandstone. The matrix is very fine-grained and nearly isotropic. Carbonate is locally abundant. Minor muscovite.

KJai **Intrusive andesite (Cretaceous or Jurassic).** This rock contains 40-50% light gray, anhedral to subhedral plagioclase 2-4 mm across in a nearly aphanitic dark brown to maroon matrix. It is very similar to the extrusive andesite (map unit KJa) but the plagioclase phenocrysts are slightly larger and are more of a chalky color. There is only one small outcrop near the southern edge of the study area where the unit apparently intrudes the Tuff of Sharp Peak (map unit Ksp).

KJss **Siltstone (Cretaceous or Jurassic).** This unit is mostly dark, very fine-grained siliceous rock. Many exposures appear massive and structureless, although exposures are generally very poor. Irregularly shaped light green spots (reduction spots?) are common. Thin, wavy, parallel bedding and laminations defined by fine-grained sandstone and siltstone suggest this unit is a fine-grained sedimentary rock. Up-indicators are nearly non-existent. Very low-angle cross-beds (?) are ambiguous and contradictory. Towards the andesite the unit contains more abundant interbeds of fine- to medium-grained arkosic sandstone and beds that appear to contain volcaniclastic detritus. In the northwest corner of section 2, T. 15 S., R 10 E., One layer about 1 meter thick contains ubiquitous irregularly shaped to subspherical forms of epidote of unknown origin, a few millimeters to 15 mm wide. Smaller, tubular-like forms defined by a dark green mineral (chlorite?) may be burrows. Near the contact with the andesite, this unit contains much andesite detritus. This unit forms low rounded hills and slopes. In thin-section taken from the easternmost hill in section 35, T. 15 S., R. 10 E., the massive, concoidally breaking unit contains mostly silt-sized, subangular to subrounded quartz grains surrounded by tiny grains possessing high birefringence and higher relief (muscovite?). Muscovite and apatite also occur as larger, irregularly shaped aggregates of crystals. Dark spots with slightly diffuse margins may be opaque minerals. Lighter-colored reduction spots contain more abundant and larger muscovite (?) and less abundant opaque minerals.

KJc **Conglomerate with sandstone clasts (Cretaceous or Jurassic).** This moderately to poorly sorted conglomerate contains subangular to well rounded clasts almost exclusively of sandstone, with rare quartzite. The lithology of the clasts resembles that of the underlying sandstone unit (map unit KJs). In rare exposures in gullies immediately east of Recortado Well, this unit is interbedded with thinly bedded fine-grained sandstone and purple shale. No bedding is visible anywhere in the conglomerate. The upper and lower contacts are sharp but rarely well exposed.

KJrx **Rhyolite breccia (Cretaceous or Jurassic).** This unit contains moderately to poorly sorted angular clasts of light gray rhyolite (map unit Kr), surrounded by a well-sorted sandy matrix composed of medium-grained quartz and minor feldspar. The rhyolite clasts are locally clast-supported but generally are matrix supported and appear to be ‘floating’ in the matrix. Southeast of Recortado Well, the rock appears as a discrete, well-defined layer. North of Recortado Well, one major layer and several smaller layers grade laterally into sandstone (map unit KJs). Commonly forms a small cliff or low rubble-covered ridge.

KJts **Tuff (Cretaceous or Jurassic).** This brown-colored tuff contains abundant phenocrysts of very fine-grained, clear, anhedral quartz and less abundant light gray to clear K-feldspar, both less than 1 mm across. A few phenocrysts are 1-2 mm. The matrix is aphanitic and brown. Contains sparse, light gray pumice. Occurs as a thin bed 1-2 m thick interbedded with sandstone (map unit KJs) in the southwest corner of section 17, T. 14 S., R. 10 E., and the southwest corner of section 28, T. 14 S., R. 10 E. Very small exposures of this rock in two gullies east of Recortado Well were too small to map separately. In thin-section most of this rock is composed of phenocrysts (over ~70%). Most of the phenocrysts are anhedral quartz with less abundant anhedral K-feldspar and minor opaque minerals. The matrix contains very abundant, fine-grained, low relief, high-birefringent minerals that are probably either muscovite or carbonate.

KJs **Arkosic sandstone (Cretaceous or Jurassic).** This unit is dominantly well-sorted, fine- to medium-grained arkosic sandstone. Thin- to medium-bedded. Locally, the rock contains beds of fine to coarse gravel with rounded pebbles of gray quartzite and smaller coarse sand- and gravel-size clasts of quartz and pink K-feldspar. Except for the absence of mafic minerals, many of the finer-grained exposures superficially resemble outcrops of the Granodiorite of Cocoraque Butte, both in texture and grain-size, but contains thin, dark iron-oxide laminae and weathers into more rounded clasts. In thin-section the rock contains poorly sorted, subangular to subrounded phenocrysts of quartz, K-feldspar, microcline, opaques, and rare sphene and possibly zircon. Apatite (?) is common between grains. Many grains are sutured together. Up-direction indicators are very rare. Very low-angle cross-beds are commonly ambiguous and contradictory. Two exposures of higher-angle cross-bedding in gullies east of Recortado Well clearly show that the conglomerate overlies this unit.

KJr **Flow-banded rhyolite (Cretaceous or Jurassic).** This felsic lava contains ~5-10% subhedral phenocrysts of light gray K-feldspar 1-2 mm long, and rare, tiny quartz, all in a gray to tan aphanitic matrix. The rock commonly exhibits strong flow-banding approximately parallel to bedding in the overlying sandstones. Some areas contain abundant subspherical to irregularly shaped blobs 5-20 mm wide of white, coarse-grained quartz. These blobs may be recrystallized spherulites. Locally, the unit contains thin interbeds of sandstone, only a few of which are mapped (as map unit KJe). In thin-section anhedral to subhedral twinned K-feldspar phenocrysts are surrounded by a fine-grained matrix containing abundant anhedral feldspar and quartz and abundant tiny flecks of muscovite.

KJm **Mafic sill (Cretaceous).** This dark green rock contains abundant 1-2 mm dark red to dark green pseudomorphs after pyroxene and olivine, in a dark green aphanitic matrix. This unit may be a mafic flow, but it pinches out and reappears within a short distance, suggesting it is a mafic sill. The rock crumbles easily and forms dark, smooth, sandy slopes.

KJe **Eolian sandstone/quartzite (Cretaceous).** This light gray, fine-grained quartz arenite contains well sorted, rounded to well-rounded quartz grains. In most areas it is a protoquartzite and fractures break both around and across grains. The sandstone is very clean and iron oxide laminae delineating bedding are rare. No large-scale cross-bedding was seen. The lower contact with andesite breccia (map unit KJax) is sharp. The upper part is interbedded with rhyolite flows (map unit KJr). Forms resistant light-colored hills. In thin-section this rock contains moderately sorted to well sorted, subrounded to well rounded quartz grains, and very minor grains of microcline. Many intergranular spaces are filled with a higher relief, medium- to high-birefringent mineral (muscovite? apatite?). Fine-grained muscovite commonly forms thin films between grains and may be altered clay particles--possibly formerly windblown dust or altered feldspars or volcanic fragments. Locally, quartz grains have partially recrystallized and have sutured with neighboring grains. Crystallographically continuous quartz overgrowths are common, and much of the rock is a quartzite.

KJax **Andesite breccia (Cretaceous).** Poorly sorted monolithic breccia. Contains angular to rounded clasts of dark gray to maroon andesite, tightly packed, surrounded by a finely brecciated andesitic and sandy matrix. Individual clasts contain abundant 1-2 mm gray plagioclase phenocrysts. Locally, the finer-grained clasts resemble granodiorite of map unit KJg. This unit is mostly massive, but thin dark sandy layers locally define faint bedding. In some exposures some clasts are well rounded. This may be an autoclastic andesite flow breccia but the well rounded clasts suggest some transport. The contact between this unit and the overlying eolian sandstones is very sharp.

Paleozoic or Mesozoic rocks

MzPzc **Interbedded chert-rich carbonate and argillite (Paleozoic or Mesozoic).** This unit is exposed in two small outcrops and consists of interbedded limestone (dolomite?), chert, and light orange argillite. Almost 50% of the rock is gray-brown bedded chert. The unit has been folded slightly.