Favorito and Seedorff - Geosphere

Part 1: DESCRIPTION OF ROCK TYPES

Part 2: METHOD OF CROSS SECTION RECONSTRUCTION AND VALIDATION

Part 1:

DESCRIPTION OF ROCK TYPES

Proterozoic and Paleozoic Rocks

Basement rocks within the study area include the Pinal Schist and Ruin Granite (Dickinson, 1991). Pinal Schist crops out in the eastern half of the study area (Fig. 3) and consists primarily of metavolcanic rhyolite to andesite (Krieger, 1974a; Keith, 1983). The unit has a maximum crustal thickness of 2 km in exposures along Swingle Wash. The large majority of basement exposures consist of Ruin Granite, a porphyritic granite distinguished by large K-feldspar crystals up to 5 cm long set in a coarsely crystalline groundmass of quartz, plagioclase, and biotite. Aplite, pegmatite, and alaskite porphyry dikes of similar age are present within the Ruin Granite, and a fine-grained alaskite phase is present near the (untilted) top of the pluton (Krieger, 1974a).

The Apache Group was deposited nonconformably on basement and consists of quartzite, siltstone, and lesser carbonate rocks (Shride, 1967; Wrucke, 1989). The Apache Group consists of the Pioneer Formation, Dripping Springs Quartzite, and Mescal Limestone (Fig. 4). In some areas, the Mescal Limestone is overlain by basaltic lava flows that are overlain by the Troy Quartzite. Proterozoic diabase sills averaging 150 m thick intruded primarily into the siltstone unit of the Dripping Springs Quartzite and as subhorizontal sheets into underlying basement rock within a kilometer of the unconformity (Fig. 3, 5). The diabase, dated at ~1.1 Ga (Wrucke, 1989; Bright et al., 2014), is dark gray-green, commonly fine-grained at chilled margins, and mediumto coarse-grained with ophitic to subophitic texture near the interior of the intrusions (Wrucke, 1989). The most abundant minerals are plagioclase, clinopyroxene, and olivine.

Paleozoic rocks are only exposed in the western section of the map (Fig. 3) and consist primarily of siltstone of the Cambrian Abrigo Formation and carbonate rocks of the Martin Devonian Formation and Mississippian Escabrosa Limestone (Bryant, 1968; Krieger, 1974b).

Laramide Rocks

A wide range of Laramide plutonic and volcanic rocks crop out in the study area and throughout the Tortilla Mountains.

Diorite

This unit is located between Smith Wash and Eagle Wash (Fig. 3), occurs in east-west elongate bodies and intrudes Ruin Granite (Krieger, 1974a, 1974b). It is fine- to medium-grained and is composed of plagioclase, hornblende, biotite, and magnetite with minor pyroxene and quartz. This unit is cut by a stock and several porphyry dikes of Smith Granodiorite (Krieger, 1974a). It is similar petrographically to the Tortilla Quartz Diorite northwest of the study area in the Sonora, Grayback, and Kearny quadrangles (Cornwall et al., 1971; Cornwall and Krieger, 1975a, 1975b). This unit has a K-Ar hornblende age of 67.2 ± 2 Ma (Krieger, 1974a; recalculated for new decay constants, Dalrymple, 1979). Keith (1983) interpreted this age to be reset by intrusion of the Smith Granodiorite.

Romero Diorite

A fine-grained diorite with plagioclase laths in a matrix of plagioclase and lesser quartz locally intrudes along the Romero Wash fault (Fig. 5). This unit also forms several east-northeast-striking dikes south of Crozier Peak (Keith, 1983). This unit is the fine-grained quartz diorite described by Krieger (1974a). The Romero Diorite intrudes along the Romero Wash fault (Krieger, 1974a) and is present north of the Southern Ridge fault, where it eventually intrudes along a diabase contact and into the diabase (Fig. 5). To the east of the Romero Wash fault, just north of Romero Wash, there are possible feeder dikes to the main intrusion. This unit has a K-Ar whole-rock date of 82.6 ± 1.8 Ma (S. B. Keith and P. E. Damon, unpublished data, in Keith, 1983)

Dacite Porphyry

A tabular body of dacite porphyry that is located northeast of Tecolote Ranch (Fig. 3) contains plagioclase, hornblende, and lesser pyroxene and intrudes along beds of the Apache Group. It has a K-Ar hornblende age of 73.1 ± 2.1 Ma (Krieger, 1974b; recalculated for new decay constants, Dalrymple, 1979).

Rhyodacite Porphyry

Two east-west trending dikes of rhyodacite porphyry crop out near Cow Fence Wash (Fig. 5), and additional dikes likely occur to the south down to Romero Wash (Krieger, 1974a). Both dikes cut the Romero Wash fault and the laccolith of Rattler Granodiorite (Keith, 1983). In Keith (1983), rhyodacite porphyry dikes near Cow Fence Wash are labeled as Rattler Granodiorite.

Rattler Granodiorite

A north-south trending intrusion of medium-grained biotite hornblende granodiorite intrudes rocks of the Apache Group near Romero Wash and Smith Wash (Fig. 3, 5). The western contact of the unit makes a generally linear, north-south trace, whereas the eastern contact is concave westward; after untilting, this suggests a laccolith-shaped intrusion (Mathieu et al., 2008). This body is cut by the Smith Granodiorite (Krieger, 1974a) and rhyodacite porphyry dikes (Keith, 1983) and is regarded as regionally equivalent to the Rattler Granodiorite (Cornwall et al., 1971). This unit has been dated using the K-Ar method, but results are highly variable, ranging from 70.5 Ma to 291 Ma (Keith, 1983).

Smith Granodiorite

Two stocks of medium-grained biotite hornblende granodiorite, roughly east-west elongate, intrude Ruin Granite north and south of Smith Wash (Fig. 3, Fig. 7). Porphyry dikes of similar composition emanate from these intrusions and intrude the Ruin Granite and Apache Group. Along portions of the contacts of the northern stock, there are areas of igneous breccia with poorly sorted, angular clasts of Ruin Granite. This unit is referred to as granodiorite by Keith (1983) and Krieger (1974a, 1974b), and it closely resembles Rattler Granodiorite. The Smith Granodiorite has a three published K-Ar biotite ages that range from 67.4 Ma to 69.7 Ma (Keith, 1983).

Miscellaneous Dikes and Intrusive Bodies

Hornblende andesite, hornblende diorite porphyry, quartz latite, various rhyodacite porphyries, and various latite porphyries (Krieger, 1974a, 1974b; Keith, 1983) occur as dikes in the area that serve as markers for structural interpretations and provide relative age constraints (Fig. 3, 5, 6).

Pyroclastic Rocks and Lava Flows

West of Jim Thomas Wash (Fig. 3), two bodies of north-south striking volcanic rock have been deposited on Paleozoic strata (Krieger, 1974b). Pyroclastic rocks are rhyodacitic, and lava flows are andesitic in composition. This unit has been intruded by hornblende andesite dikes. Identical dikes in the Sonora quadrangle to the north gave a hornblende K-Ar age of 128 Ma (Cornwall et al., 1971). Volcanic clasts here are similar in composition and general appearance to some of the lava flow breccias in the Glory Hole Volcanics in the Galiuro Mountains (Krieger, 1968).

Williamson Canyon Volcanics

This unit is exposed west of Crozier Peak (Fig. 3); its map pattern is elongate northeast-southwest; and it consists of porphyritic andesite with phenocrysts of plagioclase, hornblende, and pyroxene (Krieger, 1974b). These rocks appear to have been deposited nonconformably on Ruin Granite and diorite. Pebble-size and larger, map-scale xenoliths of Troy Quartzite, Ruin Granite, and Escabrosa Limestone are present. Large xenoliths are lens shaped, commonly measuring 150 m across and several 10s of meters wide, with their long axes oriented roughly northeast. In some places, the rocks have been mapped as volcanic breccia, but in other areas they may be intrusions. These exposures, which have not been dated, have been assigned to the Williamson Canyon Volcanics.

Cenozoic Rocks

Cenozoic rocks within the study area consist of variably tilted, syn-extensional sedimentary rocks (Fig. 3). In certain areas, lava flows and thin tuff beds occur within Cenozoic strata, providing opportunities to accurately date certain stratigraphic units (Dickinson, 1991).

Cloudburst Formation

The oldest Cenozoic unit in the region is the Oligocene to Miocene Cloudburst Formation. In some parts of the region, such as near the San Manuel mine, it contains a lower volcanic member, and these volcanic rocks correlate with the Galiuro Volcanics in the Galiuro Mountains east of the San Pedro River that are dated mostly between 30 Ma and 25 Ma, i.e., Oligocene (Dickinson and Shafiqullah, 1989). This volcanic member is not present in the Romero Wash-Tecolote Ranch area.

The oldest Cenozoic sedimentary unit is an Oligocene synextensional conglomerate that marks the beginning of Cenozoic normal faulting in the region (Dickinson, 1991). These sedimentary rocks also are placed in the Cloudburst Formation. In the San Manuel mine area, they constitute an upper sedimentary member of the Cloudburst Formation. In the Romero Wash-Tecolote Ranch area, the unit is known as the Hackberry Wash facies of the Cloudburst Formation, and it is divided into lower and upper members, both of which consist mostly of sedimentary rocks. Strata of the two members contain contrasting lithologies and bedding inclinations. Both members consistently strike north-northwest to north. Local basaltic andesite lava near the base of the formation has a K-Ar age on groundmass feldspar of 25.4 ± 0.6 Ma, and rhyolite clasts in tuff-breccia intercalated within the upper member of this formation has a sanidine K-Ar age of 22.5 ± 0.5 Ma (Dickinson and Shafiqullah, 1989).

The lower member of the Hackberry Wash facies of the Cloudburst Formation, which is present on the western side of the field area near Tecolote Ranch, consists primarily of conglomerate with a lens of lava and multiple lenses of rock-avalanche megabreccia (Dickinson, 2002). Bedding commonly dips vertically or steeply to the east (Fig. 3), consistent with observations of others at Hackberry Wash, where dips generally fan upward from ~90° to ~50°E (Dickinson, 2002; Maher et al., 2004). Locally, the basal contact of the lower member is a buttress unconformity on rocks ranging from the Apache Group through Mesozoic volcanic rocks (Dickinson, 2002).

The upper member of the Hackberry Wash facies of the Cloudburst Formation mainly consists of sandstone and conglomerate (Dickinson, 2002), and it is present throughout the study area (Fig. 3). Bedding in the study area generally dips moderately to the east. To the north at Hackberry Wash, the upper member begins with accumulation of sediment on top of the lower member without a change in dip, then a growth sequence ensues in which measured bedding attitudes fan upward from ~50° to ~30°E, then accumulate another non-growth thick sequence with dips at ~30°E (Dickinson, 2002; Maher et al., 2004), comparable to those observed at Romero Wash-Tecolote Ranch. Exceptions include outcrops in contact with the Hackberry fault, where bedding instead dips moderately to the west, and one outcrop at the base of exposure north of Romero Wash, where bedding dips 85° to the east. Considering its nearly vertical dip, the latter exception may be a landslide block or a sliver of the lower member. The basal contact of the upper member with the lower member ranges from disconformable to conformable, and its basal contact with Proterozoic rocks is a buttress unconformity (Dickinson, 2002).

San Manuel Formation

The Miocene San Manuel Formation is a synextensional conglomerate that is exposed in the western and eastern ends of the study area (Fig. 3). Near Jim Thomas Wash, silicic ash-fall tuff intercalated within the San Manuel Formation yielded a biotite K-Ar age of 20.1 Ma (Dickinson, 2002). In other localities farther from the field area, basal lavas within this formation yielded K-Ar ages of 22 Ma, and interstratified silicic tuffs are dated at ~17-20 Ma (Dickinson, 1991). In the study area, bedding generally dips to the east or west at moderate to shallow angles (Dickinson, 2002), similar to exposures to the north in the Hackberry Wash area, where dips range from ~30° to ~5°. The basal contact of the San Manuel Formation with the underlying upper member of the Cloudburst Formation at the western end of the field area is an angular unconformity, whereas it appears to be conformable at the eastern end of the field area. Where the San Manuel Formation rests on rocks of the Apache Group, the basal contact is a buttress unconformity.

Quiburis Formation

The youngest Cenozoic unit is the Miocene to Pliocene synextensional conglomerate of the Quiburis Formation (Dickinson, 2002). Ash beds from various localities within the Quiburis Formation yield K-Ar ages of 6.4 to 2.6 Ma (Dickinson, 1991). This unit crops out in the central and eastern portion of the field area (Fig. 3). Bedding is commonly flat or dips gently to the east or west by as much as 10° (Krieger, 1974a, 1974b). The contact between the Quiburis Formation and the underlying San Manuel Formation is commonly an angular unconformity.

Part 2:

METHOD OF CROSS SECTION RECONSTRUCTION AND VALIDATION

Three main steps, with associated iterations, were taken in order to create structural reconstructions at various scales that honor both geologic data from the field area and kinematically reasonable fault geometries. This began with restoring Cenozoic normal faults, followed by forward modeling of Laramide reverse faults and folds, and ended with forward modeling of erosion surfaces and deposition of synextensional sediments.

Phase 1

The first step in reconstructing a given cross section was to compile surficial geologic data such as bedding and fault orientations, contacts, and topography into a cross section using Adobe Illustrator®. This cross section was then uploaded into Adobe Photoshop®. Then, taking into account the regional geology, a conceptual model of the pre-Cenozoic geology was drawn in Photoshop®. Cenozoic normal faults in the modern cross section were then restored from youngest to oldest in order to match the pre-Cenozoic model as closely as possible. Fault displacement was restored by first defining fault blocks and then translating the entire hangingwall along the fault by the amount indicated by mapped relationships (Table 3). Tilting for each fault set was restored by rotating the entire cross section the amount indicated by corresponding synextensional sedimentary units (Table 3).

Faults with unknown displacement magnitudes were assigned arbitrary amounts of displacement in order for the restoration to match the conceptual pre-Cenozoic cross section model. In the first few trials of reconstruction, these magnitudes were relatively small but were later increased slightly in order for the restoration to match the model more closely. If there was significant mismatch between the model and results from structural reconstruction, either one was redone until a realistic result was achieved.

Normal fault restoration was performed in Photoshop® primarily due to the relative ease of use compared to Move™. However, final normal fault reconstructions were redone in Move™ in order to verify their validity. Restored sections in Move™ were identical to those using Photoshop®.

Phase 2

Midland Valley Move™ structural modeling software was used to validate the accuracy of the pre-Cenozoic geologic interpretation that resulted from the initial phase of reconstruction. Pre-Cenozoic structures along cross sections include reverse faults with related folds. The trishear kinematic algorithm, located in the 2D Kinematic Modeling module of Move™, was used to generate forward models of reverse fault-related fault-propagation folds. The trishear model of Erslev (1991) describes the folding of rock in a triangular zone caused by an upward-propagating fault tip, with points of rocks moving outward in rays from this tip (Erslev, 1991; Hardy and Ford, 1997; Allmendinger, 1998; Hardy and Finch, 2006). Forward modeling began with the creation of an undeformed section based on the local geology. Then, reverse faults were placed into the cross section and were forward modeled using the tri-shear algorithm. Various parameters (shown on Figs. 20-22) such as displacement, slip-propagation ratio, fault tip position, and trishear angle were altered until the fold geometry closely matched the reconstructed result from phase 1. If results from a forward model could not match phase 1 results, then phase 1 was repeated using insights gained from phase 2. The end result of phase 2 was a post-Laramide shortening, pre-Cenozoic extension cross section with a geometrically consistent representation of Laramide reverse fault-related folds.

Phase 3

This stage involved modeling of the erosion surfaces and synextensional sedimentary basins through each time panel in order to further test the accuracy of the reconstruction. The reconstruction has to accurately describe the distribution and orientations of synextensional strata observed within the field area even though surface geology along the line of section for the reconstruction does not contain all faults and synextensional deposits.

This phase began with the fully restored section, where an erosion surface with a realistic slope and relief was superimposed. Then, on subsequent time panels, moving forward in time, a new erosional surface was drawn and synextensional sedimentary units with fanning-up bedding sequences were deposited within normal-fault-bounded half-grabens. The amount of fanning for each synextensional unit is directly related to field observations made primarily north of the line of section AA’ for reconstruction (Table 3; Fig. 3). If a given erosion surface for a time panel suggested erosion of a present-day outcrop of pre-Cenozoic rocks, indicated by modern surface data, or Cenozoic strata could not be deposited in the place or orientation that modern surface data indicated, then the reconstruction was redone starting at phase 1.

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