Geologic maps and cross sections of selected areas in the Rawhide and Buckskin Mountains, La Paz and Mohave Counties, Arizona

by

Robert J. Scott

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Ten sheets, various scales

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

Introduction

The maps in this publication were created by Robert J. Scott during preparation of a Ph.D. dissertation at Monash University in Victoria, Australia (Scott, 1995), that was done under the supervision of Professor Gordon Lister. The Buckskin and Rawhide Mountains, along with the adjacent Harcuvar and Harquahala Mountains, are part of one of the largest metamorphic core complexes in North America. These complexes have attracted international interest because of significant scientific issues surrounding their genesis.

Detailed geologic maps of several structurally complex areas were made in the course of this study. All of the ten maps included in the Ph.D. dissertation make up this publication (three were added to version 2 of this publication). These maps should be of use to anyone interested in the detailed structure and stratigraphy of the several areas covered by the maps. Related structural and thermochronologic studies by Scott (1992, 1998) were done as part of his dissertation research. Other studies and maps of nearby areas, as well as compilation maps, are also available (Spencer and Reynolds, 1989; Bryant, 1995).

In addition, an appendix (see below) included here describes the map units in all ten of the maps.

References cited

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Appendix I

Description of map units

(Rankin Ranch, Rawhide Mine and Planet Peak areas)

Terminology

The following convention was adopted for the abbreviated letter codes for the map units used in this thesis:

(1) the first one (or two) capitalised letters stand for the period in which the rock unit was formed, e.g. Q=Quaternary, T=Tertiary, PM=Palaeozoic-Mesozoic, etc.

(2) the following lower case letters denote the formation name if one exists and/or descriptive terms for the unit, e.g. x=breccia, xv=breccia (volcanic protolith), c=conglomerate, s=sandstone, vb=volcanic basaltic, va=volcanic andesitic, l=limestone, ly=limestone (yellow colour), t=tuff, etc.

The stratigraphic subdivisions used in this study for synextensional deposits in the Rankin Ranch and Rawhide Mine areas are similar to those originally proposed for the Tertiary succession in the northern Rawhide and Artillery Mountains (Lasky and Webber, 1949); e.g. Sequence I (Early Miocene)≈Artillery Formation, Sequence II (Middle Miocene)≈Chapin Wash Formation, and Sequence III (Middle to Late Miocene)≈Sandtrap Conglomerate. The original stratigraphic names provided the basis for the abbreviated letter codes used for individual units within each of the synextensional sequences, i.e Sequence I deposits are all prefixed by *Ta*, for Artillery Formation, Sequence II by *Tcw* and so on. For other map units, the abbreviated letter codes are the same as (or similar to) those used by Bryant (1992) and/or Spencer and Reynolds (1989a) to describe similar units elsewhere in the core complex.

Post-detachment units

Quaternary

Qa

Recent alluvium (Quaternary) - Unconsolidated sand, silt and gravel in washes.

Qt

Talus (Quaternary) - Locally derived unconsolidated debris on hillsides.

Qo

Old alluvial deposits (Quaternary) - Unconsolidated to very poorly consolidated massive to poorly sorted, unstratified light-grey conglomerate. Angular to sub-angular clasts up to 1 m in diameter. Detritus predominantly derived from the lower plate of the Buckskin-Rawhide detachment system. The old alluvial deposits form terraces up to 50 m above modern drainages.

Middle to late Miocene

Tbf

Basin fill (Spencer and Reynolds, 1989a; late Tertiary) - Poorly consolidated or unconsolidated, crudely stratified tan to red-brown sandstone, conglomerate and conglomeratic sandstone in the Rankin Ranch area. Clasts are predominantly sub- to well-rounded, but sub-angular and angular clasts are locally abundant. Maximum clast size varies from <5 cm to >1 m. Individual beds are poorly sorted. Clast types include: Tertiary sandstone and siltstone, Proterozoic crystalline rocks, Palaeozoic carbonate and quartzite, Mesozoic metavolcanic schist, and chloritic breccia and mylonite derived from the lower plate of the detachment system.

Deposits generally fill steep-sided erosional channels up to 40 m deep within the upper plate. Locally the basin fill directly overlies chloritic breccias in the lower plate of the Rawhide fault. *Tbf* is distinguished from the younger alluvial deposits by their greater degree of consolidation, and red-brown colour (reflecting a greater percentage of detritus derived from the upper plate). *Tbf* is similar in both clast content and appearance to the youngest conglomerate within the syn-extensional succession (*Tst*), but are unfaulted and flat-lying throughout. The

maximum preserved thickness of the Basin fill in the Rankin Ranch area is about 35 m. However the unit was probably substantially thicker prior to erosion.

Syn-detachment units - Upper Plate

Middle to late Miocene

Tst

Sandtrap conglomerate (Lasky and Webber, 1949; Middle-Late Miocene) - Tan to red- or orange-brown fluvial±debris flow deposits including conglomerate, conglomeratic sandstone and lesser sandstone. Generally moderately well consolidated, massive to well stratified. Bedding thicknesses range from <10 cm to >1 m. Conglomeratic layers vary from matrix- to clast-supported, and are locally imbricated. Dominant clast types include: Proterozoic granite and crystalline rocks, Palaeozoic carbonate and quartzite, Mesozoic metavolcanic schist, Tertiary sandstone, siltstone and vesicular basalt. In addition chloritic breccia and mylonite derived from the lower plate of the Buckskin-Rawhide detachment system locally comprise <30% of the clasts in *Tst* (Spencer and Reynolds, 1989a) The Sandtrap Conglomerate forms distinctive rounded outcrops, particularly in the southwestern corner of the Rankin Ranch area (south of the Bill Williams River). The unit is at least 500 m thick in both the Rankin Ranch and Rawhide Mine areas, and probably over 800 m thick in the Rawhide Mine area. Regionally deposits resembling *Tst* are transitional (up stratigraphic section) to the late Tertiary Basin fill (e.g. Spencer and Reynolds, 1989a).

Tstc

Sandtrap Conglomerate, conglomeratic facies (Middle to Late Miocene) - As for *Tst*, but lacking or containing only very minor interbedded sandstone.

Tsts

Sandtrap Conglomerate, sandstone facies (Middle to Late Miocene) - Tan to red- or orange-brown well-stratified fluvial sandstone, siltstone and lesser interbedded granule to cobble conglomerate in the Rawhide Mine area. Beds are typically >30 cm, but locally >1 m thick. Clasts in the conglomerate layers are poorly sorted, sub-angular to well-rounded and up to 10 cm in diameter. Clast types as for *Tst*. Sedimentary structures include small erosional channels, cross-bedding and ripple-lamination. *Tsts* is intermediate in appearance between the Chapin Wash Formation and the Sandtrap Conglomerate, and is probably transitional between these units in the southeastern corner of the Rawhide Mine area (Plate 6: SW$^1/_4$, sect. 8 and NW$^1/_4$, sect. 17, T. 11N., R. 13W.). The exposed thickness of the unit in the Rawhide Mine area is about 300 m.

Tcw

Chapin Wash Formation (Lasky and Webber, 1949; Middle Miocene) - Brick red, reddish-brown and tan arkosic sandstone, siltstone and conglomeratic sandstone of fluvial and fluvio-lacustrine origin. The Chapin Wash Formation also includes minor interbedded tuff and thinly bedded dark-grey limestone, mapped separately in some areas. The lower conglomeratic sandstone-dominated portion of the Chapin Wash Formation is massive to moderately well stratified, but the overlying units are generally well stratified. Beds are typically 10-20 cm thick, but range from <2 cm to >1 m thick. Thin bedded sandstones are locally ripple-laminated. Metre-scale cross-bedding occurs in some thickly bedded sandstones and conglomeratic sandstones in the Rawhide Mine area. Sandstones are commonly cut by pervasive centimetre-scale, ~NW-trending normal faults and in weathered exposures the rocks appear to have an irregularly developed anastomosing spaced cleavage.

Most sediments comprising the Chapin Wash Formation are texturally and compositionally immature. Sandstones vary from fine to coarse grained, and are moderately- to poorly-sorted. The clasts are angular to sub-angular, and predominantly composed of (plutonic) quartz, feldspar, mica, lithic fragments and in places detrital manganese oxide. The sandstones have open framework supported by a clay-rich matrix stained red-brown by iron oxides. Clasts are also commonly coated by iron oxides. Secondary carbonate and manganese oxide are locally developed.

Clasts comprising the Chapin Wash Formation were predominantly derived from Proterozoic crystalline rocks, but also include Palaeozoic carbonate and quartzite, Mesozoic schist, Tertiary basalt, limestone, and sandstone. Parts of the Chapin Wash Formation contain abundant pale-coloured tuffaceous detritus. The Chapin Wash Formation locally includes a small amount (<5%) of detritus derived from the lower plate of the detachment system (e.g. Lincoln Ranch area: Spencer and Reynolds, 1989a; Artillery Mountains: Spencer et al., 1989a).

In the Rawhide Mine area the Chapin Wash Formation is about 250 m thick. There are no complete sections of the Chapin Wash Formation Rankin Ranch area, but individual sections suggest the total thickness may be 300-350 m or more. In the Rankin Ranch area the Chapin Wash is subdivided into an upper (*Tucw*), lower (*Tlcw*) and basal (*Tcwb*) member. Locally the upper member is further subdivided into sandstone-, siltstone- and conglomerate-dominated units or

facies. The lower and basal members were not mapped separately, and the upper member was not subdivided in the Rawhide Mine area.

Tucw

Interbedded sandstone and conglomerate (Middle Miocene) - Medium bedded, well-stratified sandstone-dominated interbedded sandstone, siltstone, and conglomeratic sandstone. Tan to red- or orange brown in colour; pale brown or cream where tuffaceous detritus is abundant. Detrital and diagenetic manganese oxide are locally significant. Small (3-20 cm in diameter) manganiferous nodules are common at some stratigraphic levels. Generally less ferruginous than underlying *Tlcw*. Clast composition as for *Tcw*. Locally subdivided into conglomerate-bearing (*Tcwc*), sandstone dominated (*Tcws*) and siltstone-mudstone dominated facies (*Tcwm*). Also includes silicic airfall tuff (*Tcwt*) and thinly bedded manganiferous limestone (*Tcwl*). *Tucw* is 50-130 m thick in the Rawhide Mine area, and 100-150 m thick in the Rankin Ranch area.

Tcwc

Interbedded sandstone and conglomerate (Middle Miocene) - Medium to thickly bedded, well-stratified, sandstone-dominated interbedded sandstone, siltstone, pebble to cobble conglomerate and conglomeratic sandstone. Tan to red- or orange brown in colour; locally manganiferous. This facies is best developed in the southwestern corner of the Rankin Ranch study area (Plate 2: SW$^1/_4$, sect. 8, T. 10N., R. 14W and SW$^1/_4$, sect. 8, T. 10N., R. 15W.) where it is interbedded with the marker tuff (*Tcwt*). Clast composition as for *Tcw*, including minor mylonitic clasts derived from the lower plate of the detachment system. This unit is similar and possibly equivalent to the sandstone-dominant facies if the Sandtrap Conglomerate (*Tsts*) immediately west of the Sandtrap Wash fault in the Rawhide Mine area.

Tcws

Sandstone (Middle Miocene) - Tan, red- to orange-brown, well-stratified, thin, medium or thickly bedded sandstone and lesser siltstone. Beds rich in detrital and diagenetic manganese oxide are common. Pale brown to cream tuffaceous detritus is locally significant, particularly within the strata overlying the marker tuff (*Tcwt*). Small (3- 20 cm) ovoid manganiferous nodules (concretions) occur locally within sandstones in Rankin Ranch area, north of the Bill Williams Rive. The sandstone-dominant facies is up to 100 m thick in the Rankin Ranch area.

Tcwm

Mudstone, siltstone and sandstone (Middle Miocene) - Fluvio-lacustrine facies of the Chapin Wash Formation (Rankin Ranch area). Well-stratified, laminated to thinly bedded, multi-coloured (red-brown, orange, purple, green-grey or cream) sandy-mudstone, siltstone and lesser sandstone. This facies only occurs in the Rankin Ranch area, particularly at or above the stratigraphic level of the marker tuff (*Tcwt*). The maximum thickness of the siltstone and mudstone-dominated facies may be as much as 150 m.

Tcwt

Air-fall tuff (Middle Miocene) - Cream-coloured, non-welded silicic air-fall tuff within the Chapin Wash Formation. Tuff beds up to 50 cm thick and sandstones rich in tuffaceous detritus occur throughout the upper Chapin Wash Formation. However one prominent tuff horizon, up to 5 m thick, is exposed in a number of areas within the Rankin Ranch area and forms a useful stratigraphic marker (the *"marker tuff"*). The horizon is generally represented by a single layer of massive to moderately stratified cream-coloured tuff (or series of amalgamated deposits). In several locations two tuff beds (<1.5 m thick) are separated by up to 1 m of thinly bedded sandstone, siltstone and manganiferous limestone. In some areas the tuff is overlain by 5-10 m of pale brown to cream sandstone containing abundant tuffaceous detritus (e.g. just south of Rankin Ranch, Plate 2: NE$^1/_4$, sect. 8, T. 10N., R. 14W.). Locally the tuff occurs within thinly-bedded mudstone, siltstone (*Tcwm*) and limestone (*Tcwl*) suggesting deposition in a shallow lacustrine setting.

The marker tuff contains <5-50 % (angular and fractured) clasts of plutonic quartz, feldspar and other lithic fragments up to 2 mm in diameter, ~5 % strongly aligned biotite flakes (<1 mm long) and glass shards within a siliceous micro- to cryptocrystalline matrix. Locally the tuff also contains accretionary lapilli from 5-20 mm in diameter and sub-angular to sub-rounded lithic fragments (interpreted as volcanic bombs) <6 cm in diameter. The presence of the coarser pyroclastic material suggests the tuff was deposited within several kilometres of the vent.

The marker tuff is probably coeval with similar silicic tuff and associated rhyolitic flows in the Castaneda Hills - Aubrey Peak area, 18-20 km NNE of Rankin Ranch (e.g. Suneson and Lucchitta, 1983; Lucchitta and Suneson, 1994). Silicic volcanic rocks from these areas have K-Ar (sanidine) ages in the range 15.1-12.4 Ma (Suneson and Lucchitta, 1983; Lucchitta and Suneson, 1994).

Tcwl

Limestone (Middle Miocene) - Thin bedded grey to black, manganiferous limestone and calcareous sandstone. Some limestone beds contain irregular siliceous laminations, and chert-like nodules. Sparse angular fragments of medium- to coarse-grained sand are generally

distributed throughout the limestone. Sample *101553* (Appendix III) contains poorly preserved spherical fossils that may be either gastropods or postcards. Individual limestone beds are 5-50 cm thick. Multiple limestone beds are interbedded with thinly bedded sandstone, siltstone and mudstone over intervals up to several metres thick.

Tlcw

Lower Chapin Wash Formation (Middle Miocene) - Medium to very thickly bedded brick-red, yellow orange or grey conglomeratic sandstone and sandstone. The lower part of the unit is massive to poorly-stratified and contains about 5-10% cobble-sized (or larger) clasts. The upper parts of the unit are moderately to well stratified, and transitional to *Tcws*. Clasts are predominantly derived from Proterozoic crystalline rocks but Palaeozoic and Mesozoic metamorphic rocks, Tertiary basalt, sandstone and limestone are also present. The largest clasts are well-rounded cobbles of foliated and non-foliated Proterozoic granite and gneiss, up to 20 cm in diameter. These predominantly occur near the base of the unit, and are similar to those in the underlying basal conglomerate (*Tcwb*). The large clasts may be present for 10s of metres above the base of the unit, but both the maximum clast size and abundance of conglomeratic material both decrease up stratigraphic section.

The sandstones are composed of angular to sub-rounded, coarse to very coarse grained quartz, feldspar and lithic fragments and are typically coated by iron and manganese oxides. In some areas (e.g. Rawhide Mine area) conglomeratic sandstone containing well-rounded detritus is interbedded with pebbly sandstones composed almost exclusively of angular material. The angular clasts were probably derived from the underlying sedimentary breccia (*Taxg*). In both the Rankin Ranch and Rawhide Mine areas the lower Chapin Wash Formation has a maximum thickness of ~200 m.

Tcwb

Basal conglomerate (Middle Miocene) - Poorly sorted conglomerate, conglomeratic sandstone, and sandstone probably deposited in the intermediate or distal reaches of an alluvial fan. The conglomerate predominantly has an open framework and is matrix-dominated, but locally the percentage of cobbles >5 cm exceeds 30-40% of the deposit. Clasts are rounded to very well rounded, and many have a high degree of sphericity. The largest clasts in the conglomerates are up to 50 cm in diameter. In some areas, erosion of the sandstone matrix has left a distinctive colluvium of numerous bowling ball sized clasts.

Greater than 95% of the clasts were derived from the Proterozoic crystalline basement and consist of foliated and non-foliated granite and gneiss. Other clast types present include Palaeozoic and Mesozoic metamorphic rocks, and Tertiary vesicular basalt, sandstone and limestone. The conglomerate and conglomeratic sandstone are interbedded with coarse- to very coarse-grained sandstone up to 30 cm thick. In some areas minor thin to medium bedded grey limestone also occurs near the base of the unit. The basal conglomerate grades upwards into the lower Chapin Was Formation (*Tlcw*). The boundary between the two units is gradational but approximated by the disappearance of beds containing >30% clasts >5 cm diameter. In the Rawhide Mine area, conglomeratic beds are distributed throughout the entire lower Chapin Wash Formation (*Tlcw*), and the two units were not mapped separately. The basal conglomerate is <50 m in the Rankin Ranch area.

Early to middle Miocene

Ta

Artillery Formation (Lasky and Webber, 1949; Late Oligocene-Middle Miocene) - Heterogeneous assemblage of sedimentary and lesser volcanic rocks. Poorly sorted, angular to sub-rounded coarse clastic sedimentary material is abundant. Essentially monolithologic debris flow and sedimentary breccia deposits (including rock-avalanche deposits, often termed megabreccias) are characteristic of the unit as a whole. Bedding thicknesses typically range from several metres to a few centimetres. However individual sedimentary breccias are up to 100 m thick, and amalgamated and/or megabreccia-dominated deposits are up to 450 m thick in the Rawhide Mine area. Clasts in the sedimentary breccias are up to 10s and even 100s of metres in diameter. Lesser mafic to intermediate volcanic flows, silicic tuff and limestone are interbedded with the clastic sedimentary units.

Talb

Limestone (Early-Middle Miocene) - Massive or poorly-stratified dark grey to black impure limestone ± grey calcareous sandstone and conglomerate up to 5 m thick. Commonly irregularly developed or brecciated.

Taly

Limestone (Early-Middle Miocene) - Well-stratified, thin to very thinly bedded yellow, pink and pale grey limestone, calcareous siltstone and sandstone. Soft-sediment deformation structures (including centimetre-scale isoclinal folds) are common. The unit is typically <1-2 m thick, but in some areas the limestones are interbedded with sandstone and conglomeratic sandstone (*Tas*, *Tac*) over intervals of up to 10 m.

Taxg

Sedimentary breccia, granite protolith (Middle Miocene) - Non-stratified, unsorted sedimentary breccia composed almost entirely of foliated and non-foliated Proterozoic biotite granite. Generally off-white or pale greenish-grey in colour. Clasts are predominantly angular, tending to sub-rounded locally, and vary from several centimetres to several metres in diameter. The breccia varies from open to closed-framework. Closed-framework breccias generally have an interlocking fabric. Local jigsaw fit between adjacent clasts suggests parts of the breccia body were transported as a relatively coherent mass. The fine to coarse grained grey sandy matrix is similar in composition to the clasts and is almost certainly the product of pulverisation and abrasion during transport. The matrix generally comprises <20 to 50% of the unit.

Taxg does not appear to contain interbeds of other sedimentary units, suggesting that it represents a single rock-avalanche deposit. The top of the unit locally has a more open-framework and the matrix includes ferruginous sand similar to that in the surrounding sedimentary rocks, suggesting localised reworking of the deposit. In the Rawhide Mine area (Plate 6: NW$^1/_4$, sect. 7, T. 10N., R. 13W) possible rip-up clasts up to several metres in diameter, that were apparently derived from the underlying basalt (*Tavb*) occur near the base of the unit.

Relations with surrounding rocks in the Rawhide Mine area indicate both the upper and lower surface of the megabreccia had considerable (>20 m) relief. In the Rawhide Mine area the megabreccia is up to 40 m thick, and is locally separated from older Tertiary units by an angular unconformity. In the Rankin Ranch area *Taxg* appears conformable. In this area it is typically 5-25 m thick, but up to 70 m thick locally. *Taxg* almost certainly correlates with the "Artillery megabreccia" (Spencer et al., 1989a) that underlies the Chapin Wash Formation in the Artillery Mountains.

Tac

Conglomerate and conglomeratic sandstone (Early-Middle Miocene) - Polymictic, matrix-supported, granule to cobble conglomerate and conglomeratic sandstone. Deep red to pale pink-grey or brown in colour. Poorly- to well-stratified, medium to very thickly bedded. Clasts vary from angular to well rounded. The unit includes sedimentary rocks interbedded with limestone (*Taly*, *Talb*) and granite-bearing megabreccia (*Taxg*) west of "Red Mountain" (Rankin Ranch area), north of Black Burro Mine (Rankin Ranch area) and in the Rawhide Mine area. *Tac* also includes pale brown, grey and purple polymictic conglomerate and minor breccia interbedded with sedimentary megabreccias (*Taxv*, *Taxu*), limestone (*Talx*) and tuff (*Tat*) in the Rankin Ranch area (e.g. Plate 2: NE$^1/_4$, sect. 33, T. 11N., R. 14W.).

Mesozoic metavolcanic and metasedimentary detritus dominates the stratigraphically lower units, but clasts of Proterozoic granite and gneiss, Palaeozoic carbonate and quartzite and Tertiary basalt (including clasts >2 m in diameter, e.g. Plate 3: SE$^1/_4$, sect. 31, T. 11N., R. 14W.), sandstone and conglomerate are common at higher stratigraphic levels. The coarse sandy matrix is dominated by angular fragments of Fe-oxide coated quartz and feldspar.

Tas

Sandstone (Early-Middle Miocene) - Poorly to well-stratified, thinly to medium bedded sandstone and lesser conglomeratic sandstone. Maroon to pale pink-grey or brown in colour. Finer grained equivalent of *Tac*.

Tavb

Basalt (Early-Middle Miocene) - Dark grey to black or purple-grey, vesicular basalt up to 35 m thick. Typically highly weathered, fractured and cut by numerous carbonate veins. Copper carbonate is locally present within fractures and amygdales (e.g. SW of "Red Mountain", Plate 3: NE$^1/_4$, sect. 6, T. 10 N., R. 14 W.).

Tava

Trachyandesite and andesite (Early-Middle Miocene) - Green-grey to black, fine grained trachyandesite or andesite. Typically non-vesicular, moderately to highly altered and brecciated (including (?)flow breccia). The rock contains up to 5% feldspar phenocrysts (up to 3 mm long) set in a fine grained matrix (<0.25 mm) of K-feldspar ± plagioclase(?). The matrix forms 60-90% of the rock and have a well developed trachytic texture. Interstitial iron oxides and quartz form <10% of the rock. Sample *101563* contains up to 15% interstitial epidote + chlorite after an unidentified mafic phase. Minor to locally intense carbonate alteration and veining is common. Unit is up to 15 m thick.

Tacv

Conglomerate, conglomeratic sandstone and sandstone (Early Miocene) - Massive to moderately well-stratified, thinly to very thickly bedded, deep red, maroon or pink-grey pebble to boulder conglomerate, conglomeratic sandstone and sandstone. Clasts in the conglomerates are almost entirely (>95%) derived from pale grey to purple-grey schistose Jurassic metavolcanic rocks. Other clast-types include quartzite, chert (unknown age), and carbonate rocks of Palaeozoic and (?)Tertiary age. Most clasts are sub-angular to sub-rounded and <20 cm in diameter. The largest clasts are several metres across. Conglomerates are generally matrix-supported (i.e. open-framework), but clast-

supported locally. Clasts larger than pebble-size locally form up to 70% of individual beds. Conglomerates are generally poorly sorted with random oriented clasts. However some beds are moderately well imbricated. Sedimentological characteristics suggest a mixed debris flow/fluvial origin for the unit, probably within the proximal fan environment.

The unit displays crude upward fining, although finer grained (i.e. sandstone) beds are locally present at all stratigraphic levels. Sandstone beds and the coarse- to very coarse-grained sand matrix of the conglomerates are predominantly composed of sub-angular to angular quartz, feldspar and metavolcanic material, typically with a ferruginous coating. The matrix material appears to have been derived from the same source as the larger clasts. *Tacv* is interbedded with basaltic flows (*Tavb*), limestone (*Taly/Talx*?), tuff (*Tat*) and sedimentary breccia (*Taxv*). The unit is typically less than 40 m thick (but locally up to 70 m thick) in the Rankin Ranch area and generally <150 m thick in the Rawhide Mine area.

Tat

Non-welded tuff (Early Miocene) - Pink, cream or grey tuff and tuffaceous siltstone and sandstone. Rare beds up to 1.5 m thick are interbedded the metavolcanic-derived megabreccia (*Taxv*) conglomerate (*Tacv*) and associated limestone (*Talx*).

Talx

Limestone (Rawhide Mine area, Early Miocene) - Poorly to well stratified, medium to very thinly bedded, pink, yellow, brown and grey limestone and silty-limestone in the Rawhide Mine area. Layering is defined by colour changes and thin resistant siliceous(?) laminations, and is commonly chaotically folded and disaggregated. The unit generally overlies the Mesozoic clast-bearing megabreccia (*Taxv*). However randomly oriented blocks up to several metres in diameter are also incorporated into the sedimentary breccia in the Rawhide Mine area (Plate 6: NW$^1/_4$, sect. 7, T. 11N., R. 13W.). A possibly equivalent limestone unit in the Rankin Ranch area (Plate 2: NE$^1/_4$, sect. 33, T. 11N., R. 14W.) is interbedded with brown- to blue-grey siltstone, sandstone and granule to pebble conglomerate (*Tas/c*). The maximum thickness of the unit is 5-10 m.

Taxu

Sedimentary breccia (Early Miocene) - Non-stratified, massive, poorly-sorted sedimentary breccia (rock-avalanche deposits). Dominant clast types are dark grey or brown Palaeozoic carbonate, quartzite and a dark green weathering highly altered mafic to intermediate igneous rock of uncertain origins. Similar breccias appear to occupy different stratigraphic positions, but most commonly overlie (or are incorporated into) the metavolcanic-bearing megabreccia (*Taxv*). The megabreccias are clast-supported and adjacent clasts generally have an interlocking and locally jigsaw-fit fabric. Some of the larger coherent blocks in the breccias are tens to hundreds of metres across. Isolated exposures of Palaeozoic-Mesozoic rocks, or outcrops where the stratigraphic relations are not clear could be either pre-Tertiary basement (i.e. *PM*) or large blocks within the Tertiary megabreccias.

Taxv

Sedimentary breccia, Jurassic metavolcanic protolith (Early Miocene) - Non-stratified, poorly sorted, clast-supported sedimentary breccia composed almost entirely of angular to sub-rounded schistose metavolcanic clasts (probably derived from the Jurassic Planet volcanics, e.g. Spencer et al., 1986). Lesser chert, quartzite and metasedimentary(?) schist fragments are also present. Generally off-white, pale purple-grey, pink or reddish-brown in colour. Maximum clast size varies from <5 cm to >10 m. The silt to granule-sized matrix, which locally forms up to 50% of the deposit, is composed pulverised metavolcanic material. The breccias are interpreted to be rock-avalanche deposits (e.g. Yarnold, 1993). In the Rawhide Mine area, the upper part of the unit includes interbedded Tertiary limestone, tuff, and fluvial conglomerate. In most cases the metavolcanic protolith was extensively disaggregated and clasts are randomly oriented. However, in some areas the schistosity in the "clasts" is consistently oriented over many tens of metres (e.g. Plate 6: SE$^1/_4$, sect. 1, T. 11N., R. 14W.) suggesting that the breccias either grade downwards into fractured bedrock or include clasts that are hundreds of metres in diameter. The breccias also contain relatively coherent blocks of Palaeozoic-Mesozoic metasedimentary and metaigneous rocks that are up to several hundred metres across. Some of the exotic blocks may represent a stratigraphically higher mass-flow unit (i.e *Taxu*). In the Rankin Ranch area *Taxv* is up to 110 m thick, while in the Rawhide Mine area the maximum exposed thickness of the unit is 450 m thick.

Pre-detachment units - Upper plate

Proterozoic - Mesozoic

Jv

Planet Volcanics (Spencer et al., 1986; Middle to Late Jurassic) - Pale grey, purple-grey and brown schistose to locally massive metavolcanic

rocks. A weak lineation is locally developed on the foliation surfaces. The foliation is defined by strongly aligned muscovite and biotite, and wraps around embayed and fractured phenocrysts of quartz and feldspar. The schistosity is intensely folded in some areas. Rocks mapped as *Jv* may locally include large (i.e. 10s-100s metres across) coherent blocks within the Tertiary megabreccias (*Taxv*).

PM

Undifferentiated Palaeozoic and Mesozoic rocks - Predominantly Palaeozoic carbonates, with lesser quartzite, phyllite and schist. The carbonate rocks (marble, limestone and (?)dolomite) are pale to dark grey or brown but are generally characterised by a very rough black weathering surface. Commonly intensely fractured and folded. In some instances large coherent blocks of Palaeozoic and Mesozoic rocks (up to several 100 m across) may belong to the Tertiary megabreccias.

YXg

Biotite granite (after Bryant, 1992; Early to Middle Proterozoic) - Medium to coarse grained biotite granite, with a locally developed foliation that occurs in the southwest of the Rawhide Mine area. Contains abundant quartz veins. This rock-type is a possible protolith for granite-bearing megabreccia (*Taxg*).

Lower plate and detachment fault

Late Oligocene - Miocene

Tc

Hydrothermal carbonate (Miocene) - Dark brown to grey hydrothermal carbonate developed immediately above the detachment fault. In the study areas the carbonate is best developed in the northwestern of the Black Burro Mine (Plate 2: $W^1/_4$, sect. 28 and $E^1/_4$, sect. 29, T. 11N., R. 14W.) and along the Buckskin fault northwest of Planet Peak. Maximum thickness 1-2 m. Carbonate replaces a variety of upper plate lithologies including Palaeozoic carbonate, Jurassic metavolcanics and Tertiary sedimentary rocks of the Artillery and lower Chapin Wash formations.

Tfg

Fault gouge (Miocene) - Green-grey, white, purple or brown micaceous or clay-rich foliated fault gouge locally developed immediately below the Rawhide fault in the Rankin Ranch area (e.g. Plate 3: $SW^1/_4$, sect. 32, T. 11N., R. 14W.). Varies from <10 cm to ~5 m thick. The foliation parallel or at a low-angle to the detachment fault and parallel to a pronounced colour-banding reflecting the juxtaposition or inter-layering of different generations of fault gouge. The gouge contains 5-30% sub-angular to sub-rounded fragments of mylonite, microbreccia and chloritic breccia up to 8 cm in diameter. Asymmetric and conjugate shear bands at a low-angle to the foliation are locally developed within the gouge.

Tmb

Microbreccia (Oligo-Miocene) - Dark brown, pale brown or green flinty (aphanitic) ultracataclasite developed along and up to 20 cm below the detachment fault. The microbreccia is well-indurated and relatively resistant to erosion; often weathering in relief to form a prominent ledge. The upper surface of the microbreccia is commonly highly polished, but rarely striated. The microbreccia is discontinuous and generally <2 cm thick or absent in areas where the fault gouge (*Tfg*) is developed.

Successive generations of microbreccia produced a crude to locally well-developed colour banding (~3 mm to >2 cm thick) parallel to the detachment fault. The internally microbreccia layers appear massive. However, strongly aligned, very fine grained phyllosilicates define a weak foliation in some microbreccias. Carbonate ± chlorite and quartz + chlorite ± epidote veinlets both cut and are over-printed by the microbreccias.

Three main types of microbreccia are developed in the study areas. In order of increasing age and depth of formation these are (1) pale brown to green layered microbreccia, (2) massive dark brown microbreccia and (3) massive green microbreccia. All three types contain <5 to 30% sub-millimetre-sized (and occasionally much larger), subangular to rounded fragments of chloritic breccia, mylonite, carbonate, epidote and quartz, as well as earlier generations of microbreccia. The clasts are randomly distributed throughout the micro- to cryptocrystalline matrix of the microbreccia. The green microbreccia is the only type in which the matrix is sufficiently coarse grained (<12.5 μm in diameter) that constituent grains can be optically distinguished.

Tcb

Chloritic breccia (Oligo-Miocene) - Moderately to intensely fractured and propylitically (i.e. chlorite + epidote + quartz + carbonate ± haematite) altered mylonite. Pale to dark green-grey in colour, due to the abundant chlorite and epidote. Primarily developed in a zone up to 50

m thick below the detachment fault but also adjacent to some of the larger faults in the lower plate. The intensity of the fracture and alteration is often so great that mylonitic fabrics can not be discerned in the field. The alteration assemblages also occur as vein and fracture fill throughout the unit and locally within the underlying mylonites.

Tbd

Basaltic dykes (Middle Miocene?) - Rare subvertical, NW-trending fine grained basaltic(?) dykes exposed around Planet Peak. Dykes are 30 cm to 1 m thick and have very fine grained chilled margins. The dykes cut the mylonitic fabric and all other lower plate rock types.

Thi

Felsic to mafic hypabyssal dykes and sills (Oligo-Miocene) - Thin, pale to dark grey, fine-grained porphyritic dykes and sills. The intrusions range from <5 cm to >5 m in thickness, but are typically ~1 m thick. The thicker sheets can be traced for 100s of metres. The intrusions are generally discordant to the gneissic foliation in Proterozoic rocks, but parallel to the Tertiary mylonitic fabric. A moderately- to well-developed mylonitic foliation is invariably developed within the sheets, parallel to their margins, regardless of the intensity of the mylonitic fabric in the surrounding rocks.

Compositions range from felsic to mafic-intermediate. Most consist of <10% to >30% phenocrysts of plagioclase (± hornblende in mafic intrusions) up to 4 mm in diameter, within a fine grained groundmass of biotite, quartz, feldspar, epidote and chlorite. Igneous textures are not preserved in the groundmass, but sub- to euhedral plagioclase phenocrysts commonly preserve delicate oscillatory zoning, even in strongly mylonitised rocks. The hypabyssal sheets intrude both the quartz-diorite (particularly at the margins of the body) and the Swansea Plutonic Suite. Similar syn-mylonitic biotite tonalite dykes and sills in the Whipple Mountains (G. A. Davis et al. 1982, G. A. Davis 1988) have yielded a U-Pb age of 26 ± 5 Ma (Wright et al. 1986).

Tsp

Swansea Plutonic Suite (Bryant and Wooden, 1989; Oligocene to Miocene) - Inter-layered medium to coarse grained, dark greenish-grey diorite, quartz-diorite, granodiorite and hornblendite, porphyritic granite granodiorite and diorite. Rare pegmatites intrude the more mafic members of the suite (Planet Peak area). Porphyritic intrusions contain K-feldspar augen up to 8 cm in diameter, and superficially resemble the Proterozoic augen gneiss. Limited dating of members within the suite indicates it ranges in age from 29.9 to 21.6 Ma (Bryant and Wooden, 1989; Richard et al., 1990). The Tertiary mylonitic fabric is well developed in most members of the suite. The unit mapped as *Tsp* also includes chloritic breccia (*Tcb*) immediately below the detachment fault, which was generally not mapped separately.

Tspm

Mafic and ultramafic intrusions (Oligo-Miocene?) - Hornblendite intrusions and rare hornblende-plagioclase cumulates ranging from 1 to ~10 m thick. Hornblende phenocrysts <1·0-15 mm long comprise 60-90% of the rock (e.g. sample 101679. Interstitial plagioclase biotite epidote and quartz is present in the cumulate (e.g. sample 101620). Hornblendite is locally intrudes fault breccias developed along the Planet Peak fault, Ne of Planet Peak. The cumulate occurs in proximity to the quartz-diorite (*Tspd*).

Tspd

Quartz-diorite (Oligo-Miocene?) - Medium-grained hornblende-biotite quartz-diorite intrusions. Typically consists of plagioclase (An_{30-33}) + biotite + quartz ± hornblende with lesser sphene, apatite and allanite. Retrograde epidote, chlorite and tremolite/actinolite are locally abundant. The hornblende content varies from 0 to ~20%. Plagioclase phenocrysts locally preserve delicate oscillatory zoning. Where the effects of Tertiary mylonitisation are weakest, the intrusions are massive to weakly foliated. Where strongly mylonitised, the quartz-diorite is medium to fine grained, greenish-grey and commonly has a distinctive spotted appearance due to numerous scattered 5-10 mm clots of biotite (after hornblende).

Quartz diorite intrusions range from small irregularly shaped bodies within the Swansea Plutonic Suite to large (1.5 km^2) isolated lenticular or sheet-like bodies such as the 350 m thick intrusion SE of Planet Peak (Plate 8). The margins of the intrusion near Planet Peak are generally intensely mylonitised and parallel to the mylonitic fabric in the surrounding country rocks. However locally the intrusion is concordant with and/or complexly folded with more steeply-dipping Proterozoic gneisses along its margin.

Proterozoic - Mesozoic

Kg

Leucocratic granite and pegmatite (after Bryant, 1992; Cretaceous?) - Medium to coarse grained K-feldspar + quartz + plagioclase ± biotite, muscovite leucocratic to locally granite. Larger bodies of granite in the Planet Peak area preserve a weak, discontinuous steeply-dipping foliation sub-parallel to the gneissic fabric in the Proterozoic rocks. Lenses of the Proterozoic wall-rock are also common in the granite, particularly adjacent to the margins. The smaller bodies are sheet-like and were originally intruded at a high-angle to the gneissic foliation (sub-parallel to the subsequent mylonitic foliation). In the Rawhide Mountains numerous gently-dipping

pegmatites and granite sheets were intruded parallel to lithologic layering and a strongly developed Cretaceous(?)±Tertiary fabric in the host gneisses. The intensity of the mylonitic overprint is extremely variable. Strongly mylonitised granites preserve fractured porphyroclasts of K-feldspar up to 1 cm in diameter, in a matrix of fine to very fine grained quartz, feldspar and mica. Bryant (1992) suggests this unit is correlative with the 78-80 Ma peraluminous Tank Pass Granite (DeWitt and Reynolds, 1990) in the Harcuvar Mountains.

MPs

Undifferentiated metasedimentary rocks (after Bryant, 1992; Palaeozoic-Mesozoic,) - white, tan, grey-green, and brown calc-silicate, marble and quartzite, probably derived from Palaeozoic or Mesozoic sedimentary rocks. The larger lenses of marble were mapped separately (i.e. unit *cc*). Calc-silicates contain calcite, quartz, epidote and tremolite/actinolite. The unit occurs in discontinuous, fault bounded slices within the crystalline basement. Compositional layering in the metasedimentary rocks varies from 1 mm to >1 m in thickness. Individual horizons are <1 m to ~5 m thick, and can often be traced for several 100 m. Multiple horizons occur within intervals up to 20 m thick. Pegmatites (*Kg*?) and Tertiary hypabyssal sheets (*Thi*), commonly occur in association with this unit and parallel the layering in the metasedimentary rocks. *MPs* is invariably strongly deformed, and have a well developed planar fabric parallel to the compositional layering. Quartz-rich lithologies contain the NE-trending Tertiary mylonitic extension lineation. Calc-silicate layers typically contain numerous well developed centimetre to metre scale intrafolial- and sheath-folds.

cc

Calcite marble (Palaeozoic-Mesozoic metasedimentary protolith) - Massive pale brown to white marble, probably derived from Palaeozoic or Mesozoic metasedimentary rocks. Generally occurs in association with *MPs*, and was not always mapped separately. Small lenses of calcium carbonate and associated minor Fe-Cu mineralisation (haematite, chrysocolla, malachite) that occur along some lower plate faults may be of Tertiary (hydrothermal) origin. In thin section the carbonate is extensively recrystallised and does not preserve a strong crystallographic or grain-shape fabric (e.g. sample *101655*). Layering (if present) is defined slight variations in composition (e.g. quartz, feldspar content) and/or grainsize.

Xgg

Granitic gneiss (after Bryant, 1992; Early to Middle Proterozoic) - Medium to coarse grained quartzo-feldspathic gneisses and their mylonitic equivalents. Typical mineralogy is quartz + microcline + plagioclase + biotite ± (muscovite, garnet). Apatite, allanite, Fe-oxides, sphene and zircon are common accessory minerals; retrograde chlorite, epidote and carbonate are locally abundant. Where not affected by the younger deformation the gneisses generally have a moderate to well developed foliation defined by millimetre- to centimetre-scale compositional banding and alignment of elongate minerals. In areas where the Tertiary mylonitic fabric is not well developed, the foliation in the gneisses is steeply dipping and trends northeast.

Xlg

Layered migmatitic gneiss (after Bryant, 1992; Early Proterozoic) - Medium to coarse grained Proterozoic quartz + feldspar + biotite gneiss, hornblende-bearing augen gneiss, migmatitic gneiss, leucocratic granite and amphibolite and their mylonitic equivalents. In the Planet Peak area, the gneisses preserve a steeply-dipping, NE-trending foliation in domains where the Tertiary mylonitic fabric is not strongly developed. *Xlg* includes numerous 1-10 m thick pegmatites and granitic sheets of Mesozoic (*Kg*) and Proterozoic(?) age. Adjacent to the detachment faults *Xlg* also includes the chloritic breccia (*Tcb*) which was generally not mapped separately.

mc

Undifferentiated lower plate rocks (Miocene to Proterozoic) - Proterozoic, Mesozoic and (?)Tertiary crystalline rocks, variably overprinted by the Tertiary mylonitic fabric. Includes propylitically-altered cataclasites below the detachment fault.