Geologic map of the Waterman Peak 7.5' Quadrangle and northern La Tortuga Butte 7.5' Quadrangle, Pima County, Arizona

by

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Introduction

The Waterman Mountains and La Tortuga Butte Quadrangles are located in south-central Arizona, about 50 km west-northwest of Tucson Arizona (Figure 1). The area was mapped between December, 1999 and August, 2000 as part of a multiyear mapping program directed at producing complete 1:24,000-scale geologic map coverage for the Phoenix-Tucson metropolitan corridor. This geologic map is the primary product of this study. This mapping was done under the joint State-Federal STATEMAP program, as specified in the National Geologic Mapping Act of 1992. Mapping was jointly funded by the Arizona Geological Survey and the U.S. Geological Survey under STATEMAP Program Contract 99HQAG0171.

The map area includes the Waterman Mountains and northern part of the Roskruge Mountains. These ranges are located in the Basin and Range Province of southern Arizona, and consist of groups of small mountain peaks and hills that are part of a north-south trending belt of bedrock flanked to the east and west by late Cenozoic basins. This belt of bedrock, which also includes the Baboquivari and Silverbell Mountains, is almost certainly a horst bounded by buried normal faults and flanking grabens or half grabens. Based on regional timing relationships, it is generally thought that east-west extension and associated uplift of the ranges and subsidence of the basins occurred approximately between 5 and 15 Ma (Middle to Late Miocene). This was preceded by late Oligocene-Early Miocene, large-magnitude extension accommodated by low-angle normal faults including the Catalina-Rincon and Coyote Mountains detachment faults (Figure 1) [Gardulski, 1990; Dickinson, 1991]. The Roskruge, Waterman, and Silverbell Mountains occupy the hanging wall of both detachment fault systems. Hanging wall rocks above the Catalina-Rincon detachment fault have been translated to the southwest relative to mylonitic footwall rocks now exposed in the Picacho, Tortolita, Santa Catalina, and Rincon Mountains. Hanging-wall rocks above the Coyote Mountain detachment fault were translated to the north-northeast relative to mylonitic rocks now exposed in the Coyote Mountains [Davis, 1980; Gardulski, 1990; Ferguson et al., 2000]. These mid-Tertiary detachment faults have been dismembered by Basin and Range faulting.

A great diversity of rock types and sediments are exposed in the map area, including: (1) Proterozoic granite that is probably 1.42 Ga in age and part of an aerially extensive pluton that includes the Oracle Granite north of Tucson; (2) Paleozoic carbonates, quartzites, and variably calcareous siltstones that represent a cratonic Paleozoic sequence; (3) Jurassic to early Cretaceous quartzite (some possibly eolian), red beds, volcanic-lithic sandstone and conglomerate, and mafic to felsic volcanic rocks, (4) Laramide (Late Cretaceous to early Tertiary) volcanic and sedimentary rocks, including several thick welded tuffs, and arkosic sandstone, siltstone, conglomerate and rare limestone; (5) late Oligocene to early Miocene felsic to intermediate volcanic flows and tuffs that make up the Pan Quemado ("burnt bread") hills and several other scattered outcrop areas along the eastern side of the map area; (6) late Miocene basaltic dikes in the southeastern corner of the map area, (7) Quaternary surficial deposits. Paleozoic and Mesozoic rocks of the Waterman Mountains have been studied previously by McClymonds [1959a] and Hall [1985].The Silverbell porphyry copper deposit is located just north of the Waterman Mountains.

Quaternary Geologic Mapping Methodology

Quaternary surfaces and sediments in the project area were mapped using 1:24,000 scale color U. S. Geological Survey aerial photographs taken in 1984; these were supplemented by extensive field observation of alluvial surfaces and soils. Piedmont areas were field checked by Ann Youberg, with assistance and suggestions from Philip Pearthree. Areas within the Tohono O'Odham reservation were mapped from aerial photographs and a USDA-NRCS soil survey [Breckenfeld, 1999].

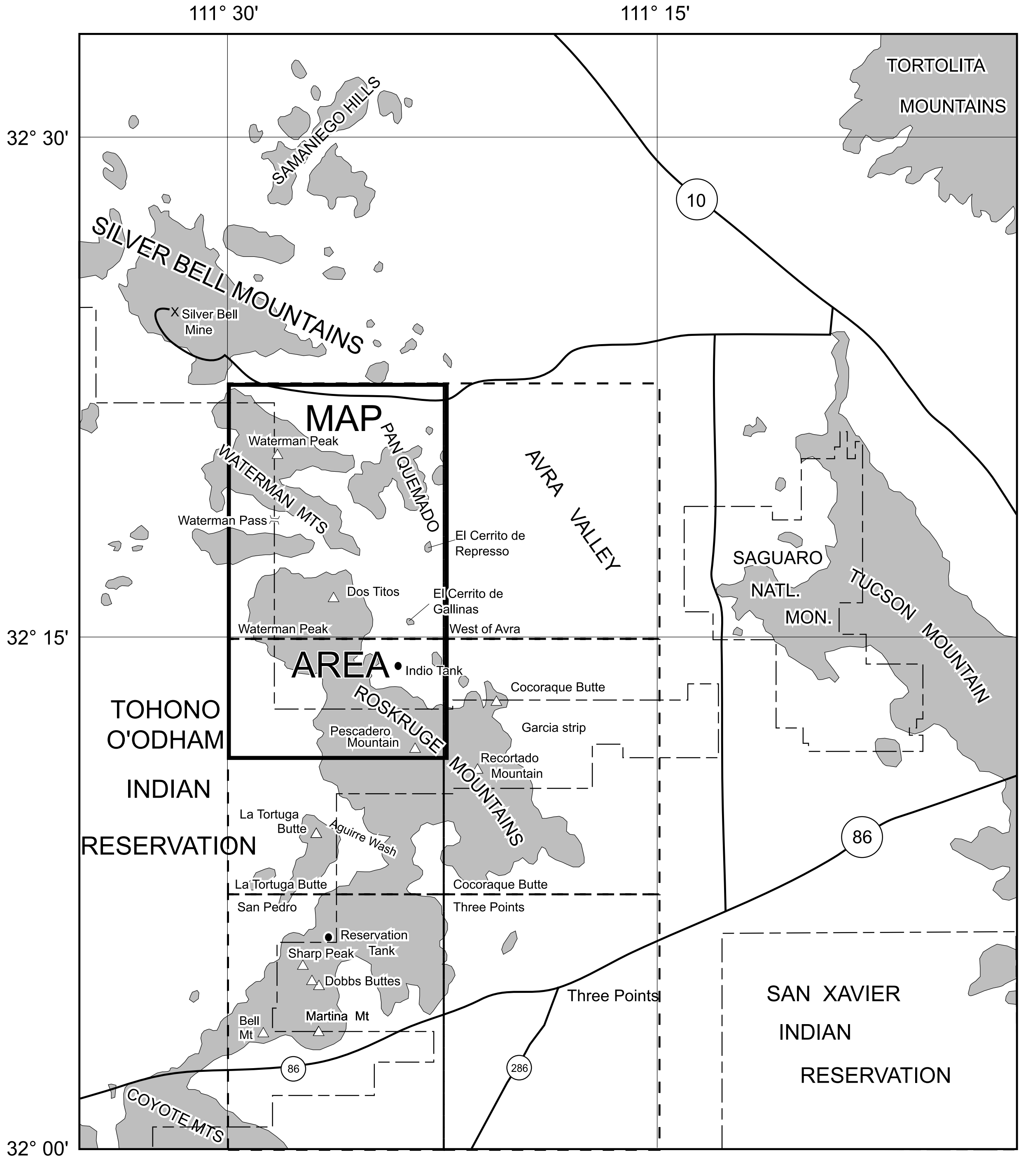

Figure 1. Important geographic features and USGS 7.5' quadrangles in the vicinity of the map area.

The physical characteristics of Quaternary alluvial surfaces (channels, alluvial fans, floodplains, and stream terraces) were used to differentiate their associated deposits by age. Alluvial surfaces of similar age have distinctive appearance and soil characteristics because they have undergone similar post-depositional modifications. They are different from both younger and older surfaces. Terraces and alluvial fans that are less than a few thousand years old still retain clear evidence of the original depositional topography, such as bars of gravel deposits, swales (trough like depressions) where low flows passed between bars, and distributary channel networks that are characteristic of active alluvial fans. Young alluvial surfaces have little rock varnish on surface clasts, minor soil development, and minimal dissection. Very old fan surfaces, in contrast, have been isolated from substantial fluvial deposition or reworking for hundreds of thousands of years. These surfaces are characterized by strongly developed soils with clay-rich argillic horizons and cemented calcium-carbonate horizons, well-developed tributary stream networks that are entrenched 1 to 10 m below the fan surface, and strongly developed varnish on surface rocks. The ages of alluvial surfaces in the southwestern United States may be roughly estimated based on these surface characteristics, especially soil development [Gile and others, 1981; Bull, 1991].

Tertiary volcanic and hypabyssal rocks

Tertiary volcanic and hypabyssal rocks are preserved along the eastern edge of the map area in a range of small rugged hills called the Pan Quemado (not to be confused with a pair of hills in the northeastern corner of the Samaniego Hills). These rocks have not been dated in the map area, but are correlated with a semi-continuous field of late Oligocene to early Miocene (approximately 26 to 22 Ma) lava flows and hypabyssal intrusions that extend along the western edge of Avra Valley from the northeastern Silver Bell Mountains and Samaniego Hills to the southern Roskruge Mountains [Bikerman, 1967; Eastwood, 1970; Ferguson et al., 1999, Ferguson et al., 2000]. The rocks in the Pan Quemado are dominantly lava flows with minor hypabyssal bodies and dikes ranging in composition from trachyandesite to high-silica rhyolite (Table 1, Figure 2). In the northern Pan Quemado lava flows overlie Mesozoic rocks with angular unconformity along an essentially horizontal contact, but to the east, the flow foliation and contacts between flows dip moderately to the east.

A series of middle Miocene pyroxene megacrystic basalt dikes are present in the southern part of the map area. The dikes are nearly identical compositionally to the basalt of Brawley Wash (Table 1, Figure 2) which has been dated at approximately 10 Ma [Bikerman, 1967]. A fragment of a black, glassy, clinopyroxene crystal, found weathered out of a dike in the southeastern part of the map area, was analyzed for its neodymium and samarium isotopic composition in order to determine if the mafic magma was derived from the asthenosphere or lithosphere, or was affected by assimilation of crust. The strongly positive ε_{Nd} value of +7 obtained from the dike indicates derivation from the asthenosphere with very little or no crustal contamination. The analysis was done by Clark Isachsen at the Dept. of Geosciences, University of Arizona, Tucson, Arizona (see Patchett and Ruiz [1987] for a description of analytical techniques).

Sample	UTM N	UTM E	Quadrangle	lithology	map unit
F0-322	3578040	462315	Waterman Peak	trachyte of Nessie's Mt	Ttn
F0-323	3578005	462410	Waterman Peak	rhyolite dike	Tri
F0-324	3577960	462420	Waterman Peak	crystal-rich trachyte	Ttx
F0-327	3577210	462670	Waterman Peak	trachyte of Nessie's Mt	Ttn
F0-688	3552785	460835	San Pedro	trachyandesite	Tm
F0-689	3552505	460750	San Pedro	trachyandesite	Tm
F0-761	3552165	461120	San Pedro	trachyandesite	Tm
F0-880	3546930	457410	San Pedro	trachyte porphyry of Martina Mt	Tz
F0-883	3547200	458050	San Pedro	trachyte porphyry of Martina Mt	Tz
F0-942	3560575	464540	La Tortuga Butte	xenocryst-bearing basalt dike	Tb
F0-1029	3575250	461150	Waterman Peak	crystal-rich rhyolite	Trx
F0-1033	3552160	468870	Three Points	xenocryst-rich basalt	Tb
JS-3-1-00-1	3566865	464460	La Tortuga Butte	xenocryst-rich basalt	Tb

Table 1a. Sample location information for Tertiary volcanic rocks from the Samaniego Hills, Waterman Mountains, and Roskruge Mountains.

Sample	Sr	Rb	Th	Pb	Ga	Zn	Cu	Ni	Fe_2O_3T	MnO	Cr	TiO_2	Ba	V	As	U	Y	Zr	Nb	Mo
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	wt. %	wt. %	ppm	wt. %	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
3-1-00-1	782	11	0	4	19	70	55	80	10.73	0.19	154	2.27	407	199	2	1	28	240	74	5
FO-322-CM1	520	149	15	18	18	62	31	32	4.35	0.12	38	0.74	1170	78	3	3	25	355	22	3
FO-322-CM2	522	151	18	18	19	62	32	32	4.35	0.12	38	0.73	1187	75	2	4	25	363	22	3
FO-322-CM3	524	150	15	19	18	63	31	30	4.37	0.12	35	0.75	1186	81	2	3	25	360	23	4
FO-323	342	168	17	18	15	46	20	11	2.93	0.05	18	0.42	1087	48	1	3	16	280	16	2
FO-324	431	192	19	20	17	47	25	15	3.02	0.06	18	0.51	939	50	2	4	21	255	22	3
FO-327	528	149	13	19	19	68	36	31	4.57	0.09	34	0.79	1317	74	2	3	26	400	24	3
FO-688	563	103	17	17	20	86	52	36	6.01	0.10	43	0.94	1222	102	3	3	29	443	22	4
FO-689	531	147	18	17	20	81	40	30	5.94	0.10	48	0.93	1267	109	4	3	30	455	22	4
FO-761	584	103	12	12	21	81	43	38	7.62	0.11	39	1.21	1390	128	2	2	30	362	22	3
FO-880	632	87	10	16	19	67	32	40	3.93	0.04	58	0.52	1148	59	5	3	15	220	13	2
FO-883	586	100	13	21	19	60	36	39	3.79	0.07	61	0.50	1082	58	2	4	15	212	14	2
FO-942	631	43	0	2	19	66	49	98	9.72	0.16	223	2.05	316	187	2	2	25	233	51	4
FO-1029	85	250	27	29	15	25	6	4	0.94	0.05	9	0.15	245	8	2	8	32	109	26	4
FO-1033	591	46	0	ND	21	95	54	70	11.73	0.18	146	2.36	303	223	3	2	28	188	43	3

All values are in parts per million, except Fe2O3-T, MnO, and TiO2, which are in weight percent; Fe_2O_3-T is total iron expressed as Fe_2O_3; ND is below the lower limit of determination; Samples with the extension -CM1, -CM2, and -CM3 are replicates.

Table 1b. Trace element chemical analyses for Tertiary volcanic rocks from the Samaniego Hills, Waterman Mountains, and Roskruge Mountains. See caption for Table 1c for analytical techniques.

sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3-T	MnO	MgO	CaO	K_2O	Na_2O	P_2O_5	LOI	Total	Ba
	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	ppm
3-1-00-1	46.88	2.40	16.99	10.57	0.18	6.65	9.11	1.14	4.36	0.60	1.27	100.15	545
FO-322	64.03	0.74	15.76	4.70	0.13	1.72	3.47	4.13	3.97	0.33	1.24	100.23	1191
FO-323	71.32	0.42	13.49	3.12	0.05	1.04	2.21	5.39	2.77	0.21	0.57	100.59	1083
FO-324-CM1	65.94	0.55	15.02	3.47	0.07	1.29	2.88	4.14	3.63	0.21	3.29	100.49	929
FO-324-CM2	66.11	0.55	15.03	3.46	0.07	1.30	2.88	4.06	3.62	0.22	3.29	100.58	960
FO-324-CM3	65.99	0.55	15.00	3.45	0.07	1.28	2.87	4.13	3.61	0.22	3.29	100.46	939
FO-327	63.00	0.78	15.99	4.79	0.09	1.99	3.50	4.38	3.88	0.36	1.54	100.30	1320
FO-688	59.38	0.95	16.04	6.22	0.10	2.81	5.01	3.44	3.79	0.43	1.63	99.80	1262
FO-689	60.69	0.91	16.11	5.95	0.10	2.08	4.42	4.03	3.98	0.39	1.02	99.68	1255
FO-761	57.16	1.37	16.22	8.10	0.12	3.19	5.67	3.06	3.89	0.46	0.69	99.93	1333
FO-880	63.95	0.54	16.13	4.05	0.05	2.48	4.04	3.23	3.90	0.20	1.88	100.45	1137
FO-883	64.70	0.51	16.44	3.95	0.07	2.02	3.67	3.50	4.05	0.19	1.76	100.85	1124
FO-942	48.04	2.16	16.82	9.75	0.16	6.92	8.93	1.54	3.88	0.54	1.91	100.65	404
FO-1029	74.91	0.16	12.63	1.09	0.06	0.20	0.88	4.30	3.62	0.05	2.66	100.56	257
FO-1033	47.29	2.47	16.21	11.85	0.18	6.28	9.25	1.18	3.45	0.45	1.17	99.77	433

All values are in weight percent, except Ba, which is in parts per million; Fe_2O_3-T is total iron expressed as Fe_2O_3; LOI is loss on ignition; Sample with the extension -CM1, -CM2, and -CM3 are replicates.

Table 1c. Whole-rock chemical analyses for Tertiary volcanic rocks from the Samaniego Hills, Waterman Mountains, and Roskruge Mountains. The samples were analyzed at the New Mexico Bureau of Mines and Mineral Resources geochemistry laboratory. The samples were crushed in a steel jaw crusher, split, and ground in a Tema mill using a WC grinding set. The samples were fused into glass disks and analyzed on a Phillips wavelength dispersive x-ray fluorescence spectrometer for major elements. A separate split of each sample was used to determine the loss-on-ignition gravimetrically.

Sm (ppm)	Nd (ppm)	$\frac{^{147}Sm}{^{144}Nd}$	$\frac{^{142}Nd}{^{144}Nd}$	$\frac{^{143}Nd}{^{144}Nd}$	$\frac{^{145}Nd}{^{144}Nd}$	$\frac{^{146}Nd}{^{144}Nd}$
5.646110	18.246222	0.187092985	1.142649	0.512998	0.348405	0.7219

Table 2. Sm/Nd data for sample 03-01-00-02, collected by J.E. Spencer, location: UTM zone 12, 464360 E, 3566900 N. Analytical techniques described in Patchett and Ruiz [1987].

$\varepsilon_{Nd(0)}$	$\varepsilon_{Nd(t)}$	$T_{(DM)}$
7.02	7.03	357

Table 3. Epsilon Nd and mantle separation ages calculated for sample 03-01-00-02, assuming an age of 10 Ma for the mafic dike.

Cretaceous Calderas

The southern part of the map area is dominated by the Cretaceous tuff of Sharp Peak and hypabyssal intrusive rock of the felsite of Dos Titos. A northwest-trending belt of rock mapped as mesobreccia (pyroclastic breccia in which many small clasts are visible within a single outcrop) forms the northeastern boundary of the tuff of Sharp Peak in the southernmost part of the mapped area. To the northwest, this belt of mesobreccia is faulted against the felsite of Dos Titos on the northeast, and grades into what may be the felsite of Dos Titos on the southwest.

The main body of the felsite of Dos Titos, which includes Dos Titos proper, is bounded on all sides by steep fault contacts or by contacts that appear to dip beneath the felsite body. The gently inward-dipping contacts are nowhere exposed because of cover by talus and colluvium from the up-slope felsite, and their dip is inferred from outcrop patterns. Except for the northwest-striking fault against the mesobreccia on the southwest side of the body, the felsite is everywhere in contact with Jurassic or Cretaceous sedimentary units. The highly variably strike and dip of these units, and the lithologic variability between outcrops, indicates that the sedimentary rocks were strongly deformed before intrusion of the felsite. In many places, particularly along the steep, faulted contacts, the felsite becomes finer grained near the contact, is highly fractured, and abundantly iron stained. We infer that most of these faults formed during shallow intrusion of the felsite. Outer parts of the body that were crystallized early were subsequently forced upward by continuing intrusion, resulting in faulting along the early formed intrusive contacts. The southeastward lobate parts of the body are bounded by contacts that dip beneath the body, and represent domains in which the body was spreading upward and outward.

On the southwest side of the mesobreccia belt, rocks mapped as the felsite of Dos Titos are locally gradational with the mesobreccia, and the contact between the two is complexly interdigitated. A separate, transitional unit, broken out after field mapping had been completed, is shown on the map (map unit Kdz). Locally, this transitional unit contains 1-20 m blocks of andesite and, in other areas, bedded tuff. Large outcrop areas of sedimentary and volcanic rocks that pre-date the tuff of Sharp Peak are mapped in the southeastern part of the felsite outcrop, in the area west of Indio Tank. These may represent the substrate for the tuff of Sharp Peak, or simply be large rafts of rock in the felsite-mesobreccia complex. The relative age of the units in the contact zone between the felsite of Dos Titos and the tuff of Sharp Peak could not be determined based on outcrop criteria. It is possible that the mesobreccia unit (map unit Kspz), the felsite of Dos Titos southwest of the mesobreccia belt, and the transitional unit between them, are all closely related and were emplaced at the same time within or adjacent to a conduit through which the tuff of Sharp Peak was erupted. The felsite of Dos Titos northwest of the contact zone is possibly slightly younger and represents a post-eruptive intrusion.

The welded zone of the tuff of Sharp Peak forms nearly all of the high-standing peaks in the Pescadero Mountain area at the southern edge of the map. To the south of Pescadero Mountain, in the northern part of the map area of Ferguson et al. [2000], the tuff of Sharp Peak overlies older rocks along a moderately northeast-dipping contact. Thick lenses of mesobreccia and megabreccia are present at the base of the tuff. The lenses contain clasts up to several meters in diameter of older volcanic rocks encased within non-welded tuff. Because the tuff of Sharp Peak is at least 1 km thick throughout most of the southern Roskruge Mountains, and because it includes significant zones of megabreccia and mesobreccia in the Pescadero Mountain area [this report; Ferguson et al., 2000], the conclusion that these areas lie within its source caldera is practically inescapable.

A southern caldera margin is proposed by Ferguson et al. [2000] in the southern Roskruge Mountains, where the tuff appears to thicken rapidly from about 200 meters on Bell Mountain to at least 1 km in the Martina Mountain – Dobbs Buttes – Sharp Peak area (Figure 1, Figure 2). We interpret the northern caldera margin to be located along the prominent northwest-striking belt of mesobreccia in between Pescadero Mountain and Indio Tank. This belt is depicted as a prominent fault zone on older maps [e.g. Wilson et al., 1960; Bikerman, 1965], separating older rocks on the north from a thick section of rhyolite on the south. The tuff of Sharp Peak dips northeast towards this zone, but the contact with older rocks is a gently dipping buttress unconformity at which mesobreccia of tuff of Sharp Peak or tuff of Sharp Peak overlies moderately southwest-dipping older rocks (UTM 463450E, 3564100N). We interpret this unconformity as a portion of a southwest-facing topographic cauldron margin, and suggest that the tuff of Sharp Peak buries a cauldron-

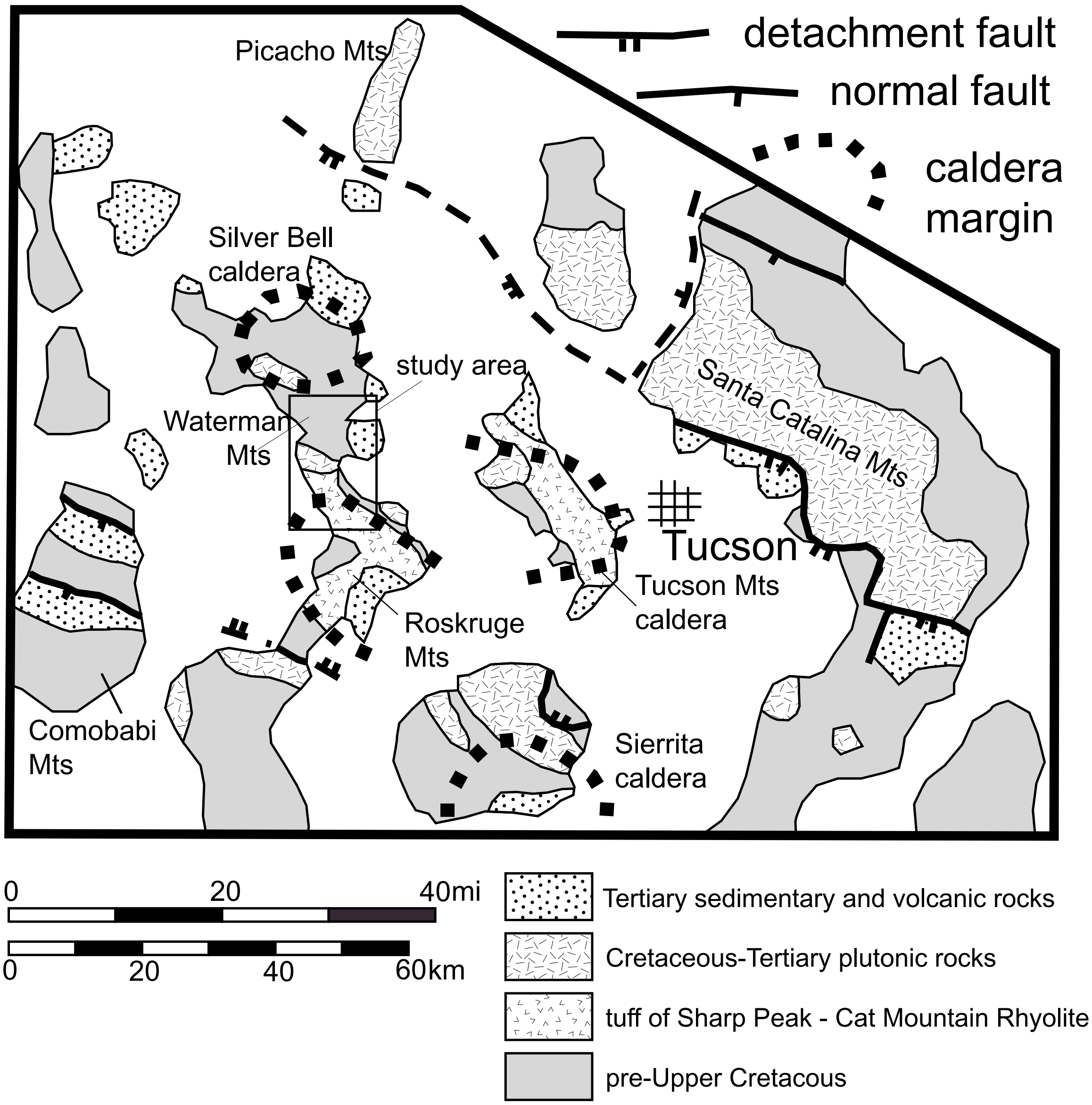

Figure 2. Generalized map showing location of proposed calderas in the Tucson area. Based on Reynolds [1988], Sawyer [1996], Lipman [1993], and Ferguson et al. [2000].

bounding structure just to the southwest of this location. We interpret the cauldron margin to curve to the west from Indio Tank. An apparently gentle south-dipping contact in the hills about 2 miles west of Indio Tank superposes tuff of Sharp Peak on older rocks (KJsu, Kr, Kcp). This contact is also the southern boundary of hypabyssal intrusive rocks included in the felsite of Dos Titos.

The linear character of the mesobreccia belt does not appear to be determined by tilting of a sheet-like body. It seems more likely that the mesobreccia represents the throat of a linear vent zone from which the tuff of Sharp was being erupted. Continuation of the mesobreccia belt northwest of Indio Tank, where the proposed caldera margin curves to the west, suggests that the northern margin of the tuff of Sharp Peak is a tilted floor or buttress zone that is truncated along the northwest-trending vent/fault. This scenario suggests a trap-door geometry for the cauldron, with the main vent/fault collapse boundary along the northeast side.

These observations suggest that the felsite of Dos Titos was intruded along a vent zone of the tuff of Sharp Peak, late in the eruption of the tuff. The felsite on the southwest side of the mesobreccia belt is possibly a slightly older intrusion, and intruded while the mesobreccia was still fluid enough to mix with the felsite (the alternative possibility of synchronous emplacement was mentioned above). The felsite on the northeast side of the mesobreccia belt is possibly slightly younger or represents a shallower level in the system. The mesobreccia had become rigid enough to fault as this part of the felsite was intruded.

The felsite of Dos Titos along with other Laramide porphyritic intrusions, including the pluton at Cocoraque Butte [Bikerman, 1965; 1967; Skotnicki and Pearthree, 2000] may represent post-caldera magmatic activity associated with the tuff of Sharp Peak.

Tuff of Sharp Peak and the Cat Mountain Rhyolite

The tuff of Sharp Peak was probably derived from a caldera that encompasses much of the Southern Roskruge Mountains, but the correlation of its outflow sheet into nearby ranges is uncertain. The tuff of Sharp Peak, which is the same as Bikerman's [1965] welded zone of the Roskruge volcanics, contains a phenocryst assemblage very similar to that of the Cat Mountain Rhyolite in the nearby Tucson Mountains [Ferguson et al., 2000; Bikerman, 1962]. In addition, its age range of approximately 67-74 Ma is the same, within analytical error, as the Cat Mountain Rhyolite [Bikerman, 1967; Lipman, 1993], and its paleomagnetic polarity and orientation are very close [Vugtaveen et al., 1981; Hagstrum and Sawyer, 1989; Hagstrum et al. 1994]. Despite these similarities and based only on a difference in Zr content, Hagstrum et al. [1994] concluded that the two units do not correlate. The Cat Mountain Tuff is reported to contain up to 4 times as much Zr as the tuff of Sharp Peak [Lipman, 1993; Hagstrum et al., 1994]. However, a geochemical analysis of the entire sequence of the compositionally zoned tuff of Sharp Peak has not been done, and it is possible that if a Zr-rich portion of it exists, it might not have been sampled. The Cat Mountain Tuff is also compositionally zoned such that only parts of the unit contain Zr concentrations greater than 300 ppm. In fact, most analyses of the Cat Mountain Tuff as presented in Table 2 of Lipman [1993] are well within the range of values for Zr as reported for samples of the tuff of Sharp Peak in the Roskruge Mountains [samples 1 and 4 in Table 2 of Hagstrum et al., 1994].

We suspect that the tuff of Sharp Peak and the Cat Mountain Rhyolite are the same, in agreement with Bikerman's [1965] original correlation. Except for the Zr content argument, there are no physical reasons to discount this correlation. It also seems highly unlikely that two nearly identical ash-flow tuffs could be so well represented in adjacent mountain ranges with no evidence of outflow sheets overlapping or underlying each other. The only real correlation problem is that both units exhibit abundant evidence of caldera-fill facies in each mountain range, which suggests that the two caldera fragments were once part of a single very large caldera.

It is conceivable that the Tucson and Roskruge Mountains were much closer prior to Mid-Tertiary faulting. Lipman [1993] shows a western caldera margin for the Tucson Mountains caldera just to the west of the range, but there is no direct evidence for this. In fact, there is some evidence that the eastern Tucson Mountains caldera margin is located much farther to the west than is depicted by Lipman [1993]. At the eastern base of Sentinel Peak in the eastern Tucson Mountains, a small area of Mesozoic sedimentary rocks includes at least one, thin, welded ash-flow tuff sheet (the Mission Road tuff of Phillips [1976]) and these rocks are overlain by an early Tertiary (~58 Ma) lava flow [Phillips, 1976] with significant angular unconformity. A closer examination of this critical outcrop shows that two welded ash-flow tuffs are present, a crystal-poor unit and a crystal-rich unit, the upper one being the Sentinel Tuff of Phillips [1976]. Since the Cat Mountain Tuff is considered to be the youngest regional ash-flow tuff in the area, the presence of two thin outflow sheets of probable Cretaceous or older age within the Tucson Mountains caldera is difficult to explain. There are three possible explanations for the outcrops at Sentinel Peak: (1) the two ash-flow tuffs are younger than the Cat Mountain Tuff, (2) the outcrops represent an area of uplifted caldera floor that was completely stripped of intracaldera Cat Mountain Tuff prior to 58 Ma, or (3) they represent an area outside the Tucson Mountains caldera.

Lipman's [1993] map of the Tucson Mountains shows a western caldera margin just to the west of the range and a poorly constrained eastern margin extending into the Tucson basin. Based on the evidence discussed in the previous paragraph, we suspect that the eastern margin of the Tucson Mountains caldera is west of Sentinel Peak and that it is the location of the western margin, rather than the location of the eastern margin, that is really unconstrained. The Tucson Mountains caldera margin, as we suggest redefining it, and the caldera margin we describe in the Roskruge Mountains, might represent the dismembered eastern and western segments of a single caldera that was the source of the Cat Mountain Rhyolite – tuff of Sharp Peak. By closing the Avra Valley basin by a combination of restoring extension and possible left-lateral strike-slip faulting, the caldera could be as small as 600 km^2 (Figure 2).

Structural Geology

The northern part of the map area is characterized by pediment areas, underlain by Jurassic or Cretaceous sandstone, separating hilly areas underlain by more resistant Paleozoic strata in the north and by Mesozoic red beds or Cretaceous(?) intrusive rocks in the central part of the map area. The southern half of the map area is dominated by the Late Cretaceous Sharp Peak Tuff and related hypabyssal intrusive rocks (Felsite of Dos Titos).

The Paleozoic rocks in the Waterman Peak area are strongly faulted and folded. The steep, northwest trending ridge along the northeast side of the Paleozoic outcrop consists of steep, tight to isoclinally folded, mostly northeast-facing, upper Paleozoic formations in a complex northwest-trending fault zone. The contact with Mesozoic sandstone and conglomerate at the top of the Paleozoic section on the northeast side of the range is mostly faulted, but in a few areas the depositional contact is preserved. South of this zone, the Paleozoic rocks are mostly arrayed in north-striking, east-dipping blocks bounded by west-dipping normal faults. In the area of the Indiana-Arizona mine, a major north-trending, west-dipping normal fault cuts one of the northwest-trending fault zone. The northern continuation of the normal fault apparently does not cut the major northwest-trending zone in the upper Paleozoic strata, but the lack of separation may indicate that the slip vector is parallel to the intersection between the north and northwest-trending faults.

Folds in Paleozoic strata generally plunge moderately to the southeast. These folds have clockwise asymmetry, with long, steeply dipping, north to north-northwest-striking limbs separated by short east-striking, south-dipping limbs. Fold wavelengths range from decimeters to several hundred meters. The fold hinges are broadly sub-parallel to the northwest-trending fault zone, become tighter in the vicinity of the fault, and are cut by the fault in slivers along the fault zone. These observations suggest that the folding is related to the northwest-trending fault zone. If this is the case, then the asymmetry of the folds indicates that fault movement during fold formation was right-oblique, up on the northwest side.

The kinematic interpretation indicated by the folds is not consistent with the northwestward separation of the generally north-trending base of the Paleozoic section across the fault, which suggests left separation across at least the southern trace of the zone. A more in depth interpretation of the structure in these rocks will not be attempted here because mapping of key outcrops on the Tohono O'Odham Reservation is of a reconnaissance nature, based on McClymonds et al. [1959], Beikman et al. [1995], and photo interpretation by the author of this report.

Mineral Deposits

Reported base and precious metal production from the Waterman District totals 1.6 million pounds of copper, 1.1 million pounds of lead, 820,000 pounds of zinc, 100,000 ounces of silver and 70 ounces of gold [Keith, 1983]. Production was principally from the Silver Hill mine (aka Crepin Group), and the Indiana-Arizona mine. At the Silver Hill Mine, iron and base-metal oxide minerals occur in veins along faults in Paleozoic carbonate units. Production at the Indiana-Arizona mine was from similar structures cutting the Abrigo Formation in a zone of intersecting faults. These deposits are probably the result of hydrothermal circulation that is peripheral to the Laramide (80-50 Ma) Silverbell porphyry or to the Oligocene-Miocene volcanism that produced the Pan Quemada volcanic rocks.

Correlation of Map Units, Waterman and Northern Roskruge Mountains

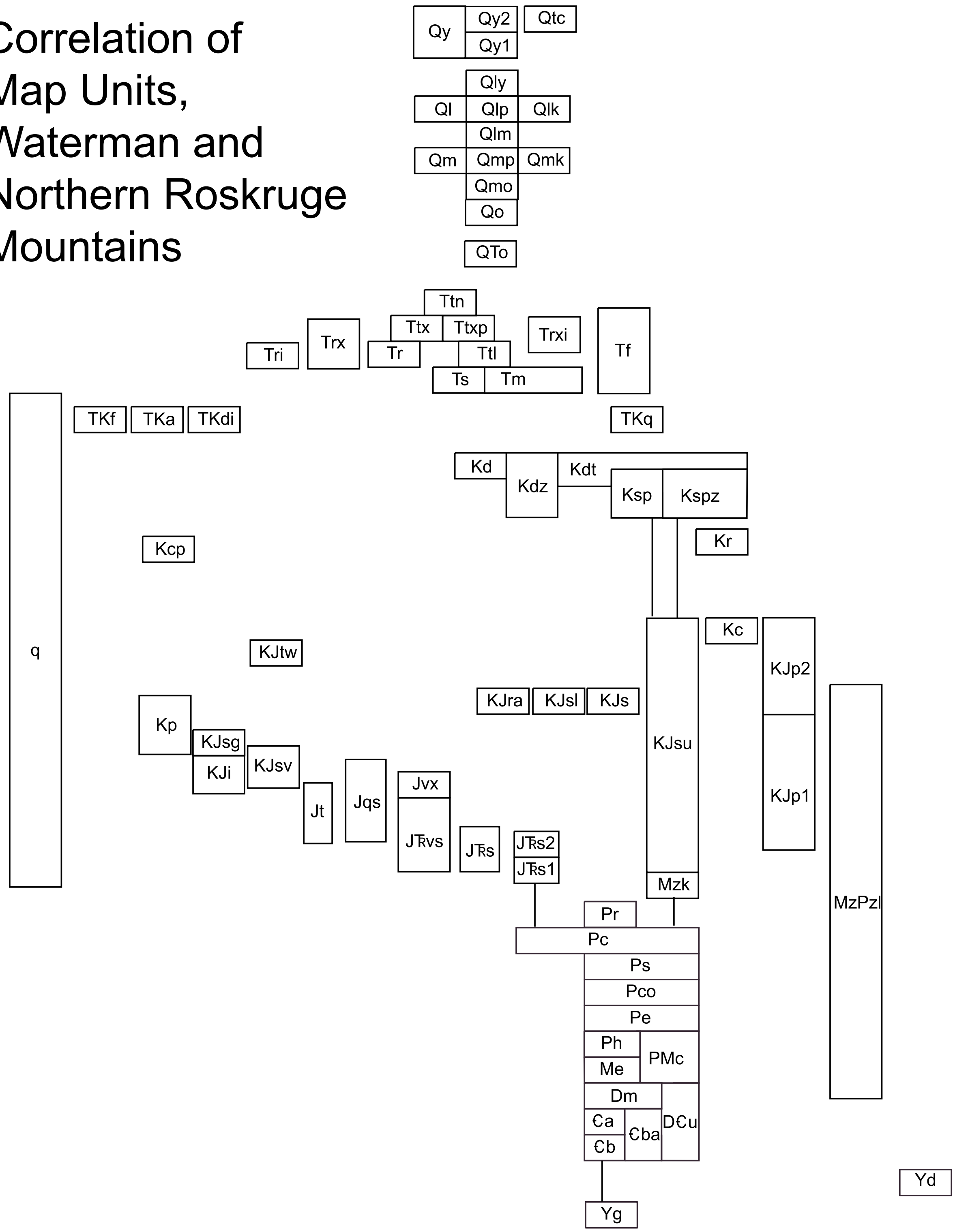

Figure 3. Correlation of map units. This figure shows the chronologic relationships between units. Units grouped (in direct contact) horizontally are known to be equivalent. Position of a unit above another unit implies that the younger unit overlies the older unit. Units stacked vertically or that are linked by a vertical line are in contact within the map area.

Geologic Map Units

The correlation of map units (Fig. 3) depicts the chronological relationships between map units in the study area.

Cenozoic Surficial deposits

Colluvium

Qtc **Hillslope talus and colluvium deposits** (Holocene and Pleistocene) – These are very poorly sorted, angular to subangular deposits that mantle some of the middle and lower slopes of the mountain ranges. Talus is composed of angular boulders and cobbles in discreet unconsolidated deposits at the base of cliffs or outcrops from which they derive. Colluvium consists of a wide range of particle sizes, from boulders to clay; most are weakly or unconsolidated. Clast lithologies vary with local variation in bedrock lithology. These sediments have been transported and deposited by hillslope processes, such as rockfall, debris flow, sheet wash, and creep. Alluvium may be intermixed with colluvium near contacts between this unit and alluvial units.

Piedmont Alluvium

These deposits cover most of the gently sloping plains (piedmonts) that surround the Waterman and Roskruge Mountain ranges within the map area. This sediment was deposited by the smaller drainages of the map area, which head either in the mountains or on the piedmonts. Deposits range in age from modern to early Pleistocene and late Pliocene. The lower margins of the piedmont are defined by their intersection with the planar, very gently north- to northwest-sloping basin floor deposits of the Brawley Wash.

A laterally extensive petrocalcic horizon underlies much of the Waterman Mountains piedmont. The thickness of this horizon is unknown. In upper piedmont areas, active washes are incised two to four meters into this unit, indicating a minimum thickness in this range. The petrocalcic horizon is intermittently exposed along ridges and in roads on older units, and in washes within units of all ages. Clasts in the petrocalcic horizon include subrounded to rounded gravels, cobbles and boulders. Most of the boulders and about 50% of the cobbles are limestone clasts from the Waterman Mountains. Other clasts are of mixed lithology. Petrocalcic horizons can form from primary (parent material) or secondary (atmospheric sources) calcium carbonate [Machette, 1985; Birkeland, 1999]. Based on the lateral extent and observed thickness of this petrocalcic horizon, it is probable that it formed from both sources of calcium carbonate.

Qy **Holocene alluvium, undifferentiated (~0 to 10 ka)** – Mixed channels and alluvial surfaces of Qy1 and Qy2 are composed of sand and silt, or are covered with unvarnished to weakly varnished, angular to subrounded, open gravel lags. Qy surfaces near the mountain fronts are found where drainage networks and associated late Holocene alluvium (Qy2) has dissected and partially covered middle Holocene alluvium (Qy1) to a depth of <1m. On the lower piedmonts, Qy surfaces are found in areas where Qy1 and Qy2 surfaces complexly interfinger such that they cannot be separated on a 1:24,000 scale. Channels are incised <1m near the mountain fronts and <1/2m on the lower piedmonts.

Qy2 **Late Holocene alluvium** (<4 ka) – This unit consists of active channels, low terraces and alluvial fans composed of sand, silt and gravel that have been transported in modern drainages. Proximal to the mountain fronts, sediment is generally coarser, composed of sand, gravel and cobbles with occasional boulders. On the lower piedmont areas, sediment is generally finer, composed of sand and silt with local fine to medium gravel. Little or no soil development has occurred in these young sediments. Channels are incised < 1 m below adjacent terraces and fans for main washes, and < 0.5 m for smaller washes. Channel patterns vary from single channel tributary drainages near the mountains to distributary networks with braided channels and diverging and converging channels on the lower piedmont. Vegetation along larger washes includes mesquite, palo verde, and ironwood trees along with creosote bushes and other small shrubs. Along smaller washes and on fans and terraces, vegetation is mainly creosote bush. Vegetation is sparse low on fans, terraces and smaller washes, and moderately dense along larger washes.

Qy1 **Middle Holocene alluvium** (~2 to 10 ka) – Qy1 surfaces are somewhat isolated from the active flow regime. Surfaces are mostly composed of fine-grained material, sand and silt, or are covered with unvarnished to weakly varnished, angular to subrounded, open gravel lags. Surface particle size fines downslope. On the lower piedmont, Qy1 surfaces are dissected by shallow distributary channels; larger channels on upper piedmont Qy1 surfaces are incised <1m. Vegetation density on these surfaces is sparse with creosote bush the dominant vegetation type.

Qly **Late Pleistocene to Holocene alluvium** (~0 to 130 ka) – Qly surfaces are broadly rounded and slightly to moderately dissected relict alluvial fans and terraces. Near the mountain fronts, active drainages have dissected and partially covered slightly reddened late Pleistocene alluvium (unit Ql) with a thin veneer of late Holocene alluvium (Qy2). Late Pleistocene alluvium (Ql) is exposed in the cut banks of washes. Qly surfaces near the mountains are incised one to three meters. On the lower piedmonts, Qly surfaces are composed of middle to late Pleistocene alluvium (Qm and Ql) covered by a thin, and sometimes discontinuous, veneer of middle to late Holocene alluvium (Qy1 and Qy2). Where the veneer of Holocene alluvium is absent, slightly reddened to reddened soil and desert pavement is exposed. Exposed Pleistocene lag is subangular to subrounded, moderately to strongly varnished gravel and cobbles. Channel incision on the lower piedmonts is less then 0.5 meter. Vegetation on Qly surfaces is sparse to moderately dense and composed mostly of creosote bush.

Ql **Late Pleistocene alluvium** (~10 to 130 ka) – Ql alluvial surfaces are broadly rounded to rounded and moderately dissected relict alluvial fans and terraces, with 1 to 2 m of active channel incision, increasing towards the mountain fronts. Weakly to moderately incised tributary drainage networks are typical. Relict bars and swales are retained in the pavement and in the topography, except adjacent to larger active washes where Ql surfaces are rounded ridges. Ql deposits consist of gravel, cobbles, and finer-grained sediments. Lag on ridges tends to be much coarser than on other Ql surfaces. Ql surfaces commonly have open, loose to moderately packed pavements, and are characterized by weakly to moderately varnished, subangular to subrounded gravels and cobbles. Pavements on the piedmonts around the Waterman Mountains typically have thin discontinuous carbonate coatings on clast surfaces. Ql soils are brown to slightly reddened sandy clay loams with subangular blocky structure, weak clay skins, and Stage II calcium carbonate accumulations. Major vegetation types include creosote bush and bursage. Other vegetation includes palo verde trees and saguaros, mainly along washes.

Qlp **Late Pleistocene alluvium over pedimented surfaces** (~10 to 130 ka) – Unit Qlp consists of fairly planar erosional surfaces cut into bedrock on the upper piedmonts with locally thin and patchy veneers of late Pleistocene (Ql) alluvium. Qlp surfaces are several meters above active channels. Where soils are well-preserved, they retain characteristics of Ql alluvium. Qlp lag is angular to subrounded. Vegetation is more diverse than on Ql surfaces, and include bursage, creosote bush, ocotillo, palo verde trees, ironwood trees, and other small shrubs and cacti.

Qlk **Late Pleistocene alluvium over a petrocalcic horizon** (~10 to 130 ka) – Qlk surfaces are found on the upper piedmont of the Waterman Mountains. These surfaces differ from Ql surfaces in that they are more deeply dissected, typically 2 to 3 m above active washes, well rounded ridges with coarse surface lag. Tributary drainage networks are typically incised < 1m. The older petrocalcic horizon is intermittently exposed throughout Qlk and covered by alluvium that is often <0.5 m thick, but may be 2 to 3 m thick. Relict bars and swales are preserved in the pavement and in the topography. Pavement is moderately to well developed with subangular to subrounded gravels and cobbles. Limestone clasts have thin, discontinuous calcium carbonate coatings. Non-limestone clasts tend to be weakly varnished. Vegetation density is moderately low and is generally more diverse than Ql surfaces. Vegetation types include bursage, creosote bush, ocotillo, palo verde trees, ironwood trees, and other small shrubs and cacti.

Qlm **Late to middle Pleistocene alluvium** (~10 to 750 ka) – Qlm surfaces are broadly rounded and are found on the piedmont north of the Waterman Mountains. Moderately incised tributary drainage networks are typical. The petrocalcic horizon is often exposed in the bottom of washes and in roads. Surface lag varies from open and loose to moderately packed. Clasts are subangular to subrounded gravels and cobbles. Non-limestone clasts are moderately to strongly varnished. Limestone clasts have thin discontinuous to continuous calcium carbonate coatings. Qlm shows up darker on the aerial photographs where varnish lag is present. Relict bars and swales are occasionally preserved in the lag. Soil varies from brown to slightly reddened late (Ql) to red middle (Qm) Pleistocene soil. Vegetation density is moderate. Vegetation types include bursage, creosote bush, ocotillo, palo verde trees, ironwood trees, and other small bushes and cacti.

Qm **Middle Pleistocene alluvium** (~130 to 750 ka) – Qm surfaces are moderately dissected relict alluvial fans, with several meters of active channel incision. Qm surfaces are drained by well-integrated, moderately incised tributary channel networks. Well-preserved Qm surfaces are smooth and have moderately to tightly packed cobble pavements. Surface lag is typically subangular to subrounded and moderately to strongly varnished. Well-preserved Qm surfaces have a distinctive dark orange color on aerial photographs, reflecting reddening of the surface soil and varnished clasts. Less well preserved surfaces are more rounded and have open to loose pavements. Finer-grained areas appear lighter orange on photos. Soils typically contain reddened, clay argillic horizons, with obvious clay skins and subangular blocky structure. Soil carbonate development is typically stage III to IV, but strongly cemented petrocalcic horizons are uncommon. Qm surfaces are found on the piedmonts of the Pan Quemado and Roskruge Mountains. Vegetation is open to moderately dense, with creosote bush, and bursage the dominant vegetation types. Other vegetation includes palo verde trees, ironwood trees, ocotillos, saguaros, and other small cacti and shrubs.

Qmp **Middle Pleistocene alluvium over pedimented surfaces** (~130 to 750 ka) – Unit Qmp consists of fairly planar erosional surfaces cut into bedrock on the upper piedmonts with locally thin and patchy veneers of middle Pleistocene (Qm) alluvium. Qmp surfaces are several meters above active channels. Where soils are well-preserved, they retain characteristics of Qm alluvium. Qmp lag is angular to subrounded. Vegetation density and diversity is similar to unit Qm.

Qmk **Middle Pleistocene alluvium over a petrocalcic unit** (~130 to 750 ka) – Qmk surfaces are found on the upper piedmont of the Waterman Mountains. Qmk surfaces are well-rounded to rounded ridges with well-developed drainages. Qmk surfaces are incised 2 to 4 m above larger active washes and 0.5 to 2 m above smaller tributary washes. The thickness of unit Qmk varies and the petrocalcic horizon is intermittently exposed in drainages and roads. Pavement is moderately developed and varies from open, loose fine to medium gravels to moderately packed, subangular to subrounded gravels and cobbles with occasional boulder. Cobbles and boulders tend to be subangular to rounded limestone clasts that may have eroded out of the petrocalcic horizon. Non-limestone clasts are moderately to strongly varnished. Limestone clasts have thin, discontinuous to continuous calcium carbonate coatings. Qmk soils are tan to white because the surface soil horizon is carbonate-rich and fragments derived from underlying cemented petrocalcic horizon litter the surface. Vegetation density is sparse to moderate. Vegetation type is diverse and includes palo verde trees, ironwood trees, creosote bush, bursage, ocotillo, and other small bushes and cacti.

Qmo **Middle to early Pleistocene alluvium** (~500 ka to 1 Ma) – Qmo surfaces are moderately dissected, relict alluvial fans found lower on the northern piedmont from Qmk surfaces. Qmo surfaces are broadly rounded ridges that are not as deeply dissected as Qmk surfaces, probably due to landscape position further out on the piedmont. Pavement in higher areas is moderately packed gravels and cobbles. Non-limestone lag is moderately varnished. Limestone lag has thick but discontinuous calcium carbonate coatings. Pavement in lower lying areas is open to loosely packed, fine to medium gravels. Surface color is lighter than most younger surfaces because the surface soil horizon is carbonate-rich and fragments derived from underlying cemented petrocalcic horizon litter the surface. Vegetation on this unit includes *krameria sp*. shrubs, creosote bush, palo verde trees, ocotillo, and chollas.

Qo **Early Pleistocene alluvium** (~750 ka to 2 Ma) – Qo surfaces are old, moderately dissected relict fans with up to 10 m of active channel incision. Tributary drainage networks are strongly developed and entrenched; depth of dissection by channels is similar to Qm surfaces, but areas between channels are more rounded by erosion. Qo surfaces have weak to moderate gravel and cobble pavements grading to gravel-sized carbonate fragments at the downslope extents of this unit. Rock varnish on non-limestone clasts varies from weak to moderate. Surface color is lighter than most younger surfaces because the surface soil horizon is carbonate-rich and fragments derived from an underlying cemented petrocalcic horizon litter the surface. Vegetation on this unit includes *krameria sp*. shrubs, creosote bush, palo verde trees, ocotillo, and chollas.

QTo **Early Pleistocene to Pliocene alluvium** (~1 to 5 Ma) – Very old alluvial fan and terrace remnants whose surfaces are composed of strongly varnished gravel, cobbles, and boulders with an abundance of carbonate litter. QTo surfaces are planar to highly eroded ridges and occupy the highest position in the landscape of any Quaternary unit; at least 10 m above adjacent active channels. Lag on highly eroded ridges is coarser than planar QTo surfaces and consists of boulders and cobbles. QTo surfaces are preserved the north and west sides of the Waterman Mountains, and at the southeastern edge of the map area in the Roskruge Mountains. Soils are dominated by pedogenic carbonate development, which is typically stage V (cemented petrocalcic horizon with laminar cap) on ridgecrests. Carbonate litter is common on ridgecrests and sideslopes.

Bedrock Units

Rocks of uncertain age

q **Vein quartz** (Tertiary to Jurassic)—Milky white quartz in veins and veinlets that were typically emplaced within highly fractured host rocks. Includes irregular cavities with drusy quartz fillings and locally it appears that vein quartz was brecciated and that spaces between breccia were filled with new vein quartz. These veins are suspected to be peripheral to Jurassic, Laramide, or mid Tertiary igneous activity.

MzPzls **Limestone** (Mesozoic or Paleozoic) – Gray crystalline carbonate, locally cherty, in slivers along fault(?) zones in Mesozoic rocks.

Tertiary volcanic rocks

Tbi **Mafic dikes** (Miocene) – Fresh, black basalt dikes with dark, glassy clinopyroxene up to 3 cm diameter and plagioclase(?) up to 2 cm diameter. This unit is equivalent to the "augite-olivine basalt” unit of Bikerman [1967] in the adjacent Cocoraque Butte quadrangle. North-northwest trending dikes on strike with dikes in the map area [Skotnicki and Pearthree, 2000] have yielded a K-Ar whole-rock date of 9.9 ± 1.7 Ma [Bikerman, 1967]. A second sample, from a correlative basalt in the southern Roskruge Mountains (‘Brawley Wash basalt’) yielded a K-Ar whole rock date of 11 ± 1.3 Ma. Bikerman [1967] also reported an $^{87}Sr/^{86}Sr$ ratio of 0.7038 from one sample (measured value and value corrected for age are the same). A fragment of a dark, glassy, clinopyroxene crystal, found weathered out of a dike, was submitted to the University of Arizona for $^{143}Nd/^{144}Nd$ analysis (sample 3-1-00-2 from hill just east of center of section 1, T. 14 S., R. 9 E., UTM 464400E, 3566900N). In thin section approximately 40% of matrix appears as microlites of plagioclase (30%) and tiny crystals of clinopyroxene(?) (10%). The rest of the matrix is dark and cryptocrystalline. Samarium-Neodymium isotopic data (see above section on “Tertiary volcanic and hypabyssal rocks”) indicate a primitive magmatic source, probably in the mantle, for these dikes.

Ttn **Trachyte of Nessie’s Hill** (Late Oligocene or Miocene) -- Moderately crystal-poor (5-20%), dark gray to dark lavender trachyte lava containing plagioclase (5-17%, 0.5-4.0 mm), biotite (<1-2%, 0.5-2.0 mm), clinopyroxene (0.5%, euhedral ≤ 0.5mm), and amphibole (trace, 0.5-1.0 mm) phenocrysts. The dominant phenocryst phase, plagioclase, ranges up to 4.0 mm, but it is typically < 1.0 mm, euhedral to subhedral, and strongly normally zoned (cores of An 60). In all thin-sections studied, plagioclase phenocrysts much larger than 1.0 mm are commonly inclusion rich with rims (0.1-0.3 mm wide) that are much less inclusion rich. Large plagioclase phenocrysts with clear cores and inclusion-rich rims are sometimes present. Typically these lavas sharply overlies older units with a strongly flow-banded, dark purple, crystal-poor contact zone a few meters thick. The lava displays flow texture variations typical of fluidal, crystal-poor, intermediate lavas. Flow breccia is relatively uncommon. A probable vent for this unit is a flat-topped hill to the northeast of the Pan Quemado (UTM 464800E, 3578250N) informally referred to as “Nessie’s Hill” by nearby inhabitants.

Ttx **Trachyte of El Cerrito de Represso**: - A thin veneer (<3 meters) of this crystal-poor lava is present locally at the base in many areas and as mappable bands (unit **Ttxp**) up to 20 meters wide in the hill at the junction of sections 34, 35 (T12S, R9E), 2, and 3 (T13S, R9E). Elsewhere, small unmappable bodies of the crystal-poor variety constitute less than 5% (and typically < 1%) of the map unit. The unit is characterized, and distinguished from the overlying trachyte of Nessie’s Hill, by ubiquitous, large (up to 1 cm), typically strongly zoned, plagioclase phenocrysts (cores of An 45). The abundance of mafic phases varies widely between flows with amphibole and clinopyroxene varying from barely present to over 1% (0.2-0.7 mm, euhedral grains), and trace amounts to 1-2% (0.5-1.0 mm euhedral grains) respectively. Biotite phenocrysts consistently represent between 1-2% of the rock (0.2-1.5 mm). Sanidine is abundant (2-3%, 1-2 mm sub- to anhedral grains) in some flows, but absent or sparse in others. Rounded and embayed, ~1 mm quartz phenocrysts make up nearly 1% in some samples.

Ttxp **Crystal-poor variety of the trachyte of El Cerrito de Represso**: Crystal-poor (~10%) lava petrographically similar to the trachyte of Nessie’s Hill. See above description (**Ttx**) for detailed discussion. One sample studied in detail contained weakly zoned phenocrysts of calcic plagioclase (7-8%, 0.5-6.0 mm, An 70), clinopyroxene (≤ 1%, euhedral 0.2-0.5 mm), biotite (minor, < 0.5 mm), and opaque mineral (trace, equant < 0.2 mm). The pyroxene in this rock is commonly glomeroporphyritic and some of it may be orthopyroxne. The lava is mapped as part of the trachyte of El Cerrito de Represso because its contact with the crystal-rich variety is always gradational, even though the contact zone is typically very narrow (< 2 cm).

Trx **Crystal-rich rhyolite lava**: Rhyolite lava containing 25-35% phenocrysts of quartz, sanidine, plagioclase, and biotite.

Trxi **Crystal-rich rhyolite dike**: A single dike of vitric matrix, crystal-rich (35%), low silica rhyolite. The dike intrudes the mafic lava (Tm) near a low saddle in the northern Pan Quemado. Phenocrysts are plagioclase (25-30%, 0.2-1.0 mm, An 48), biotite (2-5%, 0.1-1.0 mm), amphibole (trace, <0.1 mm) and opaque minerals (trace, <0.2 mm). Based on its phenocryst assemblage, plagioclase anorthite content, and chemistry, this dike is probably not related to the two rhyolite lava units found farther to the west.

Ttl **Lithic-rich tuff**: Massive to thick-bedded and medium-bedded, lithic-rich (5-60%), nonwelded rhyolite tuff with a moderately crystal-rich, quartz-phyric matrix. Lithic clast abundance varies depending on the proximity to subjacent rock units. Important clast types are mafic lava (probably of map unit **Tm**), arkosic sandstone (derived from map unit **KJs**), and rhyolite lava clasts (unit **Tr**). The relationship of this map unit to the crystal-rich rhyolite lava (**Trx**) is unknown. Locally, this map unit may include volcaniclastic sedimentary rocks.

Tr **Rhyolite lava**: In the Pan Quemado area, this units includes rhyolite lava containing about 10% phenocrysts of sanidine (5-7%, 0.7-2.0 mm), plagioclase (2-5%, 0.5-2.0 mm, An < 25), and minor altered opaque minerals (< 0.3 mm). The lava displays flow textures typical of silicic lava and is in gradational contact with the lithic-rich tuff along its southernmost contact.

Where mapped in the hills west of Cerrito de Represso (sec. 16, T. 13 S., R. 9 E., UTM 459421E, 3573470N), the unit consists of vuggy, flow-banded, gray rhyolite lava flows with 10-15%, 1-2 mm quartz, 3-5%, 1-2 mm sanidine, and <1%, 1 mm biotite. Flow banding is somewhat convoluted, with lineations on some surfaces reflecting flow. No flattened lithic fragments were seen. Vugs are spherical even where rock is strongly flow banded. Flow banding is defined by variations in weathering and is not visible on fresh surfaces. Vitrophyre is preserved low on the south and west slopes of this hill.

Tri **Rhyolite intrusion** (Tertiary)— On hill located 2 km west of Pan Quemado in the eastern half of sec. 33, T. 12 S., R. 9 E (UTM 459700E, 3578200N), consists of light tan, flow banded, rhyolite with sparse, 1-2 mm phenocrysts of quartz, biotite, and sanidine. This rock weathers to medium to dark brown or pinkish to orangish brown. This intrusive rock is interpreted to be related to Tr on Pan Quemado.

A small hill north of Dos Titos (UTM 459000E, 3571760N) consists of gray, porcelaneous to maroon flow-banded felsite with 2-3% 1-2 mm rounded and embayed quartz phenocrysts, and 0.5-1% each of 1 mm sanidine, biotite(?) (altered to tan clay), and 1 mm plagioclase (altered to white clay?). This outcrop contains irregular 2-5 cm diameter blobs of medium-gray intermediate-composition felsite (xenomelt blobs), and scattered volcanic-lithic fragments. Some xenomelt blobs contain 2-3 mm pyroxene(?) glomerocrysts.

Tf **Felsite of El Cerrito de Gallinas** (Tertiary?) – crystal poor felsite with about 5% crystals of 1-3 mm plagioclase and hornblende, with sparse but ubiquitous pyroxene crystals, locally up to 2 cm in diameter. Rock is generally massive, but is locally flow banded, and appears to be intrusive.

Tm **Mafic lava**: Crystal-poor, dark-colored mafic lava containing less than 10% phenocrysts of altered mafic minerals (probably pyroxene and/or olivine), $\pm$ plagioclase.

Ts **Sandstone and conglomerate**: Thick- to medium-bedded arkosic sandstone, and heterolithic conglomerate containing clasts chiefly derived from Pre-Tertiary rocks; limestone, porphyry, and Cretaceous volcanic rocks. Single small outcrop in the Pan Quemado area.

Mesozoic to Early Tertiary rocks

TKq **Quartz porphyry** (Tertiary or Cretaceous)-- Pink to gray, crystal-rich quartz porphyry with phenocrysts of quartz (2-10%, 1-5 mm), feldspar (2-15%, 1-5 mm), and mafic minerals (~1-3%, 1-3 mm). The porphyry occurs as small dikes in tuff of Sharp Peak in the southern part of the map area, and are more abundant in the Tortuga Butte area to the south [Ferguson et al., 2000].

TKf **Felsite dike** (Tertiary or Cretaceous)-- Aphyric to very crystal-poor felsite dikes. These contain sparse 1 mm feldspar crystals, trace of 1-2 mm biotite(?) altered to silvery chlorite, and a trace of tiny pyrite cubes altered to limonite. Some of these are vitric and green colored. Other pale gray and porcelaneous aphyric to crystal poor rhyolite dikes are interpreted to be devitrified equivalents. One or more similar dikes intrude near the contact between Permian and Mesozoic rocks along the north flank of the Waterman Mountains. May be related to aphyric felsite unit (TKd).

TKdi **Intermediate-composition intrusive rocks** (Tertiary or Cretaceous)—Various isolated bodies of hypabyssal, porphyritic intrusive rock, generally characterized by light gray to brown aphyric to very fine grained matrix, predominance of plagioclase phenocrysts, and presence of hornblende or biotite phenocrysts. Includes:

(1) Dike that contains phenocrysts of 2-5 mm plagioclase and biotite that together form 50-60% of dike core and ~20% of dike margins. Dike intrudes sandstone of map unit KJsg about 2 km south of Waterman Peak (NW¼, sec. 6, T. 13 S., R. 9 E.; UTM 455600E, 3577050N).

(2) Northeast-trending dike located about 2 km north of Waterman Peak (W½, sec. 19, T. 12 S., R. 9 E.; UTM 455520E, 3581200N to 456260E, 3581650N). This dike consists of a light gray, very fine-grained groundmass with phenocrysts of hornblende and biotite (0.5 –3 mm, 7%), feldspar (1-5 mm, 20%), quartz (2-3 mm, 3%).

(3) Medium gray to brownish gray dike or sill, with sparse 1-2 mm phenocrysts of plagioclase and biotite(?) and up to 1 cm phenocrysts of K-feldspar, intruding quartz arenite of map unit Jqs (NW ¼, NW ¼, sec. 16, T. 13 S., R. 9 E.).

(4) Greenish tan dike with 2-3% 2-4 mm altered biotite, 20% 2-6 mm plagioclase, 2-3% 2-4 mm hornblende, and 1-2% 2 mm quartz. This dike intrudes the faulted contact between Concha Limestone and Colina Limestone at about 1.5 km southeast of Waterman Peak.

(5) Two small dikes of crumbly, deeply weathered, fine-grained (< 2 mm) plagioclase porphyry (20-30%) in the northern Waterman Mountains.

(6) Massive, tan to gray weathering crystal-poor felsite near northern edge of map area (UTM 459900E, 3581250N). Very fine-grained to aphanitic light gray groundmass contains about 3% crystals, including 1-2 mm glomeroporphyritic plagioclase + mafic mineral clusters, acicular plagioclase up to 2 mm long, and sparse 1 mm mafic crystals (biotite or hornblende?). Bleached zones in the rock on this hill contain tiny disseminated pyrite altered to limonite. This unit forms an isolated hill with no contact relationships with older rocks.

(7) Andesite dike intrudes crystal-poor tuff just north of Silver Bell Mine road (UTM 459637E, 3581473N). Dike consists of drab brown very fine-grained matrix with about 40% 3-4 mm subhedral plagioclase and 2-3 mm hornblende crystals. Tiny grains of an opaque phase are scattered in the matrix. Fractures in the dike are hematite stained.

(8) A small outcrop of andesite(?)about 2 km east-northeast of Waterman Peak. This rock contains 0.5 to 1 mm diameter phenocrysts of plagioclase, hornblende, and biotite in a maroon gray aphanitic matrix.

TKa **Andesite (Tertiary) —** Several isolated outcrops of generally dark gray extrusive rocks with plagioclase and pyroxene or olivine phenocrysts:

(1) A single small outcrop of pyroxene andesite(?) at the north foot of hill 2450 (UTM 458520E, 3573750N). This rock is probably a lava flow.

(2) Andesite outcrops along the north edge of the quadrangle include purplish-gray lava with a very-fine-grained groundmass containing 5% 1 mm-diameter crystals of euhedral plagioclase and biotite altered to chlorite and a more crystal rich lava containing about 10% 1 mm-diameter plagioclase and mafic phenocrysts. About half the mafic phenocrysts are altered to iddingsite in this rock. Both rocks include bleached zones suggestive of alteration related to the porphyry system at Silver Bell, but are continuous with outcrops mapped by Sawyer [1996] as Ta and Tba.

Felsite of Dos Titos (Cretaceous) — New unit, named here for outcrops on the west side of the northern summit of Dos Titos (UTM 457750E, 3570900N). The unit consists of light-gray colored, hypabyssal intrusive rocks of intermediate to felsic character, with cryptic intrusive and faulted intrusive contacts against Cretaceous or Jurassic sedimentary rocks and tuff of Sharp Peak in northern Roskruge Mountains. Mixed, gradational contacts with mesobreccia unit of the tuff of Sharp Peak suggest that the felsite of Dos Titos intruded before complete solidification of the mesobreccia or that the two were emplaced simultaneously. Our interpretation is that the felsite of Dos Titos is a hypabyssal intrusion associated with the tuff of Sharp Peak, which intruded along the vent zone represented by the mesobreccia late in the eruption of the tuff.

Kdt **Main phase felsite --** Microgranular groundmass contains 1-2% 1-2 mm diameter euhedral feldspar crystals, sparse zones that contain 3-4 mm feldspar crystals, and sparse tiny biotite (replaced by chlorite) crystals. In a few places contains acicular hornblende(?) crystals up to 5 mm long. Quartz is rarely visible, and appears to be mostly interstitial between plagioclase, not as phenocrysts. Weathers to tan color, forming rounded cobbles and boulders on weathered surfaces. On the east-trending ridge about 3 km north-northwest of Dos Titos, the contacts with crystal-poor felsite (map unit Kd) are sharp, and the crystal-poor felsite becomes finer grained near contacts, suggesting that this unit intrudes the crystal-poor felsite. In the southwestern part of the map area rocks of this unit are more variable. Quartz is more abundant in outcrops along the ridge north and south of hill 2498 (UTM 456000E, 3567550N). Acicular hornblende and biotite are more abundant in the hills in the south part of sec. 5, T. 14 S., R. 9 E. (UTM 457900E, 3566200N).

Kd **Crystal-poor felsite —** Very fine-grained, massive, light gray, aphyric felsite or microaplite. This facies crops on the east-trending ridge about 3 km NNW of Dos Titos and on the pediment northwest of Dos Titos, but similar rock is not mapped separately along the southwestern part of the outcrop. Weathers light gray to pink, forming angular blocks. Felsite has microgranular texture with anhedral grains of quartz and feldspar, typically < 0.5 mm in diameter. Vague flow-banding is visible in some outcrops. Close association with felsite of Dos Titos suggests that this is a facies of the same intrusion.

Kdz **Mixed felsite and mesobreccia of the tuff of Sharp Peak —** Main phase felsite with 1-10 m-scale inclusions of andesite (KJi), rhyolite (Kr?), bedded tuff, and mesobreccia of tuff of Sharp Peak. Contacts with andesite are sharp; contacts with felsic inclusions are irregular and difficult to locate.

Tuff of Sharp Peak (Cretaceous) — New unit named for type section on Sharp Peak in southern Roskruge Mountains [Ferguson et al., 2000]. Formerly the Roskruge rhyolite of Heindl (1965) and the middle member of 3 members of the Roskruge volcanics of Bikerman [1965, 1967, 1968].

Ksp **Welded tuff**: Moderately crystal-rich (18-30%) rhyolite, welded ash-flow tuff, containing phenocrysts of plagioclase (5-15%, 0.5-4.5 mm), quartz (4-8%, 0.7-8.0 mm), sanidine or perthitic K-feldspar (3-9%, 1.0-4.0 mm), and biotite (0.2-1.5%, 0.5-1.5 mm). At its type section the tuff is divided into a lower non-welded zone, and an upper welded zone, and the tuff is compositionally zoned with an abrupt increase in plagioclase and biotite content corresponding to the gradual upward change from non-welded to welded. In this map area, only the welded zone has been recognized; it is pinkish, gray, or peach-colored and very resistant, forming the high-standing peaks at the southern edge of the map area. Bikerman (1967) reports a K/Ar plagioclase date of 66.90 $\pm$ 3.00 Ma, K/Ar biotite dates of 70.30 $\pm$ 1.90, 70.40 $\pm$ 1.70, 71.40 $\pm$ 1.50, 71.70 $\pm$ 1.50, 73.00 $\pm$ 1.60, 73.80 $\pm$ 1.60, and 74.20 $\pm$ 1.50 Ma, and a K/Ar sanidine date of 70.40 $\pm$ 1.70 Ma for this unit.

Kspz **Mesobreccia**: Tuff of Sharp Peak with abundant, typically aphanitic lithic fragments up to 10 cm diameter. Fragments are so abundant in some areas that rocks of this unit resemble breccia. Rock is generally strongly indurated and appears silicified. Matrix is light gray or grayish green, to maroon or brown in some areas, and contains 2-5% 2 mm quartz phenocrysts (some are embayed), 5-10% 2-3 mm diameter feldspar, and 3-5% biotite ubiquitously altered to chlorite. In one thin section some lithic fragments consist of microcrystalline quartz(?) and cryptocrystalline opaques, as well as 2-5 mm epidote(?). This mesobreccia forms a west-northwest trending zone across the northern Roskruge Mountains. The southern part of this belt bounds the Sharp Peak tuff on the northeast, possibly representing a caldera boundary. The northern part of the belt is intruded by and faulted against the felsite of Dos Titos, which may represent a resurgent intrusion along the caldera margin. To the southeast, the breccia unit is in contact with various Jurassic or Cretaceous clastic rocks. The contact with sandstone of map unit KJs due west of hill 2872 (NE ¼, NE ¼, sec. 5, T. 14 S., R. 9 E., UTM 458300E, 3567500N) appears to be a sheared intrusive contact with pervasive iron oxide staining and mineral alteration along contact.

The origin of this unit is not clear. It resembles the tuff of Sharp Peak, and is gradational with it, but is distinctive largely because it contains abundant lithic fragments and, locally, blocks of andesite(?), and contains fewer quartz phenocrysts. In addition, what appear to be fault slivers are present along its contact with the felsite of Dos Titos and the tuff of Sharp Peak. Possibly this unit is a caldera infill breccia that was deposited during eruption of the Tuff of Sharp Peak, but it is not known if the lithic fragments and blocks fell from the caldera walls or were carried upward from initial incorporation as xenoliths in a magma chamber.

Kr **Rhyolite lava** (Cretaceous) — Crystal poor rhyolite lava and associated autobreccia. Light gray rock that contains 2-5% phenocrysts of euhedral plagioclase (0.4-1 mm) and a trace of biotite (<1 mm).

Kcp **Confidence Peak Tuff** (Cretaceous)-- Crystal-rich (20-30%), quartz (10-15%, 0.5-10.0 mm), plagioclase (10-15%, 0.6-4.0 mm), K-feldspar (2-5%, 0.5-3.0 mm), biotite (1-3%, 0.5-2.0 mm)-phyric, welded ash-flow tuff. Named by Sawyer [1996] for outcrops on Confidence Peak in the Silver Bell Mountains. K-feldspar phenocrysts are typically perthitic, but in some samples, sanidine may be preserved. The Confidence Peak Tuff can be differentiated from the tuff of Sharp Peak because it is older, because its quartz phenocrysts are much larger (up to 1 cm), and because it contains very abundant biotite phenocrysts. Biotite K/Ar ages of approximately 57 and 59 Ma [Mauger et al., 1965] are too young based on stratigraphic constraints in the Silverbell Mountains [Sawyer, 1996]. Sawyer [1996] indicates a probable age range between 72.7 and 68.6 Ma based on bracketing between “well dated” units. In the Pan Quemado area, the Confidence Peak Tuff appears to overlie the arkosic sedimentary unit (**KJs**) and a body of intermediate composition, crystal-poor lava (**KJi**).

KJsu **Cretaceous or Jurassic sedimentary rocks, undivided**

KJtw **Unit of Tunnel Well** – Massive volcanic lithic conglomerate in the southeastern edge of map area. Gray-green volcanic-lithic sand matrix contains abundant subhedral crystals of feldspar and rare quartz <1 mm in diameter. Angular to well rounded clasts of andesite are the dominant clast type. Becomes sandier to W and N, and may correlate with or grade into the dark volcanic-lithic sandstone unit (KJsv).

KJp$_2$ **Photogeologic unit 2 —** Banded tan outcrop. Correlation into mapped area suggests that this is unit KJs.

KJp$_1$ **Photogeologic unit 1** — Smooth, brown outcrop. Correlation into mapped area suggests that this is a volcanic-lithic sandstone unit.

Kc **Conglomerate** (Cretaceous)—Gray to brown cobble and boulder conglomerate that contains clasts of unit KJs sandstone in a matrix of very similar appearing sandstone. Massive to crudely bedded, poorly exposed on pediments. Boulders of brown feldspathic litharenite (unit KJs?) up to 1 m in diameter are present in the outcrops south of the east-trending ridge between the Waterman and Roskruge Mountains.

KJra **Reddish sandstone and argillite (**Cretaceous or Jurassic) — Assemblage of very-thin bedded to laminated calcareous or siliceous argillite, sparse limestone, and red to brown thin- to medium-bedded sandstone. Hand samples appear to be either feldspathic litharenite or lithic arkose. Intruded by andesitic dikes

KJsg **Granitic sandstone and conglomerate** (Cretaceous or Jurassic) — Light gray to white arkose, pebbly arkose, conglomeratic sandstone, and conglomerate. Sands are generally coarse-grained to granule size. Sandstone beds typically massive, with low-angle cross-bedding delineated by magnetite-rich laminations. Clasts in conglomerates are up to about 20 cm in diameter, include various unidentified granitoid types and abundant sub-rounded vitreous quartzite pebbles and cobbles. Unit is non-resistant and invariably forms pediments with outcrops mostly in washes.

At ~1.5 km south of Waterman Peak, sandstone rests depositionally on andesitic volcanic rocks of map unit KJi. In this area, subangular to subrounded chert and quartzite clasts are up to 10 cm diameter, and sandstone is both plane bedded and cross bedded, with beds 10-50 cm thick. Sandstone has much quartz here but probably enough white plagioclase (20-40%) and lithic fragments to qualify as an arkose or lithic arkose. Sandstone and pebbly sandstone grades up section to southeast into medium- to fine-grained sandstone and sandy siltstone. The contact with Cretaceous conglomerate (Unit Kc; UTM 455650E, 3573200N) is not well exposed, but may be depositional.

KJsl **Sandy limestone** (Cretaceous or Jurassic) — Gray limestone, with fine to coarse grains of quartz, feldspar, and small pebbles locally up to 4 cm diameter. Shell fragments are locally abundant and locally form the centers of limestone concretions up to 4 cm in diameter. Lithologically similar carbonate beds are present in the reddish sandstone and argillite (unit KJra) and sandstone and local conglomerate (unit KJs) units.

KJs **Sandstone and local conglomerate** (Cretaceous or Jurassic) — Undivided brown to gray, thin- to medium-bedded arkosic, argillaceous sandstone and siltstone interbedded with lesser amounts of dark-colored mudstone, and thick- to medium-bedded heterolithic conglomerate. Sandstone is moderately to poorly sorted, fine- to coarse-grained and dark brown to reddish brown. Hand samples appear to be either feldspathic litharenite or lithic arkose. Some chert pebble and cobble conglomerate is present, which consists of subangular to subrounded clasts up to 15 cm in diameter. Intermediate composition and quartz-phyric volcanic clasts are ubiquitous in conglomerate beds, along with a variety of granitic rocks, quartzite and limestone.

Scours with pebble lag deposits are present in some areas. This unit is locally laminated with magnetite-rich sand layers. Relationship to reddish sandstone and argillite (unit KJra), granitic-clast sandstone and conglomerate (unit KJsg) and sandy limestone (unit KJsl) units is uncertain.

The contact with underlying Concha Limestone, on the south side of the long ridge that extends eastward from the Waterman Peak area (UTM 458950, 3577650), is a 40 to 80 cm thick zone of disaggregated chert fragments that is interpreted as the weathered top of the Concha Limestone and the depositional base of the sandstone and conglomerate. A similar contact on the northwest side of the same ridge (UTM 457900, 3578520) is also suggestive of cherty lag that possibly forms the weathered top of the Earp Formation, and is overlain by poorly sorted angular debris the forms base of Mesozoic sandstone.

The hill just north of the east end of this ridge (UTM 459700, 3578050) consists of reddish brown, very fine-grained sandstone, and poorly sorted sandy siltstone and siltstone, locally with poorly sorted, coarse gritty sandstone with grains up to 8 mm in diameter.

KJsv **Dark volcanic lithic sandstone and conglomerate** (Cretaceous or Jurassic) — Lithologic map unit that includes dark-weathering volcanic lithic sandstone and conglomerate. Clasts are mostly intermediate composition volcanic rocks, similar to clasts in andesitic breccia unit (Jvx) or andesitic rocks of KJa or KJi, but in some outcrops quartz-phyric rhyolite lava or tuff clasts are present. Bedding is generally indistinct.

KJp **Tuff of San Pedro** (Cretaceous or Jurassic) — Crystal-rich (20-40%), plagioclase, biotite-phyric, welded ash-flow tuff. This unit is typically dark red, but may be gray in some exposures. The tuff contains up to 35% plagioclase phenocrysts (1-8 mm, average 2-4 mm), and 1-3% biotite (0.5-2.0 mm), but no quartz or K-feldspar. In most areas, the tuff of San Pedro occurs at the contact between the mafic lava (**KJi**) and sedimentary rocks (**KJs**) map units.

KJxp **Crystal poor tuff** (Cretaceous or Jurassic) — Very light gray welded tuff with about 1% 1 mm-diameter quartz and 2-3% 1 mm-diameter feldspar. 10-20% of rocks is 0.5-2 cm lithic fragments. Strongly flattened pumice is also present. Two small outcrops at the north edge of the map. Cleavage shown in these outcrops appears to be very close to the orientation of the flattening foliation in the tuff. Tuff is intruded by a crystal rich andesitic dike immediately north of the paved road to the Silver Bell Mine.

KJi **Mafic to intermediate volcanic and shallow intrusive rocks** (Cretaceous or Jurassic) — Crystal-poor, gray to light green lava and/or hypabyssal intermediate to felsic composition igneous rock, and massive, generally dark-colored volcanic breccia (flow breccia) interbedded with vesicular and non-vesicular lava flows. The unit consists of a variety of different lava flows with or without associated hypabyssal bodies. Intrusive or depositional contact relationships with adjacent rock units are vague. A similar unit is mapped in the southern Roskruge Mountains (**Kji,** Ferguson et al., 2000). In this map area includes:

1) A body of felsic, crystal-poor lava at the north end of the Pan Quemado (UTM 463400E, 3578750N) that contains up to 10% altered mafic minerals, but little or no feldspar. A thin fine-grained, plagioclase-phyric mafic lava in a small exposure at the west end of this belt (UTM 462384E, 3578376N) is interbedded(?) with the arkosic sedimentary rocks (**KJs**).
2) Farther south in the Pan Quemado (UTM 462100E, 3577500N), the unit is characterized by up to 10% sericitized biotite phenocrysts.
3) Rocks mapped as andesite/dacite lava flows (Ksa) and dacite domes and lava (Ksd) by Sawyer [1996] at the north edge of the map area.

4) A northwest-trending belt of andesitic rocks, interbedded(?) in sedimentary rocks (KJs) north of Dos Titos (UTM 455850E, 3572150N to 457700E, 3571300N). This belt consists of dark gray to greenish gray, generally massive andesite(?) with 30-40% 1-5 mm plagioclase, sparse opaque mineral grains, and possible sparse quartz. Sparse reddish brown mudstone in bedded zones up to 10 cm thick and agglomerate indicate that at least part of this sequence is extrusive.

5) A thin belt along a fault zone on the southwest side of the Mesozoic rocks in the southern Waterman Mountains (UTM 455370E, 3576110N to 457060E, 3575080N) may be a dike or lava flow. It is characterized by 20-40% 2-5 mm plagioclase crystals, and ~5% 1-2 mm pyroxene(?). Some plagioclase prisms are up to 2 cm long. The groundmass is very fine grained and red brown, gray or purple colored.

6). Outcrops southeast of Dos Titos (UTM 459000E, 3568500N) include abundant fragmental rocks with plagioclase phyric clasts. Some outcrops contain dark, elliptical globs that are less resistant to weathering, and may be moderately flattened pumice fragments. Similar rocks mapped as KJi at the southeast end of their outcrop (UTM 462200, 3565250N) overlie the tuff of San Pedro, suggesting that some rock mapped as KJi in the southeastern part of the map may be related to the tuff of San Pedro.

Jvx **Andesitic breccia volcanic rocks** (Jurassic)—Massive volcanic-lithic breccia consisting of mixed light and dark-colored, generally intermediate composition, volcanic rock clasts. Clasts are generally subangular. Bedding is sparse and indistinct except in rare sandstone lenses. Typical fragments contain 1-3 mm plagioclase phenocrysts and chloritized, 1-2 mm mafic phenocrysts.

Jt **Tuff** (Jurassic)—Tuff marker bed(s?) in unit Jvx or J₸vs. Rock is light gray, and aphanitic with sparse quartz or feldspar grains. Contacts with overlying mudstone are sharp. Some beds have vague, bedding-like lamination in upper part. Some of these may be felsite sills.

Jqs **Quartz arenite** (Jurassic) — Very fine grained, pale red weathering, quartz arenite sandstone, plane bedded to cross bedded, with variable amounts of opaque magnetite(?) that are concentrated in laminations that reveal bedding. In thin section this unit appears as 95-99% monocrystalline quartz grains with sutured boundaries and very rare undulose extinction. Approximately 1% opaque grains, 1% high relief grains, and 1-4% calcite that is probably secondary. Considered Jurassic based on regional occurrence of quartz arenite units associated with Jurassic volcanic rocks, and the absence of such units associated with known Cretaceous volcanic rocks.

J₸s **Quartzite and red mudstone** (Jurassic or Triassic) -- On the north side of the main Paleozoic outcrop belt, this unit consists of medium- to thick-bedded, medium- to coarse-grained quartz arenite interbedded with dark maroon to brown mudstone. Quartzite contains sparse black opaque grains, ~2% feldspar altered to brown clay, and local carbonate-cemented zones. Medium-scale cross bedding is present in some beds. Coarse-grained quartzite beds are typically light gray weathering, and finer-grained quartzite beds are red-brown weathering. Mudstone is very poorly exposed except in washes, and mudstone to sandstone ratio is difficult to estimate. Mudstone beds contain very light gray carbonate nodules 1-15 cm in diameter. Mudstone intervals exposed in washes are typically 2-5 m thick. Carbonate nodules also form clasts in the lower part of coarse sandstone beds. In the northwestern part of this outcrop belt, rock is apparently silicified, and quartzite beds look like massive chert.

J₸vs **Red volcanic-lithic sandstone and mudstone** (Jurassic or Triassic) — Similar to quartzite and red mudstone unit (J₸sm), but includes abundant volcanic-lithic sandstone and sparse volcanic-lithic conglomerate, and quartzite is less abundant. Grades up section into Jvx.

JTRs2 **Greenish argillite and sandstone** (Jurassic or Triassic) – Light greenish grey siliceous argillite with interbedded feldspathic quartz arenite or arkose. Very poorly exposed on hill slopes about 1.5 km northeast of Waterman Pass and in wash bottoms about 1 km ESE of Waterman Peak. Probably related to unit JTRvs.

JTRs1 **Basal Mesozoic sandstone** (Jurassic or Triassic) -- Quartzite cobbles in a feldspathic quartz arenite matrix, grades up section into mostly sandstone. Volcanic detritus becomes progressively more abundant up section and the unit grades into volcanic-lithic sandstone and mudstone of JTRvs. The source of the quartzite cobbles is unknown. Detrital muscovite and the feldspathic petrography of sandstone in the lower part indicates exposure of granitic or metamorphic rocks in the source area. The preservation of Permian carbonate units beneath this basal Mesozoic sandstone demonstrates that little relief developed on the disconformity in the areas where it is preserved [Riggs and Richard, 1994].

Mzk **Karstic(?) breccia** (Permian(?), Triassic, or Jurassic) -- Angular to subrounded clast, boulder, cobble conglomerate or diamictite with red silty calcareous matrix. Sharply overlies Permian Concha or Rain Valley formations along a highly irregular, cavernous (?), contact along the northern flank of the Waterman Mountains. Rare silty lenses dip steeply to the northeast, somewhat conformable to the underlying Permian bedrock and to overlying arkosic red beds. The unit is highly variable in thickness and pinches out rapidly along strike from over 30 meters to 0 meters. The unit is interpreted as a karstic breccia or conglomerate sporadically preserved along the sub-Mesozoic unconformity. Well rounded cobble conglomerate that typifies this contact are present just to the southeast of the outcrops of this unit.

Paleozoic Sedimentary rocks

Pr **Rainvalley Formation** (Permian) — Mostly thick bedded (10-100 cm), tan or medium to light gray, dolostone and less common gray limestone. Chert nodules are sparse to absent. Carbonate varies from aphanitic to a wackestone to packstone of 1-3 mm fossil debris and carbonate grains. Locally, rocks of this unit have a vaguely petroliferous aroma of freshly broken surfaces. The unit also contains zones of gray carbonate with 5-15 cm thick nodules, stringers, and beds of tan to brown weathering chert. The cherty rocks are more resistant to weathering than carbonate without chert and tend to form outcrops that are more prominent.

Pc **Concha Limestone** (Permian) — Gray, thick bedded to massive limestone that varies from aphanitic to wackestone to packstone. Thick-bedded limestone has 20 to 100 cm thick beds and weathers along bedding planes into blocks and slabs. Possibly includes dolostone locally. Chert-rich zones consist of 25-75% chert in nodules and beds 5-20 cm thick. Chert nodules are aligned along bedding planes. Crinoid columnals and various sorts of bryozoa fragments are present throughout the unit. Horn corals are common in the upper half of the formation.

Ps **Scherrer Formation** (Permian) — Very fine-grained to fine-grained, clean, tan to buff quartz arenite or quartzite, with less abundant interbedded dolostone and red sandstone. Field examination suggests that feldspar and lithic fragments constitute less than 2% of the sand grains. Very sparse opaque mineral grains are possibly magnetite and weathering of these iron oxide grains may give the rock its pinkish to orangish color.

The basal part of the Scherrer is a non-resistant, reddish, very fine-grained sandstone that is rarely exposed. In some areas it can be recognized by the reddish soil formed on the unit. This is overlain by an interval of carbonated-cemented quartz arenite, with interbedded lenses of dolostone. Light gray, medium- to thick-bedded, sandy dolostone forms one or more lenses up to 10 meters thick within the middle third of the formation. This dolostone contains fine quartz grains throughout, as well as sparse siliceous stringers. The structural complexity and apparent lenticular nature of a few well-exposed dolostone beds precludes correlation of individual dolostone beds across fault zones or between outcrop areas. Above the carbonate-cemented sandstone interval is a cliff-forming quartzite. Sandstones are plane-bedded to cross-bedded, with planar cross beds up to 20 cm thick. The upper part of the quartzite contains lenses of dolostone as well, but these are less continuous laterally than those in the middle part. Throughout the map area, the contact separating the Concha Limestone from the Scherrer Formation is broken and irregular in detail, and truncates bedding both above and below, with possibly as much as tens of meters of section excised locally.

Pco **Colina Limestone** (Permian)—Massive to thick-bedded (10-100 cm), medium gray limestone, packstone to grainstone with little or no chert. Lack of chert, the sparseness of fossils, and the more massive character distinguish this unit from the Concha Limestone. Thin sandstone beds are present in the upper 10 m of the Colina Limestone. The contact with Scherrer Formation is generally an abrupt break in slope above the uppermost limestone bed. The contact with underlying Earp Formation is placed at the top of the stratigraphically highest sandstone bed in the interbedded sandstone-limestone transition between the Earp and Colina.

Pe **Earp Formation** (Permian to Pennsylvanian)— Consists of approximately 270 m of limestone, dolostone, variably calcareous siltstone, and sandstone. Rock types are interbedded on scale of 1-10 meters, and include: (1) gray limestone, (2) red to reddish brown, very fine grained, thin to thick bedded, quartzose sandstone to siltstone that is locally calcareous, (3) tannish gray, grainstone to packstone dolostone with sparse siliceous stringers, (4) orangish tan weathering silty dolostone with brown siliceous stringers and thin beds, (5) pale gray, microcrystalline limestone with sparse, 2-10 cm thick, siliceous stringers. The basal part of the unit as we have mapped it includes several laterally extensive conglomerate lenses. McClymonds [1959] placed the Earp (his Andrada Formation)-Horquilla contact at the base of the stratigraphically lowest red shale bed, but states that the contact is never exposed. He described two conglomerate beds 56 and 60 m above this red shale that are almost certainly the conglomeratic zone we have chosen to use as the mappable contact. This contact is a much better mappable boundary because the conglomeratic beds are resistant and crop out well, and because the whitish, marly carbonate interbedded with shale in the zone between the first red shale and the conglomeratic interval are much more prominent in float than the reddish shale.

The Earp Formation was deposited on a shallow marine platform that was undergoing accelerated subsidence at the northwestern margin of the Pedragosa Basin, which is centered southeast of southeastern Arizona in northwestern Chihuahua. The conglomerate beds in the lower part of the Earp Formation in the Waterman Mountains have been correlated with a distinctive conglomerate unit in the Earp Formation elsewhere in southeastern Arizona and southwestern New Mexico [Rea and Bryant, 1968; Armin, 1985, 1987]. This conglomerate unit commonly contains red chert pebbles and is sometimes referred to as the “jelly bean conglomerate.” Rea and Bryant (1968) and Armin [1985, 1987] interpreted the conglomerate and related clastic rocks as braided stream deposits based on various characteristics, including the following (from Armin [1987]): (1) Unimodal imbrication of conglomerate clasts indicating consistent stream flow. (2) Planar cross-bedded conglomerates and locally interbedded sandstones that were interpreted as products of deposition in gravel bars in braided streams. (3) Crude horizontal stratification of conglomerate beds that was interpreted as the likely product of deposition as diffuse gravel-sheet bedloads in low-relief, longitudinal bars in braided streams during periods of high sediment and water discharge. (4) Planar-laminated sandstones that were interpreted as products of upper planar flow conditions in shallow streams, and where interbedded with conglomerates were interpreted as deposits on bar surfaces in upper flow-regime conditions during water-level lowering. Clast imbrication and planar and trough cross beds yield dominantly north-northeastward paloeflow directions for the Waterman Mountains and southerly (but highly variable) directions at most other locations in southeastern Arizona [Armin, 1987].

Armin [1987] interpreted the conglomerate beds in the lower Earp formation as the result of a period of marine regression, subaerial exposure, and reworking by braided streams. This occurred synchronously with a period of deep subsidence in the southeastern Pedragosa Basin in northern Chihuahua that has been interpreted as part of the tectonically loaded foreland of the Allegheny-Ouachita-Marathon thrust belt that extended from the northern Appalachians to northern Mexico [Dickinson, 1981; Pindell, 1985]. The brief, minor, and aerially extensive uplift that caused subaerial exposure and fluvial reworking of the Earp Formation, and deposition of the conglomerates in the lower Earp, was interpreted by Armin [1987] as the result uplift above a flexural forebulge in front of advancing Marathon thrust sheets in central Chihuahua.

Ph **Horquilla Limestone** (Pennsylvanian) — Lower part is thick bedded to massive, light gray bioclastic grainstone and packstone. Up section, very light gray marl, and very-fine grained sandstone are interbedded with medium-bedded limestone. Above the lowermost massive limestone beds, carbonates in the Horquilla tend to be more micritic than carbonate in the Escabrosa, with porcelaneous, light gray weathering surfaces. Nodular carbonate beds are also distinctive of the Horquilla. These consist of irregular globby carbonate nodules 2-15 cm in diameter, immersed in more clay and silt-rich carbonate that is less resistant to weathering. Marly beds in the upper part of the Horquilla weather to produce a distinctive white soil. Sparse red-brown mudstone in the upper part of the formation (as we have mapped it, see discussion of Earp Formation, above) are exposed only in road cuts.

A regional disconformity separates the Pennsylvanian Horquilla Limestone from the underlying Mississippian Escabrosa Limestone, but the massive limestone of the lower Horquilla is lithologically identical to limestone in the upper Escabrosa. The contact between these can only be mapped with confidence when the karst horizon formed by weathering before deposition of the Horquilla can be observed. This horizon consists of red siltstone or fine-grained sandstone, commonly with chert-pebble conglomerate, and local limestone breccia. The breccia consists of subrounded, 1-10 cm, pale gray limestone clasts within a tan to brown, silty carbonate matrix. The breccia is interpreted as the product of subaerial weathering and dissolution of the top of the Escabrosa Limestone before deposition of the overlying Horquilla Limestone. Maroon mudstone may be present filling cavities in Escabrosa Limestone for several meters beneath the contact. Where this distinctive karstic horizon was not observed, the contact has been placed where distinct marl/mudstone partings between thick limestone beds produce ledgy outcrops of Horquilla Limestone that contrast with the cliff-forming Escabrosa. The upper contact with Earp Formation is placed at the base of the conglomeratic interval used here as the marker to separate the two formations. Where the conglomeratic interval is absent, the contact is placed where light-tan, fine-grained sandstone becomes the predominant lithology, and the white marly interbeds of the upper Horquilla disappear.

Me **Escabrosa Limestone** (Mississippian) — Escabrosa Limestone is massive, faintly laminated, medium- to light-gray limestone, locally with abundant crinoid fragments. The unit typically forms a cliff. In some areas where the karst zone at the top of the Escabrosa is well exposed, crinoid grainstone at the top of the Escabrosa Limestone has had its calcite cement removed, allowing 1 cm-diameter crinoid columnals to weather out.

Dm **Martin Formation** (Late Devonian to Middle Devonian) — Medium-bedded tan to gray dolostone, with sparse interbedded sandstone. The Martin Formation is distinguished from Escabrosa Limestone because it is more distinctly bedded, is dolomitic, and is more variable in color. Martin

Formation is commonly recrystallized to a pinkish or lavender dolomitic marble in the vicinity of the contact with the Escabrosa. The contact with underlying Abrigo Formation is placed at the top of the last shale/marl bed.

Ꞓa **Abrigo Formation** (Middle Cambrian) **--** The Abrigo Formation in the Waterman Mountains consists of a lower sandstone and mudstone unit, a middle mottled carbonate unit, and an upper sandstone, marl, and limestone unit. The lower Abrigo Formation is a dark, slope forming unit consisting of thinly interbedded shale and quartzite. Various sorts of worm-burrow type trace fossils are common in bedding surfaces in the shale. The middle limestone consists of thick-bedded gray limestone with abundant, cm-scale, gray or tan silty/clay rich globs along the bedding planes, which give the beds a distinctive mottled appearance. Thin beds of intraformational conglomerate are present in this limestone unit. These consist of elongate chips of limestone, identical to the hosting limestone unit, in a silty limestone matrix. These beds probably represent deposits formed by large storms that produced turbulent flow strong enough to break up and re-deposit partially indurated sediment. The middle limestone unit is lithologically identical to Muav Limestone in the Grand Canyon. The upper unit consists of tan marly shale, with very thin interbedded limestone or sandstone beds. It generally forms a slope between the cliff-forming middle limestone of the Abrigo and the overlying Martin Formation. According to Hayes and Cone [1975], the entire Abrigo Formation in the Waterman Mountains correlates with the lower member of the Abrigo Formation defined in mountain ranges to the east.

Ꞓb **Bolsa Quartzite** (Cambrian) — Gray to dark brown quartzite and feldspathic quartzite. Basal part is very coarse-grained, with scattered 1-5 cm diameter white, bull-quartz pebbles or cobbles. Unit fines up section to fine-grained quartzite with mudstone partings and thin interbeds. Bedding in lower part is thick to massive, and bedding generally thins up section to thin bedded. Contact with overlying Abrigo Formation is gradational, and is placed where shale becomes the predominant lithology.

Middle Proterozoic Igneous Rocks

Yd **Sierra Ancha Diabase** (Middle Proterozoic) **--** Dark gray, dark greenish gray, and grayish black sills and dikes with typical sub-ophitic, diabasic texture.

Yg **Porphyritic biotite granite** (Middle Proterozoic) — Medium grained, non-foliated granite with gray to pale pinkish gray to red K-feldspar phenocrysts up to 3 cm, in some areas with included biotite(?). Pegmatites and quartz veins are generally absent, which is characteristic of many 1.4 Ga granites elsewhere in Arizona. This granite is probably correlative with the Oracle Granite [Peterson, 1938], based on lithology and its location on strike with the southwestern continuation of large 1.4 Ga batholith that includes the Oracle granite. Six radiometric age determinations considered likely to represent the approximate age of the granite by Reynolds et al. [1986] range from 1380 to 1430 Ma.

REFERENCES CITED

Armin, R.A., 1985, Red chert-clast conglomerate in the Earp Formation (Pennsylvanian-Permian), southeastern Arizona: Stratigraphy, sedimentology, and tectonic significance: Tucson, University of Arizona, Ph.D. dissertation, 338 p.

Armin, R.A., 1987, Sedimentology and tectonic significance of Wolfcampian (lower Permian) conglomerates in the Pedregosa Basin: Southeastern Arizona, southwestern New Mexico, and northern Mexico: Geological Society of America Bulletin, v. 99, no. 1, p. 42-65.

Beikman, H.M., Haxel, G.B., and Miller, R.J., 1995, Geologic map of the Tohono O'Odham Indian Reservation, southern Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I-2017, 2 sheets, scale 1:125,000.

Bikerman, Michael, 1962, Geologic-geochemical study of the Cat Mountain Rhyolite: Tucson, University of Arizona, M. S. thesis, 43 pp.

Bikerman, Michael, 1965, Geological and geochemical studies of the Roskruge Range, Pima County, Arizona: Tucson, University of Arizona, Ph.D. dissertation, 112 pp.

Bikerman, Michael, 1967, Isotopic studies in the Roskruge Mountains, Pima County, Arizona: Geological Society of America Bulletin, v. 78, no. 8, p. 1029-1036.

Birkeland, P.W., 199p, Soils and Geomorphology, New York: Oxford University Press, 428 p.

Breckenfeld, D.J., 1999, Soil Survey of Tohono O'Odham Nation, Arizona, Parts of Maricopa, Pima, and Pinal Counties, USDA, Natural Resource Conservation Service, 350 p., 91 sheets, scale 1:24,000 p.

Bryant, D.L., and McClymonds, N.E., 1961, Permian Concha Limestone and Rainvalley Formation, southeastern Arizona: American Association of Petroleum Geologists Bulletin, v. 45, no. 8, p. 1324-1333.

Bull, W.B., 1991, Geomorphic Response to Climatic Change, New York: Oxford University Press, 326 p.

Dickinson, W.R., 1981, Plate tectonic evolution of the southern Cordillera, in Dickinson, W.R., and Payne, W.D., eds., Relations of tectonics to ore deposits in the southern Cordillera: Arizona Geological Society Digest, v. 14, p. 113-135.

Dickinson, W.R., 1991, Tectonic setting of faulted Tertiary strata associated with the Catalina core complex in southern Arizona: Geological Society of America, Special Paper 264, 106 p.

Eastwood, R. L., 1970 A geochemical-petrological study of mid-Tertiary volcanism in parts of Pima and Pinal Counties, Arizona: Tucson, University of Arizona, unpublished Ph.D. dissertation, 212 pp.

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

Gardulski, A.F., 1990, A structural and petrologic analysis of a quartzite – pegmatite tectonite, Coyote Mountains, southern Arizona: Tucson, University of Arizona, M.S. thesis, 69 p.

Gile, L.H., Hawley, J.W., and Grossman, R.B., 1981, Soils and geomorphology in the basin and range area of southern New Mexico -- guidebook to the Desert Project: New Mexico Bureau of Mines and Mineral Resources Memoir 39, 222 p.

Hagstrum, J. T., and Sawyer, D. A., 1989. Late Cretaceous Paleomagnetism and clockwise rotation of the Silver Bell Mountains, South Central Arizona: Journal of Geophysical Research, v. 94, p. 17,847-17,860.

Hagstrum, J.T., Lipman, P.W., and Sawyer, D.A., 1994, Paleomagnetism, stratigraphy, and petrology of the upper Cretaceous Roskruge Volcanics at Bell Mountain, southeast Arizona: Journal of Geophysical Research, v. 99, no. B8, p. 15,097-15,102.

Hall, D.L., 1985, Stratigraphy and sedimentary petrology of the Mesozoic rocks of the Waterman Mountains, Pima County, Arizona: Tucson, University of Arizona, M.S. Thesis, 92 p., 1 sheet, scale 1:12,000.

Hayes, P.T., 1978, Cambrian and Ordovician rocks of southeastern Arizona and southwestern New Mexico, in Callender, J.F., Wilt, J.C., Clemons, R.E., and James, H.L., eds., Land of Cochise, southeastern Arizona: New Mexico Geological Society 29th Field Conference Guidebook, p. 165-173.

Hayes, P.T., and Cone, G.C., 1975, Cambrian and Ordovician rocks of southern Arizona and New Mexico and westernmost Texas: U.S. Geological Survey Professional Paper 873, 98 p., 1 sheet.

Heindl, L.A., 1960, Cenozoic geology of the Papago Indian Reservation, Pima, Maricopa, and Pinal Counties, Arizona (a preliminary summary): Arizona Geological Society Digest, v. 3, p. 31-34.

Heindl, L.A., 1965, Mesozoic formations in the Comobabi and Roskruge Mountains, Papago Indian Reservation, Arizona, Chapter H, in Contributions to stratigraphy: U.S. Geological Survey Bulletin 1194-H, p. H1-H15.

Heindl, L.A., and McClymonds, N.E., 1964, Younger Precambrian formations and the Bolsa(?) Quartzite of Cambrian age, Papago Indian Reservation, Arizona, in Geological Survey Research 1964, Chapter C: U.S. Geological Survey Professional Paper 501-C, p. C43-C49.

Le Bas, M. J., Le Maitre, R. W., Streckeisen, A., and Zanettin, B., 1986, A chemical classification of volcanic rocks based on the total alkali-silica diagram: Journal of Petrology, v. 27, p. 745-750.

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

Machette, M.N., 1985, Calcic soils of the southwestern United States: in Weide, D.L., ed., Soils and Quaternary Geology of the Southwestern United States: Geological Society of America Special Paper 203, p. 1-21.

McClymonds, N.E., 1957, Stratigraphy and structure of the Waterman Mountains, Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 157 p.

McClymonds, N.E., 1959a, Paleozoic stratigraphy of the Waterman Mountains, Pima County, Arizona, in Heindl, L.A., ed., Southern Arizona Guidebook II, combined with the 2nd annual Arizona Geological Society Digest: Arizona Geological Society, p. 66-76.

McClymonds, N.E., 1959b, Precambrian and Paleozoic sedimentary rocks on the Papago Indian Reservation, Arizona, in Heindl, L.A., ed., Southern Arizona Guidebook II, combined with the 2nd annual Arizona Geological Society Digest: Arizona Geological Society, p. 77-84.

McClymonds, N.E., and Heindl, L.A., 1965, Stratigraphic sections of younger Precambrian and Paleozoic formations, Papago Indian Reservation, Arizona: U.S. Geological Survey Open-File Report, 101 p., 5 sheets, scale 1:62,500.

McClymonds, N.E., Page, H.G., and Haynes, C.W., 1959, Stratigraphy of the Waterman and Silver Bell Mountains; Trip II, road log, in Heindl, L.A., ed., Southern Arizona Guidebook II, combined with the 2nd annual Arizona Geological Society Digest: Arizona Geological Society, p. 212-217.

Patchet, P.J., and Ruiz, J., 1987, Nd isotopic ages of crust formation and metamorphism in the Precambrian of eastern and southern Mexico: Contributions to Mineralogy and Petrology, v. 96, 523-528.

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

Pindell, J.L., 1985, Alleghenian reconstruction and subsequent evolution of the Gulf of Mexico, Bahamas, and proto-Caribbean: Tectonics, v. 4, p. 1-40.

Purves, W.J., 1978, Paleoenvironmental evaluation of Mississippian age carbonate rocks in central and southeastern Arizona: Tucson, University of Arizona, Ph.D. dissertation, 672 p., 6 sheets, scale

Rea, D.K., and Bryant, D.L., 1968, Permian red chert-pebble conglomerate in Earp Formation, southeastern Arizona: American Association of Petroleum Geologists Bulletin, v. 57, p. 809-819.

Reynolds, S. J., Florence, F.P., Welty, J.W., Roddy, M.S., Currier, D.A., Anderson, A.V., and Keith, S.B., 1986, Compilation of Radiometric Age Determinations in Arizona, Arizona Geological Survey Bulletin 197, 258 p., 2 sheets, scale 1:1,000,000.

Riggs, N. R. and Richard, S. M. 1994, Timing of post-Permian uplift in S. and W. Arizona: Geological Society of America, Abstracts with Program, v. 26, no. 2, p. 84.

Ross, C.A., 1973, Pennsylvanian and Early Permian depositional history southeastern Arizona: American Association of Petroleum Geologists Bulletin, v. 57, no. 5, p. 887-912.

Ross, C.A., 1978, Pennsylvanian and Early Permian depositional framework, southeastern Arizona, in Callender, J.F., Wilt, J.C., Clemons, R.E., and James, H.L., eds., Land of Cochise, southeastern Arizona: New Mexico Geological Society 29th Field Conference Guidebook, p. 193-200.

Ruff, A.W., 1951, Geology and ore deposits of the Indiana mine area, Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 64 p.

Sawyer, D. A., 1996, Geologic map of the Silver Bell and West Silver Bell Mountains, southern Arizona: United States Geological Survey Open-file Report 96-006, 21 pp., 1 sheet, 1:48,000 scale.

Schumacher, Dietmar, 1978, Devonian stratigraphy and correlations in southeastern Arizona, in Callender, J.F., Wilt, J.C., Clemons, R.E., and James, H.L., eds., Land of Cochise, southeastern Arizona: New Mexico Geological Society 29th Field Conference Guidebook, p. 175-181.

Schumacher, Dietmar, Witter, D.P., Meader, S.J., and Keith, S.B., 1976, Late Devonian tectonism in southeastern Arizona, in Wilt, J.C., and Jenney, J.P., eds., Tectonic digest: Arizona Geological Society Digest, v. 10, p. 59-70.

Skotnicki, S. J., and Pearthree, P. A., 2000, Geologic map of the Cocoraque Butte 7.5' quadrangle, Pima County, Arizona: Arizona Geological Survey Open-file Report 00-08, scale 1:24,000, 28 pp.

Vugteveen, R.W., Barnes, A.E., and Butler, R.F., 1981, Paleomagnetism of the Roskruge and Gringo Gulch Volcanics, southeast Arizona: Journal of Geophysical Research, v. 86, no. B5, p. 4021-4028.

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].