BEDROCK GEOLOGY OF THE EASTERN AND CENTRAL TANK MOUNTAINS, YUMA COUNTY, ARIZONA

by
Charles A. Ferguson, Steven J. Skotnicki,
and Jon E. Spencer

Arizona Geological Survey
Open-file Report 94-8

June, 1994

Arizona Geological Survey
416 W. Congress, Suite #100,
Tucson, Arizona 85701

Includes 1:24,000 scale geologic map, cross-sections,
16 page report, and 8 figures

Jointly funded by the Arizona Geological Survey
and the U.S. Geological Survey STATEMAP Program.
Contract #1434-93-A-1144

This report is preliminary and has not been edited or reviewed for conformity with Arizona Geological Survey standards

INTRODUCTION

Physiography

The Tank Mountains of southwestern Arizona are a west-northwest trending range which represent an approximately 30 km-long extension of a southeastern arm of the Kofa Mountains. On all other sides, the Tank Mountains are surrounded by gently southeast-sloping Quaternary peidmonts of the Gila River drainage basin; Palomas Plain on the north, east, and south and King Valley on the southwest. Elevations in the Tank Mountains are between 2,200′ and 900′, and in general elevation decreases to the southeast.

The Tank Mountains lie within the Sonoran biozone, and although there are no active springs, washes within the range that cut into bedrock are renowned for deep potholes or "tanks" which hold water for long periods of time. The mountain range derives its name from these features, the most prominent of which is White Tanks in the north-central part of the range. Originally, the western Tank Mountains were known as the Frenchman Mountains, and the southeastern part of the range were called the Puzzles Mountains (Wilson, 1933).

There are only five formally recognized place names in the map area according to the 7.5′ USGS quadrangles (Palomas Mts. NW, NE, SW, SE). Two other informal place names are used in this report and they are identified on Figure 1. The informal name Malley mesa is derived from a triangulation station at the crest of the prominent mesa at the northeast terminus of the Tank Mountains. Dummy gulch is a major southeast flowing wash in the eastern Tank Mountains named by local inhabitants for a dog named "Dummy" who was lost there chasing deer during a family outing. Apparently the dog's name was given before this episode.

Most of the western Tank Mountains, including the White Tanks area, lies within the east arm of the Yuma Proving Ground, and access is restricted. The Proving Ground boundary is not delineated by a fence, and warning signs are sparse. Access to the eastern Tank Mountains is provided by two primitive road systems which can be reached from a paved county road connecting the towns of Hyder and Dateland. These primitive roads, known to the locals as the "low road" and the "high road", can usually be negotiated with high-clearance two-wheel-drive vehicles well into the Tank Mountains, but local inquiry into their condition is recommended. The "low road" turns north from pavement near White Wing Ranch and follows Hoodoo Wash around the eastern termination of the Palomas Mountains, before it turns west and splits into a number of tracks that follow south-flowing washes draining the southeastern Tank Mountains. The "high road" runs north from pavement just east of White Wing Ranch about 15 miles before it turns west and splits into a number of tracks that can be followed southward from Palomas Plain into the Tank Mountains. The only connecting route between the "high road" and "low road" networks is at White Tanks on the Yuma Proving Ground, and this road is barely passable to even the most rugged 4-wheel drive vehicle.

Previous investigations

Previous geologic studies of the Tank Mountains are limited to the reconnaissance study of Wilson (1933) whose map was incorporated into the regional geologic maps of Wilson and others (1969) and Reynolds (1988). There are no detailed published accounts of the area's stratigraphy, geochronology, or economic potential, even though the southeastern end of the range was prospected as early as the 1860s (Kieth, 1978). To the west across King Valley, the Castle Dome Mountains have been mapped by Grubensky and others (1993). To the northwest, the western Tank Mountains have been mapped by

Grubensky and others (in press), and the Little Horn Mountains which lie approximately 25 km to the north, across Palomas Plain, were mapped by Grubensky and Demsey (1991). The Palomas Mountains, which lie about 8 km to the south, across an unnamed western arm of the Palomas Plain, were mapped concurrently by Skotnicki and Ferguson (1994).

Geologic setting and summary of principal observations

The Tank Mountains lie along the eastern edge of a prominent negative Bouger gravity anomaly (Lysonski and others, 1980) that Grubensky and Bagby (1990) interpreted as evidence for a synvolcanic plutonic complex associated with Miocene silicic calderas of the southern Kofa Mountains, King Valley and northeastern Castle Dome Mountains. The crust which underlies the Miocene volcanic rocks of the Tank Mountains probably consists largely of early Proterozoic plutonic and high-grade metamorphic rocks. This area, along with most of southwestern Arizona was apparently stripped of its Paleozoic and possibly Middle and Upper Proterozoic sedimentary cover during Mesozoic uplift (Spencer and Reynolds, 1989).

The study area is within the Basin and Range physiographic and tectonic province, much of which underwent severe Tertiary extension and magmatism (Spencer and Reynolds, 1989), but the study area itself is within a region of weak extension.

Bedrock geology of the Tank Mountains is dominated by Mid-Tertiary, probably Miocene, volcanic rocks that range in composition from basalt to rhyolite. Most of the volcanics are lavas, and based on their phenocryst assemblages, they appear to represent a fairly continuous calc-alkaline series. The volcanics conformably overlie basement rocks of two types; probable Proterozoic high-grade metamorphic rocks and Proterozoic or Mesozoic plutonic rocks, intruded by a quartz monzonite of probable Mid-Tertiary age at the southeastern terminus of the range, and a sequence of low-grade metavolcanic and metasedimentary rocks of probable Mesozoic age along the western edge of the study area.

The map pattern of volcanic rocks in the Tank Mountains probably reflect, to a large degree, the original limits of lava flows. Sedimentary units are virtually absent, and those thick enough to be represented as map units are typically preserved in depressions formed along the steep fronts of silicic lava flows. The upper autobrecciated carapace of the silicic lavas are typically preserved, and evidence of erosion during the hiatus between lava flows is rare.

Intervals between lava flows are occupied, for the most part, by unwelded, medium- and thin-bedded, low-angle cross-stratified tuffs that are likely surge units related to the eruptions of nearby silicic lavas. Also, monolithic, clast-supported breccias interpreted as avalanche deposits are interleaved with a thick sequence of bedded tuff in the central part of the range. There are only two occurrences of ash-flow tuff that may correlate to outflow sheets of far-travelled ignimbrites; a 30 meter-thick welded tuff near White Tanks, and a 30 to 50 meter-thick poorly welded tuff at Malley mesa at the east end of the range. Outflow facies tuff of Ten Ewe Mountain, a regional ash-flow tuff derived from a caldera in the southwestern Kofa Mountains, occurs along the western edge of the map area, but unfortunately it is not interleaved with volcanic units that can be reliably traced into the Tank Mountains.

Volcanic units of the Tank Mountains are slightly to moderately tilted, and only a narrow band of these rocks along the crest of the range shows evidence of significant crustal extension. Structures in this band accommodate about 0.5 km of extension, and the band corresponds to a northwest-striking anticlinal tilt-domain boundary. No major

detachment faults have been identified, and the disconformity at the base of the volcanic sequence is everywhere believed to be a depositional contact.

Tilt patterns of the Tertiary rocks in the Tank Mountains also define two gentle synclines which flank the prominent crest-forming anticline. Faulting and presumably tilting that produced these northwest-striking "folds" probably occurred soon after the cessation of volcanism. In the northeastern part of the range some north-side-down faulting can be constrained, because there are degraded fault scarps buried by the youngest volcanic unit, to have occurred during the later stages of volcanism. No evidence of neotectonic activity, in the form of young fault scarps or tilted alluvial deposits was in the vicinity of the Tank Mountains.

Acknowledgements

Research was funded jointly by the Arizona Geological Survey and the United States Geological Survey STATEMAP program contract 1434-93-A-1144. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Permission for geologic mapping on Yuma Proving Ground was expedited by Soheir Ibrahim and Lance Moulinet of the Environmental Safety Office, and their assistance with logistical support is greatly appreciated. George Fischbach is thanked for assisting us with the study of air photographs at the Proving Ground. Special thanks are also extended to Jim Bunte for his help with the radios and all of the people at Kofa Range Control and at the security desk of Yuma Proving Ground for expediting our access requests.

We would also like to thank Tom McGarvin for his assistance with field vehicles, Rick Trapp for setting up our computer system, and Pete Corrao for assistance with drafting problems. Steve Richard, Michael Grubensky, and Phil Pearthree are also thanked for geologic discussions.

Methods of investigation

The western Tank Mountains where mapped during the winter field season of 1993-94, primarily using four 1:24,000 scale, USGS 7.5′ quadrangle base maps: Palomas Mts. NW, SW, SE, and NE (Figure 2). In some topographically indistinct areas, air photographs were used for mapping. Numerous samples were collected during the field season, but this report was prepared without the benefit of micropetrographic, geochemical, or geochronological information derived from these or any other samples from the study area. The samples are stored at the Arizona Geological Survey.

STRATIGRAPHIC FRAMEWORK

Introduction

Geologic units of the study area can be divided into three sequences: 1) partially consolidated to unconsolidated sediments of probable Late Tertiary and Quaternary age, 2) Miocene volcanics, and 3) pre-Tertiary basement rocks which can be further divided into two distinct packages, one in the southeastern corner of the range and the other exposed along the western edge of the study area.

Pre-Tertiary units

Southeastern basement sequence

In the southeastern corner of the Tank Mountains, felsic plutonic and amphibolite facies metamorphic rocks are exposed below a gently north-dipping disconformity. Locally, coarse, angular, sedimentary breccias mantle the contact (map unit Txs). The oldest of the basement rocks in this area is a banded quartzofeldspathic gneiss, most of which was mapped as orthogneiss based on the dominance of leucosome. Lesser amounts of melanosome-rich, banded paragneiss, and rarer schists were also recognized. The paragneiss is locally migmatitic with ptygmatically folded melanocratic segregations. Bull quartz veins are present but not common.

The gneisses are tentatively assigned a Proterozoic age because structural elements have the northerly trend typical of Proterozoic basement rocks elsewhere in Arizona (eg. Anderson, 1987).

Both types of gneisses are intruded by a suite of variably foliated biotite-rich granitoids ranging in composition from syenogranite to diorite. Generally, the granitoids are medium-grained and equigranular along contacts with the gneisses, and toward the core of the bodies, they are commonly K-feldspar porphyritic or megacrystic. The more foliated versions of the porphyritic granites display classic augen textures.

The foliated granitoids are intruded, apparently from below, by a fine-grained to medium-grained quartz monzonite stock which grades into a cogenetic suite of magmatically layered, hornblende-rich, diorites, monzodiorites, and hornblende gabbros. Contacts with older rocks are well exposed in a number of places, always with the older granitoids overlying the quartz monzonite. This younger plutonic suite is tentatively assigned a Miocene age, because the rocks do not exhibit tectonic fabrics, and because, except for the layered amphibolites, they are petrographically identical to phases of a quartz monzonite pluton exposed in the southern Palomas Mountains (Skotnicki, and Ferguson, 1994), that has been dated at 23.2 $\pm$ 0.5 Ma (Bagby and others, 1987).

Western basement sequence

Along the western edge of the study area, two occurrences of pre-Tertiary basement rock are exposed. There are also two other isolated exposures of these rocks along the northern flank of the range. The contact with overlying volcanic rocks is clearly a southwest-dipping disconformity at the northern occurrence, and it also appears to be a southwest-dipping disconformity at the southern occurrence, although these relationships are poorly exposed. These basement rocks consist of three lithologies; a greenish, porphyritic volcanic and hybabyssal suite of intermediate composition, younger metasedimentary rocks, and a suite of granitoids which locally intrude the metasedimentary rocks.

The oldest rock at both localities is a green, chloritic, crystal-rich, densely welded and massive, but locally thin- to medium bedded, rhyodacite tuff. This metavolcanic sequence may correlate with a granite porphyry unit mapped by Grubensky (in press) in the western Tank Mountains and Neversweat Ridge area immediately to the west of the study area. The rhyodacite porphyry of this study is interpreted as an ash-flow tuff because it contains fairly large and conspicuous, dark green (chloritic?) compacted fragments interpreted as fiamme (Figure 3), and because its phenocrysts are typically broken and unevenly distributed within the matrix, which is suggestive of pyroclastic processes. The rhyodacite ash-flow tuff appears to be intruded locally by a compositionally similar porphyry that is interpreted as intrusive because it does not contain green, fiamme-like fragments, and its

phenocrysts are evenly distributed and unbroken. These intrusive bodies are also found within the younger metasedimentary rocks. Both the intrusive and volcanic porphyries contain between 30% and 60% phenocrysts, mostly of feldspar with lesser amounts of embayed quartz grains up to 5mm. Mafic phenocrysts are probably also present, but they are not recognizable in hand specimen due to the greenschist facies metamorphism.

The rhyodacite porphyritic rock is overlain and locally interbedded with a metasedimentary sequence of purple and rarer green argillites which host lesser amounts of two other lithologies. 1) quartz-pebble conglomerates and cross-bedded to planar laminated quartzites which occur together or separately in 1 to 20 meter-thick fining upward sequences, and 2) thin, discontinuous beds of dark brown, bioturbated, fossiliferous limestone. The limestones contain abundant skeletal fragments (echinoids?) and one sample has been processed for conodonts. A southwesterly stratigraphic facing direction for the metasedimentary sequence is based on rare cross-beds within quartzites at both localities. Sedimentologically, the conglomeratic intervals are interpreted as alluvial channel-fills, shore-face deposits, or marine gravel lag sequences, and the quartzites are interpreted as either alluvial (trough cross-bedded) or marginal marine, shore-face (parallel-laminated) sequences. A marine to marginal marine depositional environment for the entire sequence is implied by the presence of marine fossils in the brown limestone beds. In addition, a burrowed white marble sequence occurs at the base of the metasedimentary sequence at the southern locality, and these burrows strongly resemble the marine ichnofossil *Thalassinoides* (Figure 4).

A thin, white, crystal-poor rhyolite (ash-flow tuff?) is present at the base of the metasedimentary sequence at the northern locality. Below this tuff, the upper 50 meters of the rhyodacite tuff unit is arranged in a medium-bedded, fallout-like sequence which may be subaqueous. This bedded unit is separated from the underlying massive, welded, fiamme-bearing tuff by a 2 to 3 meter-thick, argillaceous matrix-supported olistostrome with cobble to boulder-sized angular blocks of bedded tuff (Figure 5).

Metasedimentary rocks at the southern locality are intruded by medium-grained, equigranular to K-feldspar porphyritic, felsic granitoids. Small isolated diorite bodies are also present. At the northern locality, a southwest-dipping fault overlain by a fault breccia composed of granite is interpreted as a Pre-Tertiary thrust because it appears to be intruded by an elongate stock of diorite.

The basement rocks in the western study area closely resembles the descriptions of other Pre-Tertiary "basement" rocks of southwest Arizona (e.g. Harding and Coney, 1985; Tosdal and Stone, 1994). The Jurassic to Cretaceous McCoy Mountains Formation which consists of slate, quartzite, and quartz-pebble conglomerate (Harding and Coney, 1985), and which locally overlies and is interbedded with a rhyodacitic porphyry and/or ash-flow tuff (Tosdal and Stone, 1994) is one likely candidate for correlation. Two other possible correlative units have been described from areas to the west. These are the Winterhaven Formation in southeastern California (Haxel and others, 1985) and the unit of Slumgullion (Haxel and others, 1985; Grubensky and others, 1993).

Mid-Tertiary units

The Mid-Tertiary stratigraphic sequence of the Tank Mountains consists mostly of lavas interleaved with unwelded bedded-tuffs. Only three massive, welded to partially welded ash-flow tuffs, which have the potential for regional correlation, were recognized. There are three principal types of lava; crystal-rich dacite, crystal-poor to aphyric rhyolite, and mafic flows. Generally, the felsic and intermediate lavas occur near the base of the

sequence, and the mafic lavas lava are younger.

This section is divided into seven subsections. The first six describe the 6 principal volcanic lithologies that occur in the study area, and section 6 discusses their areal distribution and correlation.

Bedded tuffs

Many of the lava flows in the Tank Mountains are separated by sequences of unwelded, lithic-rich, bedded tuff that have been, for the most part, mapped generically as Tt. Two exceptions are the Ttb and Tts map units which are separated because they include other distinctive lithologies such as welded tuff or eolian sandstone. The bedded tuffs are mostly medium-bedded and thin-bedded and most commonly low-angle cross-stratified. In some areas, volcaniclastic sandstones make up part of these sequences. The volcaniclastic sandstones are typically medium-grained and medium-angle to high-angle cross-stratified, suggesting an eolian origin.

Because most of the bedded tuffs display low-angle undulose cross-stratification, they are interpreted as surge deposits, and because the volcanic pile is dominated by felsic to intermediate lava flows, the surges are most likely related to the collapse of nearby lava domes. Parallel, thin-bedded and medium-bedded tuffs are also present which probably represent ash-fall sequences, and rare, massive, thick-bedded tuffs probably represent true ash-flow tuffs.

Ash-flow tuffs

Three ash-flow tuffs that can be traced over distances of more than a few hundred meters are present in the Tank Mountains, but unfortunately they do not overlap. The most distinctive of these is the tuff of Ten Ewe Mountain, an orange-colored, densely welded, feldspar and biotite-bearing, 5-15% phenocrysts, rhyolitic ash-flow tuff. The tuff of Ten Ewe Mountain is a regional outflow sheet derived from a caldera in the western Kofa Mountains approximately 30 km to the northwest (Grubensky and Bagby, 1990; Grubensky and others, in press). The tuff of Ten Ewe Mountain, in the Tank Mountains and the Palomas Mountains to the south, contains distinctive spherulitic, devitrified pumice fragments and typically contains between 5 and 10% lithic fragments. No vertical zonation was recognized in the 30 to 50 meter-thick section of the tuff exposed in the study area.

Exposures of the tuff of Ten Ewe Mountain in this study area are contiguous with a tuff on the map sheet to the west (Grubensky and others, in press) that is labeled tuff of Hoodoo Well. This is unquestionably an error because the tuff of Hoodoo Well is a very distinctive, crystal-poor, pumice-poor rhyolite ash-flow tuff characterized by large embayed quartz phenocrysts, and the lack of mafic phenocrysts. The tuff we examined here (west edge of sec. 6, T4S, R 14W) contains very abundant biotite, little or no quartz, and is pumice-rich.

The tuff of White Tanks (new name) is a densely welded, light-gray colored, crystal-poor, pumice-poor, rhyolitic ash-flow tuff with between 5 and 10% phenocrysts of feldspar. It occurs over a 10 to 15 km^2 area centered on White Tanks in the north-central part of the study area. The tuff of White Tanks ranges in thickness from less than 1 meter to 40 meters. Locally, its poorly welded upper portion contains concentrically laminated, spherical concretions which may be accretionary lapilli. A measured section of this tuff and a suite of samples were collected at an exposure about 100 meters west of White Tanks, from which is derived its informal name.

Correlation of the tuff of White Tanks with any previously recognized regional ash-flow tuff in the Kofa Mountains-Castle Dome Mountains area is problematic because its phenocryst assemblage does not, even remotely, match the mineralogical descriptions of any of these units (Grubensky and Demsy, 1991; Grubensky and others, in press; Ferguson and Skotnicki, current investigations). All of the regional ash-flow tuffs that do not contain quartz, like the tuff of White Tanks, contain fairly abundant mafic phenocrysts, and those that lack mafic phenocrysts, also a characteristic of the tuff of White Tanks, are characterized by large, embayed, quartz phenocrysts. Interestingly, an unnamed welded tuff from a road cut in the Ajo volcanic field south of Why, Arizona examined by Ferguson is mineralogically similar to the tuff of White Tanks, and it is tentatively suggested that the tuff of White Tanks may represent the distal fringe of a far-travelled ignimbrite that was erupted from a volcanic field to the east or south of the Tank Mountains, but not necessarily the tuff exposed near the town of Why.

A poorly welded to unwelded, massive, peach-colored ash-flow tuff that ranges between 0 an 75 meters thick is exposed over a 2-3 km^2 area at the northeast end of the Tank Mountains. This ash-flow is restricted to Malley mesa, which forms the east end of the range. The ash-flow tuff contains between 10 and 20% lapilli-sized, light brown pumice fragments, but its phenocryst assemblage could not be described except that it contains minor biotite. This tuff, informally referred to as the tuff of Malley mesa, may merely represent a local tuff related to eruption of the dacite lava it overlies or another nearby silicic lava. However, the lack of associated thin- and medium-bedded unwelded lithic tuffs, which are ubiquitous features of all other tuff sequences adjacent to the silicic lava eruptive centers of the area, suggests that it may represent the distal part of a regional ash-flow sheet that ponded in this area.

Monolithic breccias

Monolithic breccias represent the most enigmatic and potentially the most important, in terms of understanding volcanic setting, Tertiary unit in the Tank Mountains. The breccias units are tabular bodies of clast-supported, angular to subangular breccia that are interbedded with bedded tuff, tuff of White Tanks, or olivine pyroxene basalt. They are rarely found in contact with pre-Tertiary basement rocks, but where they are (see structural cross-section 1-1') the contact is a southwest-dipping surface interpreted as an erosional scarp.

The clasts of the breccias are composed of pre-Tertiary gneisses or granitoids that are angular and typically unweathered, although locally, deeply weathered populations can be found. In any area, the clasts are monolithic, either granitic or gneissic, but this monolithic character may change laterally or vertically across narrow contact zones. In some areas individual lenses of breccia or amalgamated lenses consist of alternating gneissic and granitic layers. The matrix in the core of the breccias appears to be autoclastic, but contacts with interbedded unwelded tuffs are typically gradational and these transitional zones have pyroclastic matrix. Locally however, the contacts may be sharp and some may be erosional. Some of the breccia units are inversely graded with maximum clast-sizes increasing gradually upward from 30 cm to 600 cm. In areas where the breccias are thin (between 2 and 15 meters thick) lateral gradation into tuff and/or pebbly sandstone has been observed. North of White Tanks, the breccias are at least 100 meters thick, and they occur as a monotonous sequence of amalgamated units or units with very thin interbeds of tuff. Farther to the south and west the breccias occur in two units each up to 20 meters thick, the upper one overlying basalt lava, and the lower one overlying tuff of White

Tanks. These units become thinner, on average, to the south where they pinch out about 5 km south of White Tanks (Figure 6).

The monolithic breccias are interpreted as dry rock avalanche deposits derived from a southwest-facing erosional scarp or scarps. The angular nature and freshness of the clasts, autoclastic matrix, and locally homogeneous clast compositions are compelling arguments for an avalanche origin. The interpretation of a southwest-facing erosional scarp is based on three lines of evidence. 1) Basement occurs at a higher level to the north of the proposed scarp. 2) The breccias thin dramatically and are finer grained towards the southwest. 3) A contact dipping nearly 40° southwest, after restoration of Basin and Range tilting, occurs between pre-Tertiary basement and a sequence of bedded tuff and breccia.

Rhyolite lavas

A number of rhyolitic lavas and probable lava domes occur in the Tank Mountains, mostly in the central part of the study area. Most of these flows are very crystal-poor, containing between 0.5 and 5% phenocrysts of feldspar, quartz, with minor biotite and/or hornblende. The rhyolite lavas occur as flow-banded vitrophyre, vitric autobreccia, and as flow-banded microcrystalline matrix lava.

Because of their petrographic similarity, differentiation of the rhyolite lava flows is, for the most part, dependent on local stratigraphic relationships, such as in the area southwest of White Tanks. In the eastern study area, however, three distinct stratigraphic units can also be recognized on the basis of phenocryst assemblage. In this area, a very crystal-poor hornblende-bearing flow occurs near the base of the volcanic pile, and the youngest flow is aphyric. Between these two flows lies at least one crystal-poor feldspar, biotite and hornblende-bearing flow, which is typical of the flows farther west. The young aphyric rhyolite is the only rhyolite lava known to occur above the distinctive monolithic breccia and bedded tuff sequence which can be traced across much of the study area.

Dacite lavas

Dacite lavas occur throughout most of the study area, and they are present throughout the volcanic pile in the eastern Tank Mountains. The dacites are moderately- to very crystal-rich with phenocrysts of feldspar (mostly plagioclase?) and abundant hornblende and biotite. The lavas are typically flow-banded with a gray to light pink, microcrystalline matrix, but locally, vitric flow-banded lava and vitric autobreccia occur near the base. At least three separate flows of dacite lava are recognized in the eastern Tank Mountains based on stratigraphic relationships. The upper two flows are petrographically indistinguishable from each other and a lava that occurs at the base of Malley mesa.

Two other dacite lavas occur at or near the base of the volcanic pile on the southern and western edges of the study area. These two flows are similar to the younger dacites, but can be separated from them based on slight petrographic differences. The westernmost dacite lava is moderately crystal-rich, with tabular feldspars, and its matrix is typically red-colored. This western dacite is correlated with a the dacite of Courthouse Mountain, a widespread flow or group of flows named and mapped by Grubensky and others (in press), in the westernmost Tank Mountains. The dacite of Courthouse Mountain in this map area, forms a large complex of flows and thin local tuffs that is locally interleaved with a volcaniclastic sandstone and basalt lava.

A dacite lava exposed in the southern Tank Mountains directly west of the Golden Harp Mine is characterized by abundant needle-shaped hornblende phenocrysts, and in general,

a higher proportion of mafic minerals than the other dacite lavas of the Tank Mountains. Although altered and reddish colored in many areas, particularly west of Flat Top Butte, locally this lava is light gray-colored, vitric, and "fresh-looking".

Mafic lavas

Five distinct varieties of mafic lavas are recognized in the Tank Mountains based purely on their phenocryst assemblages. These are: 1) olivine-pyroxene basalt, aphyric basalt, crystal-poor to aphyric plagioclase-bearing basaltic andesite, moderately crystal-rich plagioclase-bearing basalt or aluminous basalt, and hornblende andesite. In areas where these varieties of mafic flows occur in sequence, flow breaks, defined by intervening thin bedded tuffs, sandstones, and regoliths or soil horizons, can usually be found which confirm that they are separate flows.

In the southwestern study area, the volcanic sequence locally includes 6 distinct mafic flows representing all of the varieties of mafic flow except the basaltic andesite. This sequence includes three olivine-pyroxene basalts, one near the base, one at the top, and one in the middle of the sequence. The other three lavas in ascending order are: aluminous basalt, aphyric or "sugary" basalt, and hornblende andesite. This triplet succession is consistent throughout the Tank Mountains, with one minor exception (a thin aphyric basalt occurs "out-of-sequence" in sec. 35, T3S, R14W unsurveyed). The basaltic andesite is only present in the northeast Tank Mountains where it overlies the hornblende andesite. The olivine pyroxene basalts occur throughout the sequence and each flow is petrographically indistinguishable, although there is a general trend of decreasing phenocryst content upwards (from 15% to <5%) in some areas. One of these older basalts (sample 3.14.943) in the south-central part of the study area locally contains biotite flakes which may be phenocrysts or xenocrysts.

Distribution and correlation

The distribution and correlation of volcanic units in the Tank Mountains is summarized in three stratigraphic cross-sectional diagrams; two north-south sections and an east-west section (Figure 7). The high-standing central crest of the Tank Mountains is constructed chiefly of silicic lavas; dacite of Courthouse Mountain to the west and rhyolite lavas to the east, and these lavas form the base of the volcanic pile. Basalt lavas are present throughout the volcanic stratigraphy, but in general they represent the youngest rocks and they are distributed mostly along the northern and southern flanks of the Tank Mountains. This pattern may reflect the preservation of older rocks along the central crest because it corresponds to an anticlinal arch, but there is good evidence to the north that mafic volcanics directly overlie basement rock.

The most widespread units in the Tank Mountains are mafic lavas, the aluminous basalt in particular occurs over 50 km^2. Olivine pyroxene basalts occur vertically and laterally throughout the volcanic pile, but they are difficult to trace over long distances because of their petrographic similarity to each other. A younger tripartite sequence of mafic flows are potentially good markers because they are petrographically distinctive, and because they occur in an established sequence. This tripartite sequence, consisting of aluminous basalt, olivine pyroxene basalt, and aphyric basalt is present on both the north and south sides of the Tank Mountains. The two younger units are preserved only at the extreme southern and northern limits of the triplet's outcrop area, and the basal aluminous basalt thins to zero thickness across the crest. In addition, the aphyric basalt is ponded into south-thickening wedges along the southern edges of some north-side-down fault blocks

south of the White Tanks area. These thickness patterns suggest that the anticlinal arch, which currently corresponds to the central crest of the Tank Mountains, was a positive feature during deposition of these mafic lavas. The tripartite sequence of basalts is overlain by a widespread hornblende andesite that occurs throughout much of the central Tank Mountains. The hornblende andesite is cut by normal faults to the north of the anticlinal crest, but to the south it appears to overlie some faults.

The youngest mafic flows in the study area are isolated patches of olivine pyroxene basalt lavas that cap mesas in the eastern Tank Mountains and a basaltic andesite lava in the northeastern Tank Mountains that buries at least three north-side-down fault scarps. Interestingly, the youngest volcanic unit of the Palomas Mountains is an andesite that also buries north-side-down fault scarps along the northern flank of that range (Skotnicki and Ferguson, 1994).

Individual silicic lava flows are restricted to relatively small areas, generally less than a few km^2. The most widespread are the oldest dacite lavas. The oldest dacite in the eastern Tank Mountains may cover as much as 5 km^2, and a complex of younger dacite lavas, known to represent at least two flows in the northeast, cover an area of about 12 km^2. The dacite of Courthouse Mountain to the west, which consists of at least two flows, covers an area of about 10 km^2. Rhyolite lavas occupy an at least 25 km^2 area in the central Tank Mountains, and this complex probably consists of several coalescent flows derived from a number of vents. The most laterally extensive individual rhyolite lava is the aphyric flow in the northeast which is at least 5 km long.

The volcanic stratigraphy of the Tank Mountains undergoes a fairly abrupt upward change from silicic lava-dominated to mafic lava-dominated, and this transition is marked by distinctive succession of monolithic breccias interbedded with unwelded bedded tuffs, the tuff of White Tanks, and a basalt lava. This succession is herein referred to as the unit of Dummy gulch after good exposures of the unit in the area around the wash, informally named Dummy gulch, that flows through White Tanks. The vertical succession of map units within the unit of Dummy gulch is consistent throughout the area, although each unit is not always present. A type section, consisting of bedded tuff, tuff of White Tanks, lower breccia, basalt, and upper breccia is exposed on the southwest face of the 2168′ elevation mountain directly west of White Tanks.

The monolithic breccias of the unit of Dummy gulch, which are interpreted as avalanche breccias shed from a proximal northeastern source, imply that a topographic high was degraded during deposition of the unit. The scarp may be volcano-tectonic or purely tectonic in origin, but its close association with a thick succession of volcanic rocks suggest some link to magmatism. Besides serving as a chronostratigraphic marker that helps tie together the volcanic stratigraphy of the area, the unit of Dummy gulch may represent an important transitional interval in terms of magmatism and tectonism in the area.

Late Tertiary and Quaternary sedimentary units

A fairly thick sequence of coarse-grained, volcaniclastic sedimentary rocks occurs locally along the northern and southern flanks of the Tank Mountains in the western part of the study area. To the south, these rocks are nearly continuous with similar rocks which make up most of the northwestern Palomas Mountains. The clasts in these rocks consist mostly of the mafic flows that they overlap in both the Tank Mountains and Palomas Mountains. To the north, the younger volcaniclastic sequence contains both mafic and felsic clasts and it includes a thin rhyolite lava near its base. The northern

sequence is continuous with exposures of the unit of Kofa Butte, the youngest recognized bedrock unit of the Kofa Mountains area (Grubensky and others, in press).

The Quaternary geology of the study area was not investigated during this study. However, obvious exposures of active alluvial surfaces on the Palomas Plain within Yuma Proving Ground where compiled from air photos at the Proving Ground headquarters.

STRUCTURAL GEOLOGY

Pre-Tertiary structure

The compositionally banded amphibolite facies gneisses of the Golden Harp metamorphic suite in the southeastern Tank Mountains exhibit evidence of polyphase ductile deformation. The prominent structural fabric of these rocks is a synmetamorphic foliation defined by phyllosilicates within the melanosomes and granoblastic texture in the leucosomes. The prominent foliation is locally axial planar to tight to isoclinal mesoscopic folds, and it is also locally crenulated and/or broadly warped by younger more open folds. Lineations reported from these rocks on the geologic map are either hinge lines of these secondary, broad folds or crenulation lineations, and they are mostly north-south trending.

Based only on hand specimen examination, two episodes of ductile deformation are suggested. The oldest is a synmetamorphic phase of tight to isoclinal folding which produced the prominent foliation, and which may be responsible for some of the compositional banding. A post-peak-metamorphic phase of folding produced northerly trending crenulations and broad folds, and may be responsible for the map patterns in the SW/4 of sec. 9, T4S, R13W.

The Golden Harp metamorphic suite is intruded by a suite of variably foliated granitoids. These foliations are defined by preferentially oriented felted masses of biotite and locally granoblastic quartzofeldspathic structures. Although locally intensely developed, this foliation never produces compositional layering in the younger granitoids. The intensity of foliation in the granitoids generally decreases away from contacts with the older gneisses, implying that deformation may have been related to emplacement. The overall northerly trend of these foliations, and the general northerly trend of many of the contacts within and along the margins of this suite suggest a relationship to the second phase of deformation proposed for the banded gneisses.

Pre-Tertiary rocks exposed along the west edge of the study area form a homoclinal southwest-dipping structural package that is locally broadly to tightly folded and cut by a penetrative southwest-dipping slaty cleavage. The cleavage is developed best within the argillites and it is rarely and weakly developed within the bedded and welded ash-flow tuff. The cleavage is essentially nonexistent in the quartzites and limestones. Poor exposures make it difficult to define folds on a map scale, but a small number of southwest- or southeast-plunging intersection lineations and fold hinge lines were measured in these rocks. The orientation of the slaty cleavage is fairly consistently southeast or east-striking and southwest-dipping, and its relative orientation to bedding, both steeper than and shallower than bedding, suggests that its formation was not directly related to folding.

The low-grade metamorphic rocks exposed along the northwest edge of the study area consistently dip very steeply to the southwest which is also the stratigraphic facing direction. The strata are cut by slaty cleavage that dips consistently 20 to 45° southwest, an orientation that is approximately parallel to an overlapping contact with monolithic, granite breccia (Mgb map unit). The breccia has a dark green, well-indurated matrix and it is tentatively interpreted as fault gouge that formed below, and in part in front of, a north-vergent thrust sheet. Only the basal portion of the hangingwall, which was probably

composed mostly of granite, is now preserved below the Mid-Tertiary unconformity. The fault surface and the hangingwall breccias are intruded by a diorite stock which is in turn unconformably overlain by mid-Tertiary volcanics. The slaty cleavage of the footwall to this proposed thrust fault is tentatively interpreted as a prograde metamorphic fabric produced by top-to-the-northwest shearing during faulting and tectonic burial of the footwall rocks. Cleavage-bedding relationships in the area, suggest that if folding was responsible for the steep regional attitude of bedding, that this folding was either not associated with axial planar cleavage formation, or that if any axial planar cleavage existed, it was later obliterated.

Tertiary structures

Geometric relationships

Tertiary volcanic rocks of the Tank Mountains are cut by northwest-striking normal faults which, on average, trend slightly more northerly than the overall west-northwest trend of the range. Fault surfaces are commonly well exposed. Kinematic indicators are unfortunately sparse, but rare slickenlines indicate principally dip-slip. An exception is a population of north-northwest striking, straight faults in the western study area, two of which have very low-angle slickenlines, suggesting strike-slip motion. These north-northwest striking faults are also very straight which is characteristic of strike-slip faults.

Normal faulting in the Tank Mountains accommodates about 0.5 km of extension, most of which occurs across a fairly narrow corridor corresponding to the central crest of the range (Plate 2). In cross-sections 2,3,4 this corridor is up to 5 km-wide, but farther west along cross-section 5, the corridor is much narrower, and consequently the magnitude of tilting and percent extension locally much greater. These corridors of relatively higher extension are balanced assuming plane strain in the plane of the sections. Listric geometries are shown for most of the faults because many of them display concave up map patterns. In the easternmost cross-section, there appears to be little or no extension, and it is believed that most of the extension in this area is accommodated along one major fault at the south end of cross-section 1-1′.

The narrow corridor of extension along the crest of the Tank Mountains is also an anticlinal arch and tilt-domain boundary (Figure 8). The tilt reversal occurs across a very narrow zone adjacent to or immediately to the south of the southernmost south-side-down fault of cross-sections 2,3,4 and 5. Strata at two localities in the hangingwall of this zone exhibit angular relationships with older northeast-dipping strata overlain sharply by southwest-dipping strata (see cross-section 3-3′, Plate 2).

To the north of the anticlinal arch all volcanic strata are cut by south-side-down normal faults, and the northeasterly dips appear to be consistent in magnitude throughout the section. To the south of the arch, younger units have shallower dips and there is also evidence that one of the younger mafic flows (Tbs) locally ponded in troughs generated by the southwest-tilted fault blocks. The triplet of mafic flows (Tab, Tbm, and Tbs) thins to zero across the arch and the youngest unit (Tha) appears to overlap some faults.

There is evidence of syn-volcanic, north-side-down faulting on the north side of the anticlinal arch in the northeastern Tank Mountains. In this area, at least three degraded fault scarps are buried by the youngest volcanic unit of the area (Tba). The faults cut the underlying silicic lava flows and bedded tuffs. Other faults, mostly south-side-down, cut all of the volcanic units.

Timing of deformation

A relative chronology of extensional deformation in the Tank Mountains can be established in relation to the volcanic stratigraphy in the area. These events are summarized. The older sequence of silicic lavas and the unit of Dummy gulch record the greatest amount of tilting and the youngest of these are considered to represent a minimum age for the onset of deformation. Evidence of northeasterly and then southwesterly tilting is preserved with the lower to middle part of the unit of Dummy gulch. The monolithic avalanche breccias of the unit of Dummy gulch are linked to the degradation of a southwest-facing scarp which may have been formed by southwest-side-down faulting. That avalanche events were triggered by volcano-tectonic activity is suggested by the relationship of two prominent tongues of breccia directly overlying volcanic units of the unit of Dummy gulch (Twt and Tbg). The tripartite mafic lava sequence which overlies the unit of Dummy gulch thins across the anticlinal arch and appears be syntectonic with respect to some faults south of the arch, and the next younger unit (Tha) is probably syn to post-tectonic with respect to some of the faults south of the arch. The basaltic andesite lava of the northeast Tank Mountains is post-tectonic with respect to a number of north-side-down faults, but is cut by other, mostly south-side-down faults. The younger basalt lavas (Tby) and the younger sedimentary (Tsy) unit show no evidence of faulting anywhere in the Tank Mountains, but are gently tilted and locally the sedimentary unit helps define broad synclinal structures that flank the anticlinal arch. It is not clear if these tilts represent tectonic tilting or depositional slope into preexisting synclinal troughs.

Overall, the extensional history of the Tank Mountains can be divided into three episodes: 1) southwest-side-down faulting(?) and formation of a southwest-facing scarp during deposition of the unit of Dummy gulch with local northeasterly tilting along the future axis of the anticlinal arch, 2) southwesterly tilting and north-side-down faulting south of the arch followed by and apparent uplift of the arch before and during deposition of the tripartite mafic lava sequence, and hornblende andesite, and 3) burial of north-side-down faults by the basaltic andesite lava to the north of the arch and continued south-side-down faulting. Post-tectonic overlap of all faults by a younger sequence of basalt lava and sediments is probable, but these units also record gentle dips that may be tectonic in origin.

The anticlinal arch and central crest of the Tank Mountains represents a narrow corridor of normal faulting that accommodates most of the Basin and Range extension known for this area. There are of course very large areas of adjoining Quaternary peidmonts that could easily bury extensional features that might dwarf the anticlinal arch of the Tank Mountains in terms of extensional magnitude. Extension within the Tank Mountains was initiated soon after, and possibly during the later stages of, a silicic lava eruptive event which was concentrated along the future axis of the arch, and it is tempting to genetically link these events. No cause and effect relationship, however, is suggested.

MINERAL DEPOSITS

The volcanic rocks of the Tank Mountains are characteristically fresh and, for the most part, unaltered by hydrothermal fluids, and economically these rocks probably offer little in terms of metallic ore deposit potential. The thick bedded tuff sequences offer some potential as hosts for zeolite minerals, but none were recognized during this study. There is potential for uranium mineralization in and adjacent to any felsic volcanic field, but the sedimentary rocks that typically host these kinds of deposits are very rare in this area.

The vitric breccias of the aphyric rhyolite lava of the northeast Tank Mountains are altered to perlite in some areas, but not extensively.

The basement rocks in both areas of the Tank Mountains are locally extensively altered, and these areas have been prospected and exploited minimally. The geology economic history of these mining areas is described in reports by Wilson (1933) and Kieth (1978).

In the amphibolite facies rocks of the southeastern Tank Mountains, virtually all areas of mineralization are characterized by strong red and black hematite staining on fracture surfaces and clast surfaces, and this alteration is also present within fine-grained matrix of a sedimentary breccia that mantles the basement rocks (map unit Tsx). In most areas, and in particular the most mineralized areas such as at the Golden Harp mine, shearing of host rocks is extreme and was probably due to faulting. Extreme hematite mineralization is associated with alteration of plagioclase to clay minerals. Unfortunately, diverse fracture orientations precluded identification of shear zone trends. Mineralization was possibly most intense where two faults intersect and complex fracturing in these areas obscures fault orientations. Locally older quartz veins are shattered and pervasively stained with hematite and, at a shaft in the SW/4 of sec. 33, T3S, R13W, coated with secondary copper minerals. Relict pyrite and limonite stains are also present locally. At the section 33 location, mineralization occurs within the orthogneiss map unit near a contact with a younger felsic granitoid. Fragments of a porphyritic border phase to this granite are present in the spoil piles and dikes of it occur in the area. Heat from emplacement of this granite and these dikes may have caused or assisted fluid circulation and mineralization in this area.

Along the western edge of the map area a group of small mines are clustered along the contact between metasedimentary rocks and the metarhyodacite tuff unit. Copper mineralization occurs in quartz and dark-colored carbonate veins and fracture fillings (F-PG-322b), and there are also unconfirmed reports of fairly high gold values from these rocks. Mineralization appears to be related to an elongate fine-grained diorite or gabbro body that intrudes along the contact between the supracrustal rocks. Mineral prospecting in this area is restricted because the mines occur along the border of Yuma Proving Ground and Kofa National Wildlife Refuge. The granitoids of the western study area are typically propylitically altered, suggesting that a mesothermal circulation system may have affected these rocks at some time.

The extreme brittle and by inference near surface character of mineralized areas and presence of hematite mineralization in the sedimentary breccia that mantles the basement in the southeast suggests that mineralization was middle Tertiary in age. However, some mineralization may be linked to the emplacement of two plutonic bodies that appear to be pre-Tertiary; a granite at the section 33 mine, and a diorite along the western edge of the map area. It is possible that mineralization in the basement rocks of the Tank Mountains is the result of multiple phases of fluid circulation or concentration.

RECOMMENDATIONS FOR FUTURE STUDIES

Geochronology of the volcanic rocks of the Tank Mountains will provide a temporal framework that will help constrain the onset and duration of magmatism and extension in the area. It is recommended that chronological studies focus on $^{40}Ar/^{39}Ar$ analyses of three rock sequences which contain fresh and apparently unaltered hornblende, sanidine, or biotite phenocrysts. Fresh samples of the oldest dacite lavas with abundant fresh-looking hornblende phenocrysts were acquired at two localities: F-PG-214 (Td1), and F-PG-

287 (Tcm). Hornblendes from an older rhyolite lava could also be separated from sample F-PG-231. In the middle of the volcanic sequence, two large blocks of the tuff of White Tanks were sampled (F-PG-146-2,3) which appear to contain fresh sanidines. A date of the hornblende andesite should help constrain the younger limit of volcanism and extension along the crest of the Tank Mountains. This lava was sampled for hornblende separates at two localities (F-PG-67, F-PG-212). Many other samples were obtained throughout the volcanic section which have potential for whole rock or mineral separate geochronology.

Most of the older plutonic and metamorphic suites where also sampled for geochronology and geochemistry. The sample location map is coded for easy recognition of geochronlogic samples, and a listing of many of these samples is also available which lists for each sample its intended use (petrology, geochronology, or geochemistry), minerals that could be used for geochronology, and a check if the sample is "clean" (for geochemistry) or crushed down to a size suitable for most primary crushers.

Unfortunately, the diorite pluton which appears to cross-cut a low-angle fault that we have interpreted as a thrust cutting the metasedimentary sequence in the western study area was not sampled. Although this rock is fairly mafic-looking, a large sample may yield datable minerals.

Other possible analytical studies of interest in the Tank Mountains include paleomagnetism of the volcanic succession, and a geochemical study of the lavas, particularly the varied mafic flow sequence. There is also potential for a paleontological study of limestones within the Mesozoic metasedimentary sequence.

REFERENCES

Anderson, P. A., 1989, Proterozoic plate tectonic evolution of Arizona, *in* Jenney, J. P, and Reynolds, S. J., (eds.), Geological evolution of Arizona: Arizona Geological Society Digest 17, p. 17-55.

Bagby, W. C., Haxel, G. B., Smith, D. B., Koch, R. D., Grubensky, M. J., Sherrod, D. R., and Pickthorn, L. B. G., 1987, Mineral resource assessment of the Kofa National Wildlife Refuge, Arizona: United States Geological Survey Open-File Report 87-609, 45 pp.

Grubensky, M. J., and Bagby, W. C., 1990, Miocene calc-alkaline magmatism, calderas, and crustal extension in the Kofa and Castle Dome Mountains, southwestern Arizona: Journal of Geophysical Research, v. 95, no. B12, p. 19,989-20,003.

Grubensky, M. J., and Demsey, K. A., 1991, Geologic map of the Little Horn Mountains 15′ quadrangle, southwestern Arizona: Arizona Geological Survey Map 29, 10 pp., 1 map.

Grubensky, M. J., Haxel, G. B., and Koch, R. D., 1993, Geologic map of the Castle Dome Mountains, southwestern Arizona: U. S. Geological Survey Miscellaneous Investigations Map 1-2138, scale 1:62,500.

Harding, L. E., and Coney, P. J., 1985, The geology of the McCoy Mountains Formation, southeastern California and southwestern Arizona: Geological Society of America Bulletin, v. 96, p. 755-769.

Haxel, G. B., Tosdal, R. M., and Dillon, J. T., 1985, Tectonic setting and lithology of the Winterhaven Formation: a new Mesozoic stratigraphic unit in southeasternmost California and southwestern Arizona: USGS Bulletin 1599, 19 pp.

Kieth, S. B., 1978, Index of mining properties in Yuma County, Arizona: Arizona Bureau Geology and Mineral Technology Bulletin 192.

Lysonski, J. C., Sumner, J. S., Aiken, C., and Schmidt, J. S., 1980, Residual Bouger Gravity Anomaly Map of Arizona (IGSN 71): Laboratory of Geophysics, University of Arizona, Tucson.

Reynolds, S. J., 1988, Geologic map of Arizona: Arizona Geological Survey Map 26, scale 1:1,000,000.

Skotnicki, S. J., and Ferguson, C. A., 1994, Geologic map of the Palomas Mountains, Arizona: Arizona Geological Survey Open-File Report 94-9.

Spencer, J. E., and Reynolds, S. J., 1989, Middle Tertiary tectonics of Arizona and adjacent areas, *in* Jenney, J. P., and Reynolds, S. J., (eds.) Geologic evolution of Arizona: Arizona Geological Society Dogest, v. 17, 539-574.

Tosdal, R. M., and Stone, P., 1994, Stratigraphic relations and U-Pb geochronology of the Upper Cretaceous upper McCoy Mountains Formation, southwestern Arizona: Geological Society of America Bulletin, v. 106, p. 476-491.

Wilson, E. D., 1933, Geology and mineral deposits of southern Yuma County, Arizona: Arizona Bureau of Mines Bulletin 134, p. 126.

Wilson, E. D., Moore, R. T., and Cooper, J. R., 1969, Geologic Map of Arizona: Arizona Bureau of Mines and United States Geological Survey (out of print).

DESCRIPTION OF MAP UNITS, TANK MOUNTAINS

(Listed in semi-chronologic order. See correlation chart for age relationships)

CENOZOIC VOLCANIC, SEDIMENTARY, AND PLUTONIC ROCKS

Q, Qa **Unconsolidated to partially consolidated sediment** (0-100s meters) Undifferentiated peidmont deposits, alluvium, colluvium, and talus. Differentiation of active alluvial surfaces as Qa, made only on uppermost Palomas Plain.

Tsy **Younger sedimentary rocks** (0-100 meters) Volcaniclastic debris flows, conglomerate, pebbly sandstone, and sandstone. These deposits form hills above surrounding Quaternary peidmont surfaces and alluvial terraces.

Try **Younger rhyolite lava** (0-25 meters) Moderately crystal-poor rhyolite lava interleaved with the Tsy unit in the extreme northwestern corner of the study area.

Tby **Younger basalt lava** (10-50 meters) Basalt lava with 5 to 15% phenocrysts of olivine and pyroxene. Forms cap to Malley mesa, Flat Top Butte, the elongate mesa north of Golden Harp Mine, a number of other small mesas in eastern Tank Mountains, and one small exposure in the southwestern Tank Mountains.

Ttm **Tuff of Malley mesa** (0-75 meters) Massive unwelded light-colored tuff with 10-20% light brown pumice fragments, and approximately 5% phenocrysts of quartz, feldspar, and minor biotite.

Tdu **Undivided crystal-rich dacite lava** (0-60 meters) Dacite lava with 20%-30% phenocrysts of plagioclase, hornblende, and biotite. Indistinguishable from the other crystal-rich dacites (Td1,2,3) and parts of it may be correlative to one or all of these units. Upper surface within central and northern Malley mesa with up to 30 meters of local relief.

Tt **Generic bedded tuff** (0-100 meters) Medium-bedded to thin-bedded, unwelded, lithic tuffs which occur between lava flows throughout the Tank Mountains.

Tba **Basaltic andesite lava** (0-100 metres) Aphyric to crystal-poor basaltic andesite lava, which locally overlies an older flow (Tbao). The lava is typically blueish-gray-weathering and nonvesicular, flow-banded, but locally with a red-weathering, scoriaceous, blocky base. Phenocrysts are clear, tabular to equant plagioclase which increase upwards from less than 0.5% to 5% near the top. The matrix also becomes more crystalline upwards.

Tts **Bedded tuff and sandstone** (0-20 meters) A tripartite unit, where complete, of **1)** an upward-fining, medium-bedded to thin-bedded lithic tuff overlain by **2)** a tan to reddish-brown, friable, parallel-bedded, or cross-stratified volcaniclastic sandstone. This sandstone subunit is very thin or absent, except in areas where the unit fills depressions. Gradationally overlying **2** is **3)** a thin- to very thin-bedded (locally low-angle cross-stratified), partially welded, vitric, crystal-rich tuff. The welded tuff ranges in color from dark gray to light pink. It is also well-sorted, containing black vitric lithic fragments, and up to 20% phenocrysts of feldspar, quartz, and biotite.

Tha **Hornblende andesite lava** (0-100 meters) Gray-colored, crystal-poor mafic to intermediat lava containing 2-5% equant plagiclase phenocrysts and distinctive needle-shaped hornblendes. Typically, the flow consists of an autobrecciated base and carapace with a flow-banded internal core. The flow occupies a 3 km-wide northeast-trending band across the middle of the study area that may represent its original extent. A well-exposed NE-trending flow front occurs in the south 1/2 of section 18, T3S, R13W. The flow overlies a wide variety of older volcanic units, generally from northeast to southwest; aphyric rhyolite lava, monolithic breccia, crystal-poor rhyolite lava, bedded tuffs, aphyric basalt, and aluminous basalt. The hornblende andesite is the youngest preserved volcanic unit throughout most of its outcrop area except at its north margin where it is overlain by sandstone, bedded tuff and basaltic andesite, and near its south margin where it is overlain by bedded, basalt, and the younger sedimentary unit.

Tbs **Aphanitic "sugary" basalt lava** (0-25 meters) Basalt lava characterized by lack of phenocrysts and a sugary matrix. Chilled margin of flow is very aphanitic and almost vitric locally. Present only in the western Tank Mountains.

Tbm **Middle basalt lava** (0-10 meters) Olivine-pyroxene basalt with between 5 and 10% phenocrysts. Present only locally in western Tank Mountains.

Tab **Aluminous basalt** (0-40 meters) Moderately crystal-rich basalt, characterized by abundant, large (3-10 mm), equant, typically clear, tabular plagioclase phenocrysts and minor mafic minerals (probably pyroxene). Present only in western Tank Mountains.

Td3 **Upper crystal-rich dacite lava** (0-100 meters) Light pinkish-gray dacite lava with between 15% and 30% phenocrysts of plagioclase, hornblende, and biotite.

Tr3 **Aphyric rhyolite lava** (0-100 meters) Aphyric rhyolite lava occuring in three basic forms: **1)** flow-banded, pink and light-gray, microcyrstalline core, **2)** dark blueish-gray, flow-banded vitrophyre in gradational contact with the the crystalline core. Vitrophyre grades outward into **3)** light-brown, vitric autobreccia which always occurs at the base, and usually overlies the flow-banded core and vitrophyre. Locally a black, flow-banded vitrophyre with a radiating fibrous texture caps the upper autobreccia, and its upper contact with Tts is a distinctive in-situ vitrophyre breccia injected with a reddish lithic-rich tuff. The aphyric rhyolite overlies bedded tuffs, monolithic breccias, or older crystal-rich dacite lava. It is overlain by hornblende andesite, younger crystal-rich dacite lava, or bedded tuff and sandstone.

Td2 **Middle crystal-rich dacite lava** Light gray to light pinkish-gray, lava with between 10% to 20% phenocrysts of plagioclase, hornblende and biotite. The lava typically occurs with a 5 to 10 meter-thick, autobrecciated base overlain by up to 15 meters of dark gray, flow-banded and locally isoclinally folded vitrophyre. It overlies bedded tuffs, monolithic breccias and basalt lava, or Pre-Tertiary crystalline rocks. It is overlain by the aphyric rhyolite lava.

Tdg **Unit of Dummy gulch: a composite unit of generic bedded tuff (Tt) and monolithic breccia (Tx) locally interbedded with basalt lava (Tbg), and tuff of White Tanks** (0-150 meters) This unit overlies either Pre-Tertiary crystalline rock, or older silicic lavas.

Tx **Monolithic breccia** (0-100 meters) Tabular bodies of clast-supported, angular to subangular breccias which occur throughout the middle and upper portion of the unit of Dummy gulch, but which also occur locally below it. Maximum clast sizes range from 50 cm to over 700 cm. The breccias are composed of monolithic gneisse or granitoid. The clasts are angular and typically unweathered although locally, deeply weathered populations can be found. The matrix in the core of the breccias appears to be autoclastic, but contacts with interbedded unwelded tuffs are typically gradational and these zones have pyroclastic matrix. Locally, contacts with tuff are sharp and some may be erosional. In areas where the breccias are thin, lateral gradation into tuff and/or pebbly sandstone has been observed. North of White Tanks, the breccias are very thick (at least 100 meters) and they occur as a monotonous sequence with very thin, interbeds of tuff. In areas between these extremes, tabular breccia units are up to 20 meters thick and stacked into sequences of two or more with tuff interbeds up to 60 metres thick. Some of these breccia units are inversely graded with maximum clast-sizes increasing gradually upward from 30 cm to 600 cm.

Tbg **Basalt lava** (0-60 meters) Moderately crystal-rich, olivine-pyroxene

basalt lava which underlies an upper tongue of the monolithic breccia unit within unit of Dummy gulch, hence the suffix "g" for gulch.

Twt **Tuff of White Tanks** (0-45 meters) Moderately crystal-poor, pumice-poor, welded, light-gray, rhyolite ash-flow tuff that underlies or is interbedded with a lower tongue of the monolithic breccia unit within the unit of Dummy gulch. Tuff contains between 5 and 10% equant feldspar (sanidine?) phenocrysts, but no quartz, and only a trace of mafic minerals. Lithic fragments are small and sparse. Concentrically banded concretions up to 30 cm wide, occuring in poorly welded zones may be accretionary lapilli.

Tr2 **Upper crystal-poor rhyolite lava** (0-200 meters) Rhyolite lavas which underlie and locally intertongue with the lower part of the unit of Dummy gulch and which overlie older rhyolite lavas. Lavas of this age occur in at least three separate, but possibly contemporaneous, flows and domes in central Tank Mountains. The lavas contain between 1 and 5% phenocrysts of quartz, feldspar, and traces of biotite and/or hornblende, and are generally more cystal rich to the west. The map unit consists of vitric autobreccia, black vitrophyre, pink or gray microcrystalline, flow-banded lava, and locally block and ash-flow deposits adjacent to domes.

Tr1 **Lower crystal-poor rhyolite lava** (0-200 meters) Rhyolite lavas which underlie the upper rhyolite lavas. In western Tank Mountains this lava is petrographically indistinguishable from the younger rhyolite lavas, but to the east (directly east of Flat Top Butte (sec. 30,31, T3S, R13W) it is very crystal-poor, nearly aphyric, and characterized by neddle-shaped hornblende (and pyroxene?) phenocrysts.

Tru **Undivided crystal-poor rhyolite lava** (0-120 meters) Rhyolite lavas in the southern Tank Mountains petrographically indistinguishable from nearby Tr1 and Tr2 lavas, and which can not conclusively be assigned to either of these generations. Locally this lava occurs as composite flows with intervening bedded tuffs, tuff breccia, and block and ash-flows, none of which were differentiated due to their lack of lateral continuity.

Trt **Tuffs associated with rhyolite lava domes or flows** (0-50 meters) Coarse-grained, massive, lithic-rich, unwelded tuff interpreted as block and ash-flow material derived from nearby domes or flows. Lithic fragments are composed almost entirely of rhyolite lava and clast-supported texture dominates. These deposits are mapped separately only where the associated lava is not exposed (sec. 6, T4S, R14W).

Td1 **Lower crystal-rich dacite lava** Dacite lava with between 10% to 20% phenocrysts of plagioclase, hornblende, and biotite. Usually light pinkish-gray color. This dacite lava is distinguished from younger crystal-rich dacites mainly by its position at the base of the volcanic sequence and because it contains a higher proportion of mafic minerals.

Tcm **Dacite of Courthouse Mountain** (0-250 meters) Moderately crystal-rich, plagioclase, biotite, and hornblende-bearing dacite lava restricted to the western edge of the study area. Correlated with an extensive dacite lava complex mapped in adjacent area to the west where its informal name, dacite of Courthouse Mountain, is derived. The lava disconformably overlies either chlorite-grade metasediments, and metavolcanics or propylitized granite and diorite. It is locally interleaved with sandstone and basalt lava, and overlain by basalt lava or crystal-poor rhyolite lava.

Tbo **Older basalt lava** (0-60 meters) Moderately crystal-rich, olivine-pyroxene basalt that occurs at the base or near the base of the volcanic stratigraphy. To the west, lavas of this age assingment are locally interleaved with dacite lava flows of Courthouse Mountain, and they also directly overlie metamorphic basement rocks. To the east another flow overlies a basal dacite lava (Td1) and underlies a rhyolite lava (Tru). The eastern flow locally contains biotite.

Ts **Sandstone** (0-20 meters) Volcaniclastic sandstone between flows of the dacite lava of Courthouse Mountain. Restricted to the western part of the study area.

Tsx **Sedimentary breccia** (0-10 meters) Massive to weakly stratified, clast-supported breccia. Clasts are generally angular, 1 to 20 cm in diameter, and consist of underlying pre-Tertiary crystalline rocks. Matrix and clast surfaces are extensively stained with hematite. Contact with underlying crystalline rocks is locally silty.

Ttb **Basal tuff sequence** (0-70 meters) A sequence of mostly medium-bedded unwelded (ash-fall?) tuffs interleaved with bedded and locally massive, paritally welded, moderately crystal-rich ash-flow tuffs. Occurs at base of volcanic stratigraphy along western edge of study area.

Tqm **Quartz monzonite** Medium-grained to fine-grained, equigranular, biotite and hornblende-bearing quartz monzonite with between 5 and 20% mafic minerals. Locally gradational with magmatically layered dioritic granitoids (Td), or hornblende gabbros (Ta).

GREENSCHIST FACIES METAMORPHIC ROCKS (MESOZOIC?)

Mp **Rhyodacite porphyry** Relatively small, irregular-shaped bodies of greenish crystal-rich rhyodacite porphyry with local intrusive relationships into metasedimentary (Ms) and metavolcanic (Mt) rocks. Phenocrysts assemblage is similar to the rhyodacite tuff unit (Mt), containing large (>5mm) quartz crystals.

Mg, Md **Granodiorite (Mg) and diorite (Md)** Medium and rarely coarse-grained equigranular and locally porphyritic granodiorite and granite. Small bodies of possibly cogenetic or locally younger diorites are also present. These plutonic rocks are typically intensely propylitized and locally highly fractured.

Mgb **Granitoid breccia** Coarse-grained, clast-supported breccia of granite clasts in well indurated greenish matrix. Interpreted as tectonic breccia.

Ms **Argillite, quartzite, quartz-pebble conglomerate, and brown limestone** (up to 400 meters) A metasedimentary sequence dominated by purple argillite and argillaceous siltstones. Interbedded within the argillite, in decreasing order of abundance, are cross-bedded to parallel-laminated quartzites, quartz-pebble conglomerates, brown, quartz-sandy, bioclastic, bioturbated limestones, and green argillites and siltstones. Quartzites and conglomerates are thick- to medium-bedded and typically arranged in fining-upward sequences, and the limestones and green argillites are thin-bedded.

Ml **Limestone** (0-10 meters) White to light gray limestone with *Thalassinoides* burrow networks, which occurs at the base of metasedimentary sequence at one locality in the western Tank Mountains (SW/4 sec. T3S, R14W unsurveyed).

Mr **Rhyolite** (0-5 meters) White, argillicly altered, moderately crystal-poor, rhyolite ash-flow tuff or lava which occurs at the base of the metasedimentary sequence along western edge of study area (NW/4 sec. 7, T3S, R14W unsurveyed).

Mt **Rhyodacite ash-flow tuff and ash-fall tuff** (up to 300 meters) Greenish crystal-rich rhyodacite tuff containing large (>5mm) quartz phenocrysts. The unit occurs as a massive, welded, ash-flow tuff with green, fiamme-like clasts which define a eutaxitic foliation, and subordinate amounts of medium-bedded ash-fall tuffs which are found locally at the top of the unit interbedded with green and purple argillites. Lithic fragments are sparse to absent and the unit is interpreted as a subaqueous pyroclastic flow sequence.

AMPHIBOLITE FACIES METAMORPHIC ROCKS (PROTEROZOIC?)

Xg, Xgl,
Xgl, Xd

Granitoid (Xg), leucogranitoid (Xgl), K-feldspar porphyritic granitoid (Xpg), and "diorite" (Xd) Variably foliated and nonfoliated granitoids differentiated into four main types, all apparently cogenetic and with gradational contacts. Foliation is tectonic-metamorphic in origin, and defined by parallel alignment of mafic minerals, and quartzofeldspathic granoblastic textures. Compositional banding is notably absent. Granitoid, leucogranitoid, and "diorite" are medium-grained equigranular rocks with highly variable mafic mineral contents. Leucogranites typically contain less than 5% mafic minerals, and diorites up to 50% mafics, but the rocks are not strictly classified according to mafic mineral content. The "granitoids" are quartz-bearing, ranging in composition from granite, quartz monzonite, quartz syenite, quartz monzodiorite, and granodiorite with few exceptions. The "diorites" are quartz-free plutonic rocks with compostions ranging from diorite, through monzodiorite to monzonite. The porphyritic granitoid unit is a true granite that is locally megacrystic.

Xo, Xp

Golden Harp metamorphic suite, Orthogneiss (Xo) and paragneiss (Xp) Amphibolite facies, quartzofeldspathic, compositionally banded gneiss divided into two basic types based on relative abundance of leucoscome and melanosome. Gneisses with greater than 50% melanosome were mapped as paragneiss. Melanosomes are typically dominated by biotite with lesser amounts of hornblende. Gneisses with less than 50% melanosome, were mapped as orthogneiss, and these rocks typically contain less than 20% melanosome. The prominent foliation is generally parallel to compositional banding and it is locally parallel to the limbs of isoclinal mesoscopic folds.

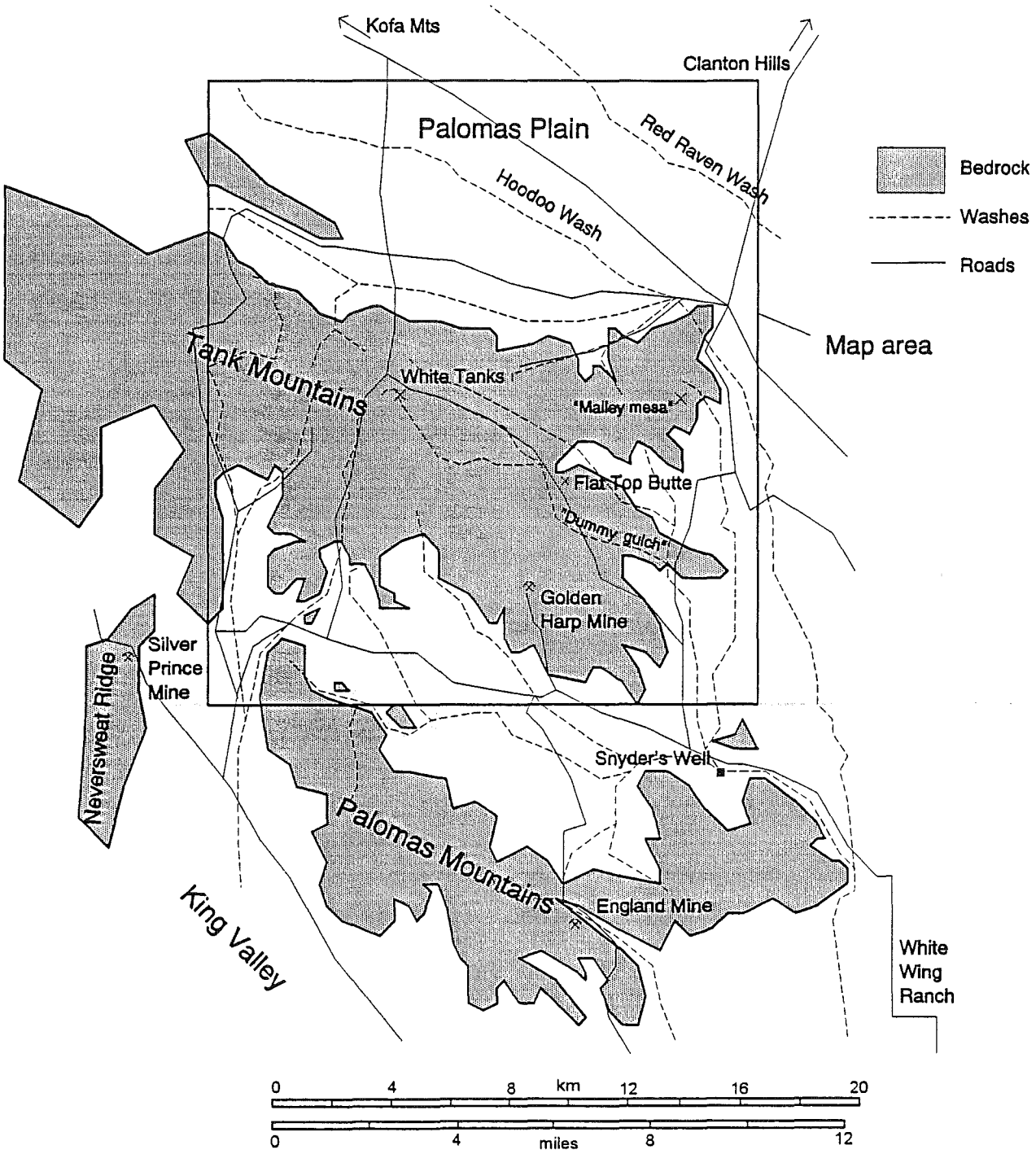


Figure 1. Simplified physiography, access, and place names of the Tank Mountains area. Malley mesa and Dummy gulch are informal place names used in this report.

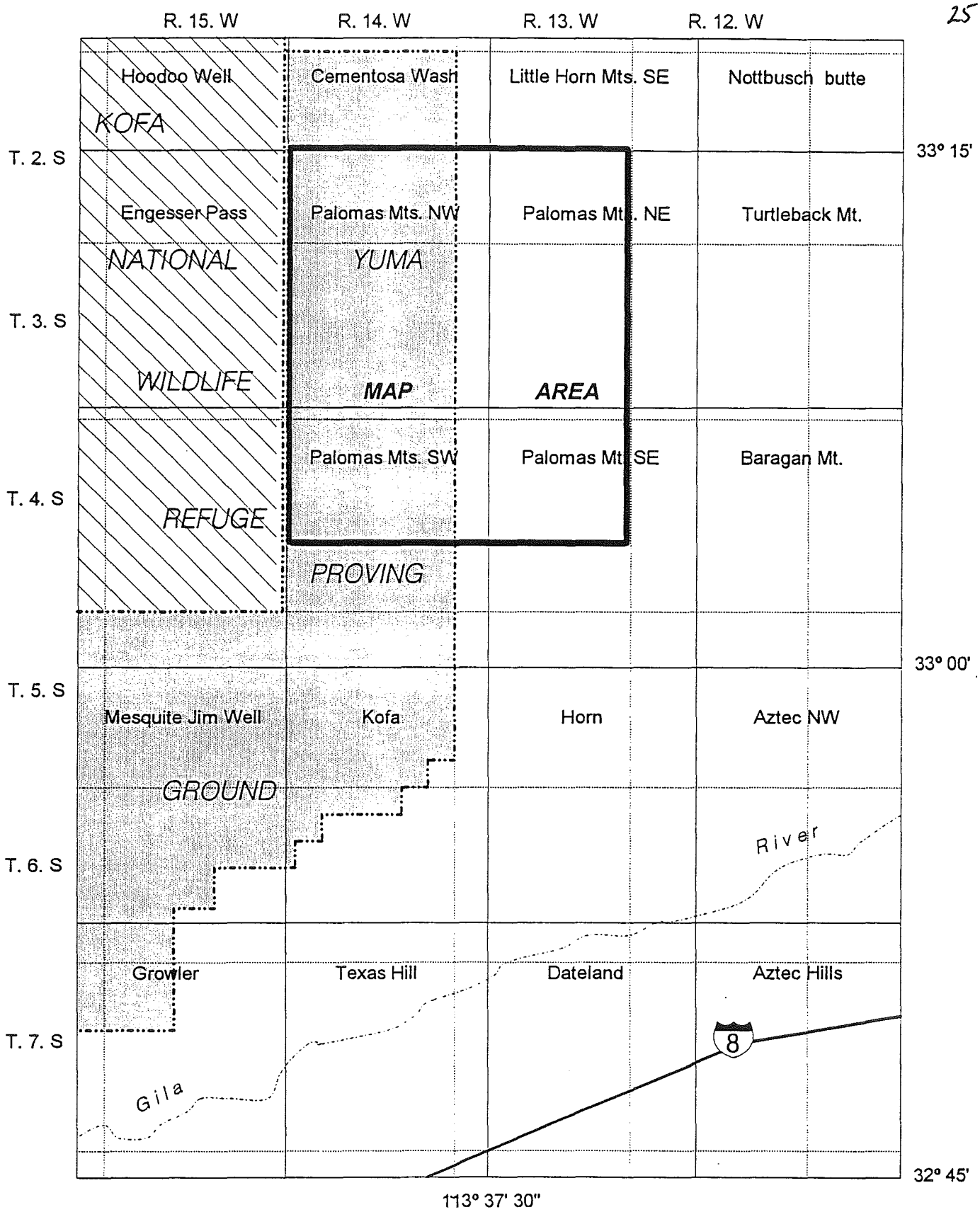


Figure 2. Political boundaries and location of USGS 7.5′ quadrangles in the Tank Mountains area.

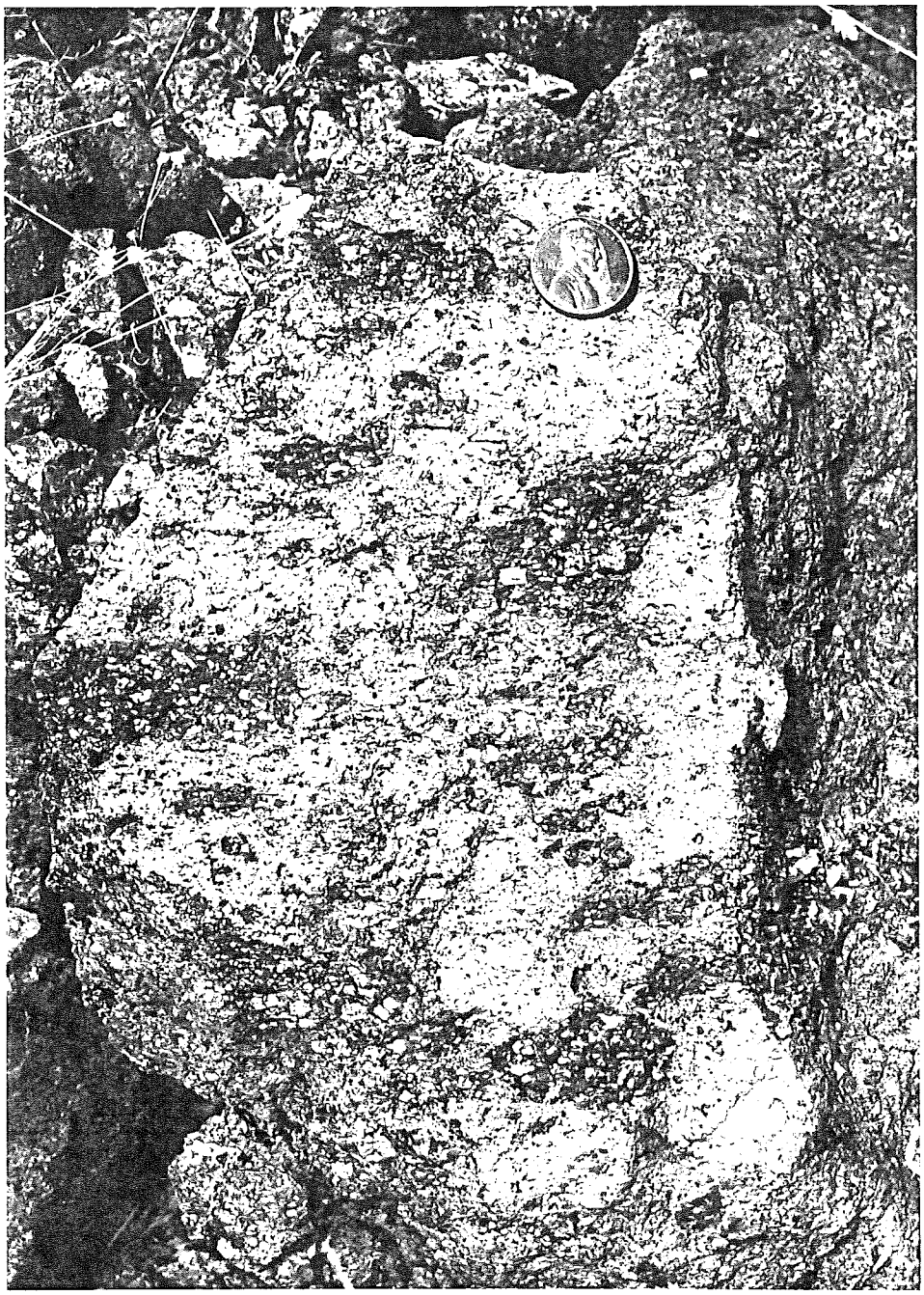


Figure 3. Photograph of crystal-rich rhyodacite (map unit Mt) with dark-colored, compacted clasts believed to be fiamme. The rhyodacite is interpreted as a welded tuff.

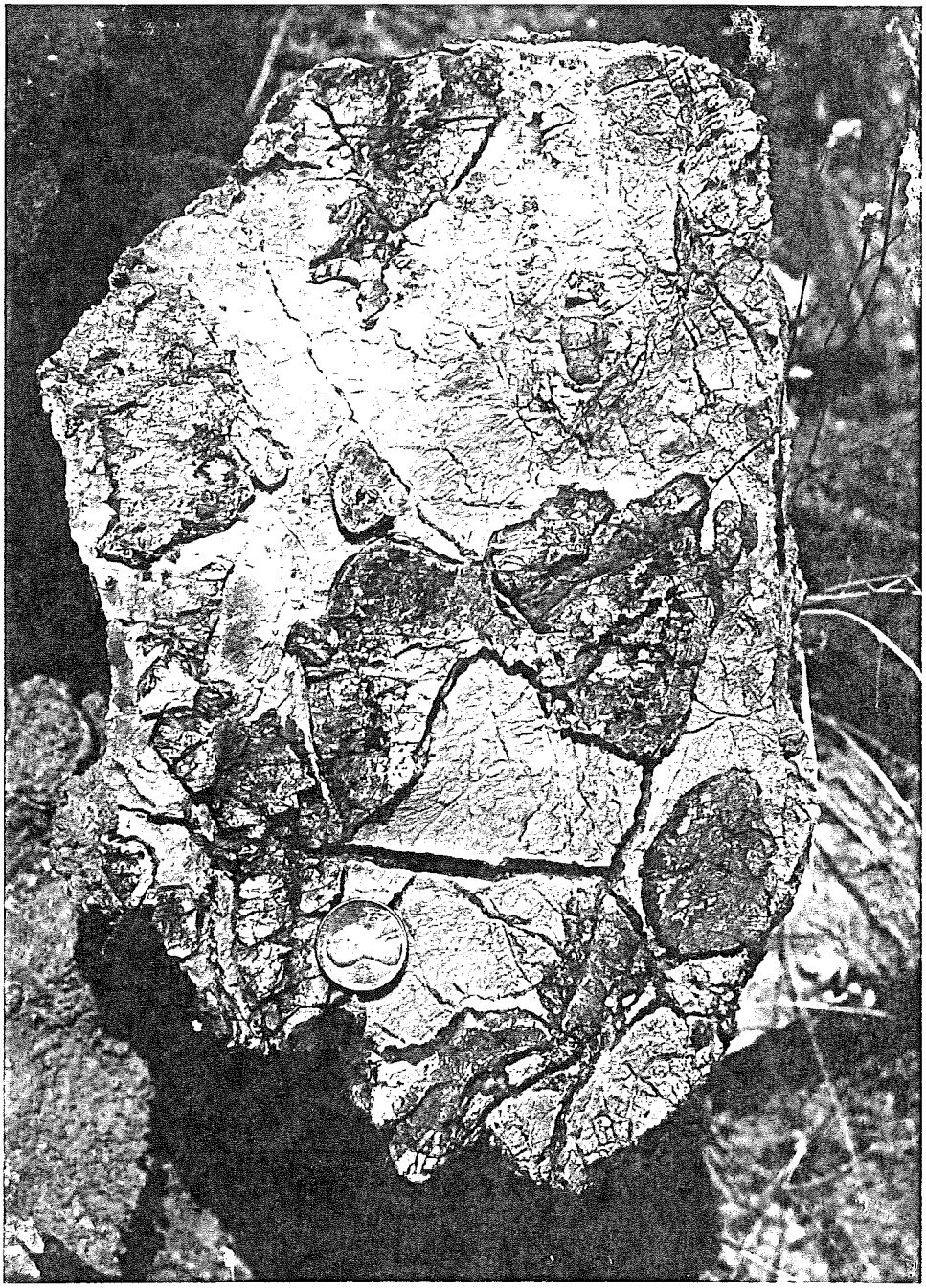


Figure 4. Photograph of light-colored limestone (map unit Ml) with darker-colored, more resistant burrow networks interpreted as *Thalassinoides*.

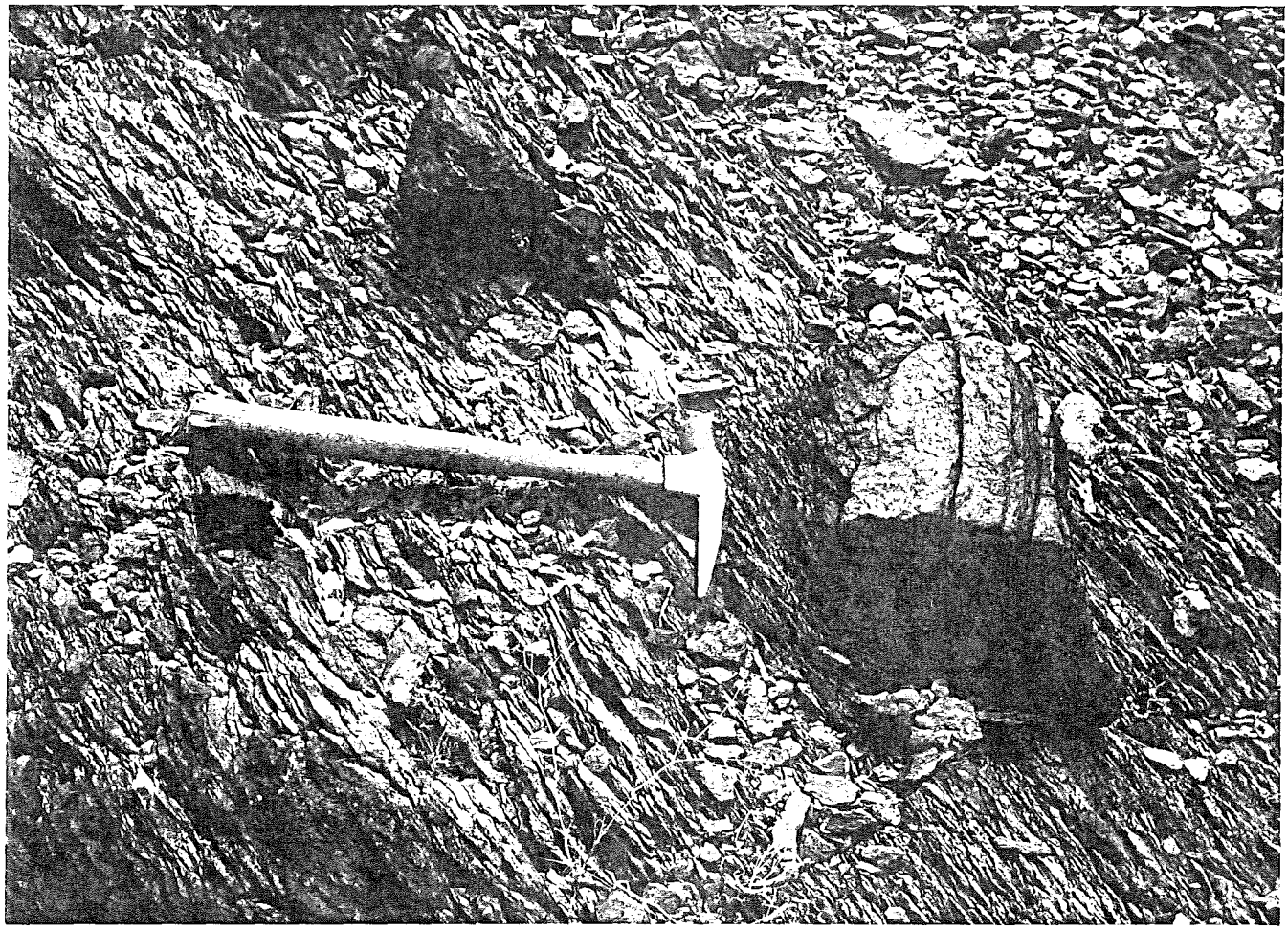


Figure 5. Photograph of bedded tuff clast within dark-colored argillite cut by slaty cleavage.

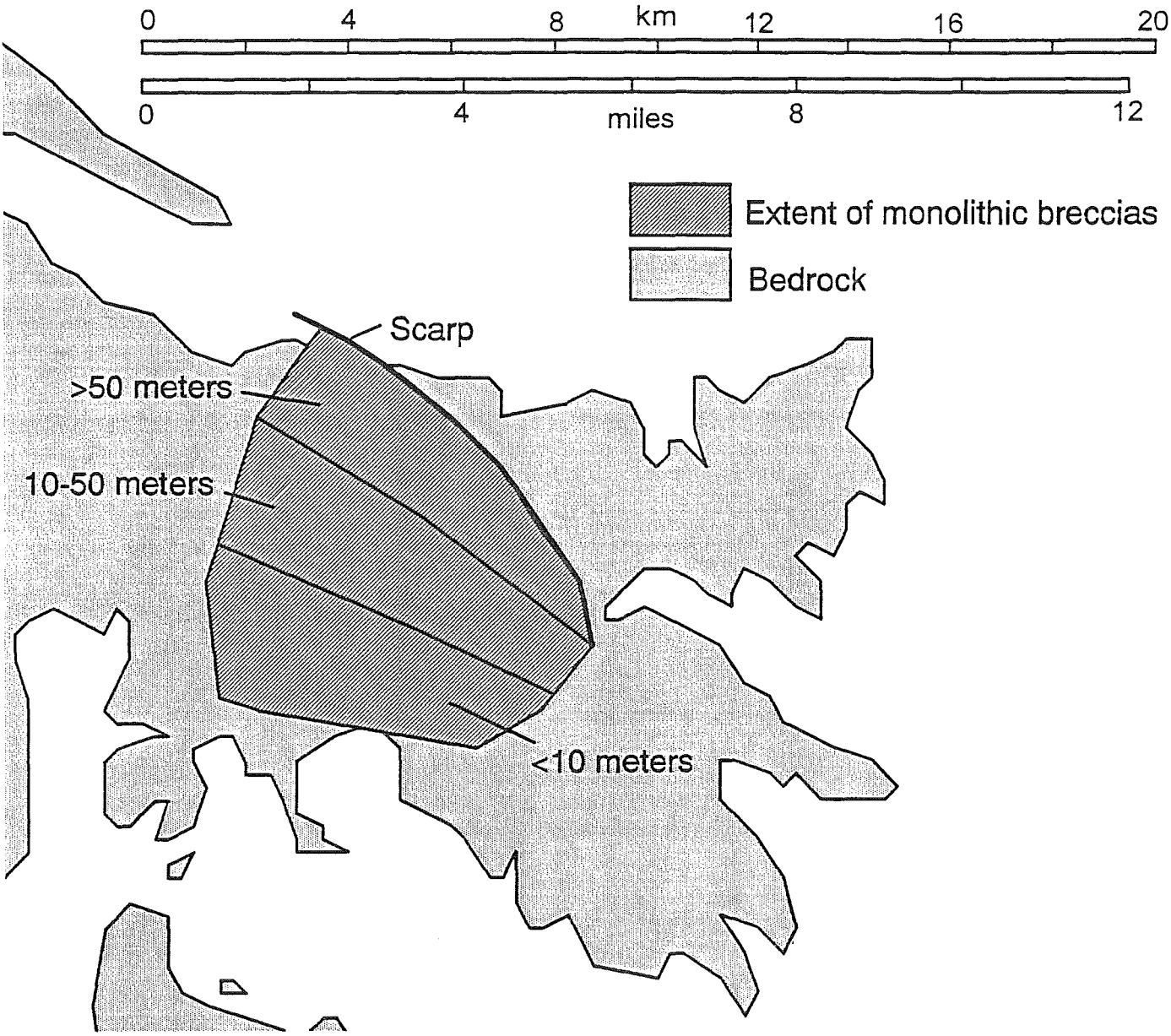


Figure 6. Known distribution of monolithic breccias, their cumulative thickness, and probable location of southwest facing scarp from which they are believed to have been derived.

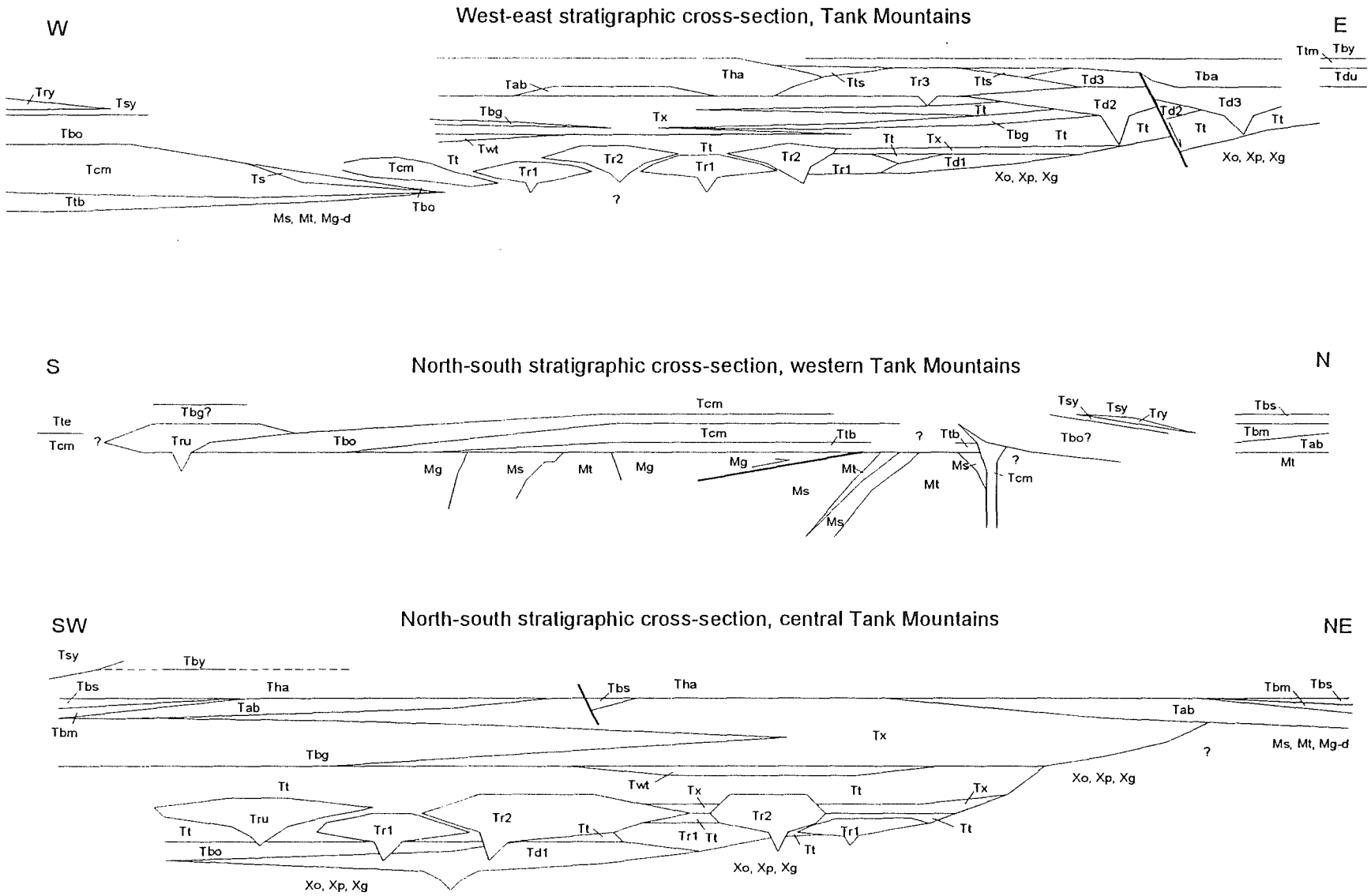


Figure 7. Cross-sectional stratigraphic correlation diagrams for the Tank Mountains.

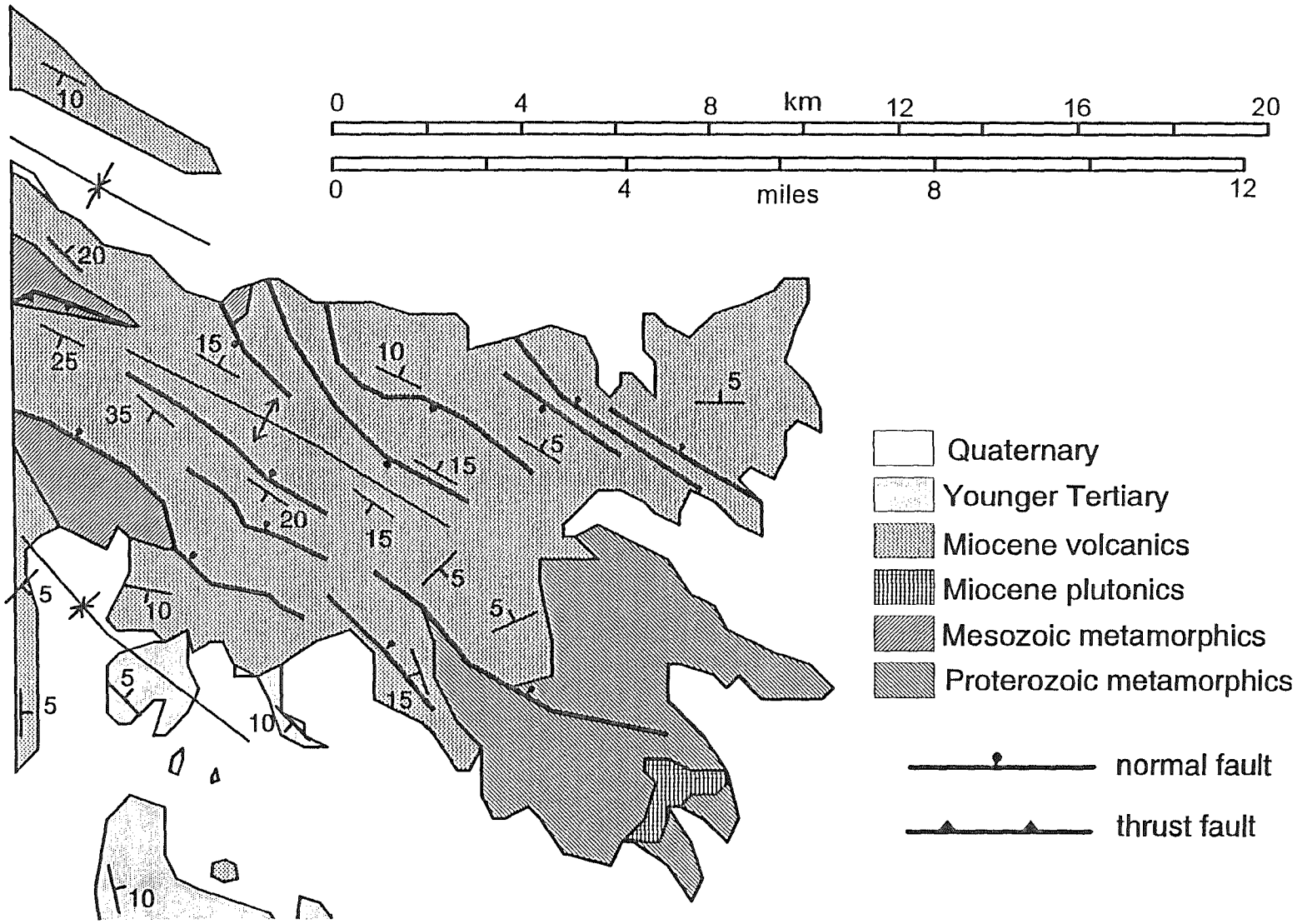


Figure 8. Simplified geology of the Tank Mountains and northwesternmost Palomas Mountains. Fold axes are anticlinal and synclinal tilt-domain boundaries defined by dips of middle Tertiary volcanic and sedimentary rocks.

Explanation of geologic symbols, Geologic map of the Tank Mountains

Contacts and planar map-scale features

depositional contact, dashed where approximately located

fault, dashed where approximately located, dotted where concealed, and queried if concealed relationship is equivocal

strike-slip fault

12 trend and plunge of slickenlines on fault surface

m mafic dike or intrusive body

f felsic dike or intrusive body

54 dip of depositional contact, fault, or dike

Strike and dip symbols

32 bedding

44 bedding, tops known

26 contact between lavas

67 flow-banding within lavas

12 eutaxitic (compaction) foliation

24 slaty cleavage

78 gneissic foliation or metamorphic foliation in granitoids

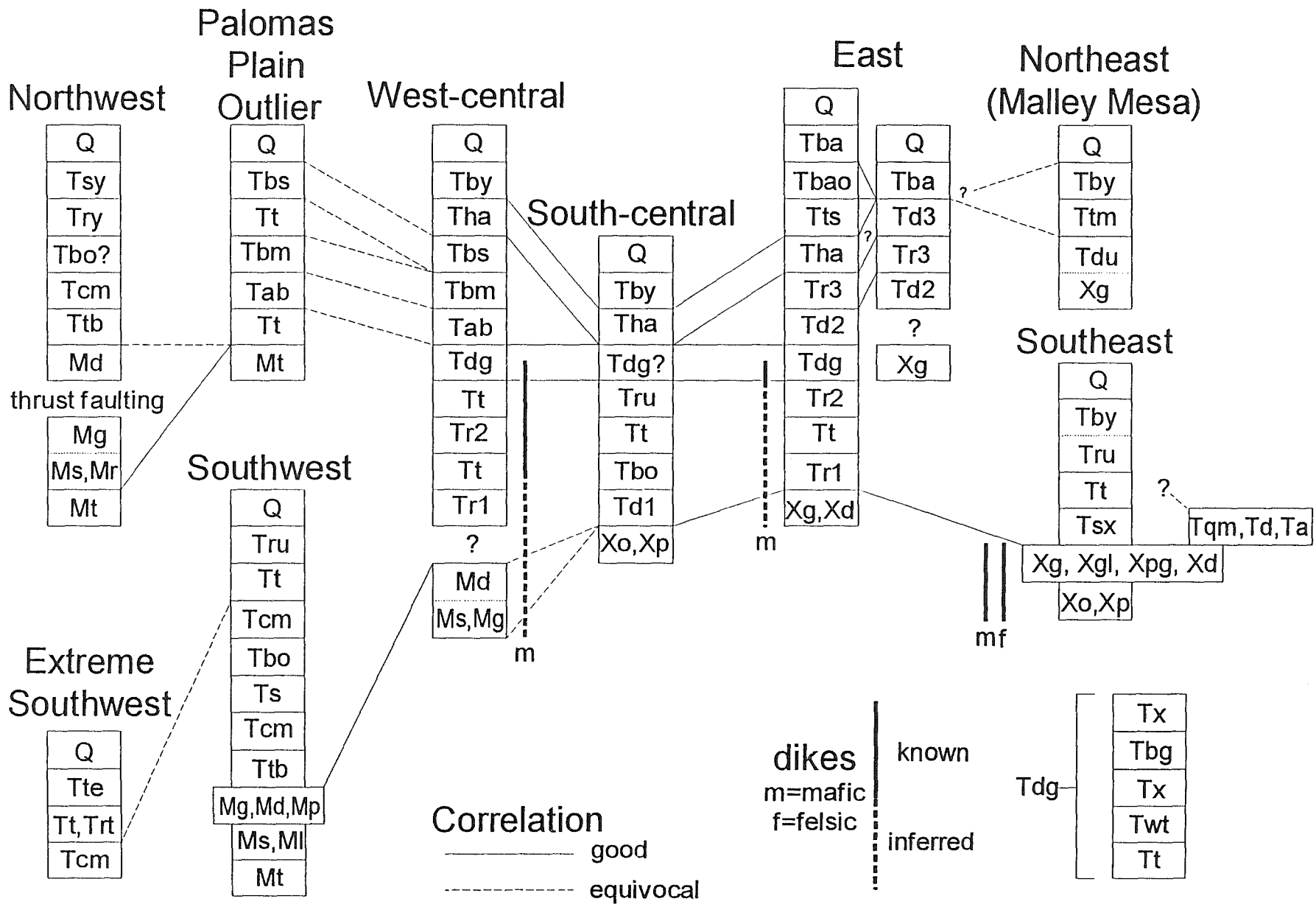
14 magmatic layering in granitoids

Trend and plunge symbols

41 67 lineation coplanar with flow-banding in lavas

horizontal lineation in lavas

14 24 fold hinge line, intersection lineation, or crenulation lineation coplanar with foliation in metamorphic rocks. plunge value omitted in some areas

52 fold hinge line in metamorphic rocks

Correlation of map units, Tank Mountains, Yuma county, Arizona