SEGMENTATION AND TERMINATION OF LOW-ANGLE NORMAL FAULT DOMAINS: INSIGHT FROM HIGLEY BASIN AND VICINITY, CENTRAL ARIZONA

by

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Abstract

Higley Basin, located near the western margin of the Basin and Range Province in central Arizona, is a deep (>3,000 m), Miocene half-graben characterized by displacement along both high- and low-angle normal faults; displacement along these faults has created accommodation space for thick volcanic sequences followed by more recent fluvial, alluvial, and colluvial deposits. Higley Basin occupies a unique location near a transition in the vergence of major detachment fault systems largely responsible for the exhumation of a belt of metamorphic core complexes in the region. To the west and north, major detachment faults generally dip to the northeast, while to the south and east of the basin, major detachment faults generally dip to the southwest. Kinematic arguments require these detachment surfaces to terminate in a zone between the two fault domains (zone of accommodation), trending roughly parallel to regional extension. Interpretation of geophysical datasets from central Arizona indicate that oppositely vergent, low-angle faults partly terminate as branching, overlapping fault systems within Higley Basin and the immediate vicinity. Features other than those within the basin must also partly accommodate the opposing vergence of the two dominant detachment systems. Thus, the zone of accommodation is inferred to extend either to the northeast buried beneath later volcanic rocks of the Superstition Mountains or to the southwest beneath young surficial deposits.

Multiple major fault systems are observed or inferred to decrease in throw and tip out within or near Higley Basin. As slip along an individual structure is reduced, the formation of local, large-offset detachment surfaces is prevented. This could preclude sufficient tectonic unloading to promote isostatic response of the lower plate in the detachment system and may preclude the development of core complexes near the terminations of detachment domains. Also, the lack of major isostatic response may prevent progressive back rotation of major fault
systems near their terminus, and thus the faults remain at steeper dips and produce a deeper basin.

**Keywords:** Accommodation zone, Higley Basin, crustal extension, low-angle faulting
1. Introduction

Higley Basin (Figure 1A) is located in a belt of metamorphic core complexes along the length of the North American Cordillera (Coney, 1980). To the southeast, detachment faults generally dip to the southwest with top-to-the-southwest sense of movement, whereas to the northwest, detachment faults generally dip towards the northeast, with top-to-the-northeast sense of shear (Wust, 1986; Richards et al., 2000). The two adjacent core complexes, South Mountains and Picacho Mountains, located to the northwest and southeast of the study area, respectively, each show evidence for oppositely vergent (antithetic) detachment surfaces (Richards et al., 2000). Each of the respective detachment domains must somehow terminate in the vicinity of Higley Basin. The diffuse region in which these domains terminate is non-genetically referred to here as a zone of accommodation (Figure 1B). Much attention has been focused toward extensional culminations, namely the metamorphic core complexes of the region, whereas the lateral terminations and segmentations of the same extensional regimes have received relatively little attention. However, understanding the kinematics and geometries of terminating fault domains (regions of generally uniform fault dip) is becoming increasingly important in the study of extended orogens and associated basins as interest in subsurface mineral, hydrocarbon, and water resources increases.

Recent and vintage geophysical datasets provide new insight into the style, timing, and geometry of Cenozoic extension in the vicinity of Higley Basin, a complicated half-graben near the Basin and Range—Colorado Plateau transition in central Arizona. The Higley Basin is bounded by the Superstition Mountains to the north and east, the Santan Mountains to the south, and the South Mountains core complex to the west. Deformed Cenozoic basin fill records regional crustal extension since the mid-Tertiary. Accommodation space was created along a
series of high- and low-angle faults, and has been filled with volcanic and sedimentary strata from the nearby Superstition volcanic field and overlying, silts, salt, and gravels.

Heterogeneous slip on individual faults and across fault systems produces regional segmentation of uniformly dipping extensional terranes (Faulds and Varga, 1998; Schlische and Withjack, 2009). These fault systems must somehow terminate both along and perpendicular to strike in transform faults or features variously named transform zones, accommodation zones, and fault-domain boundaries (e.g., Scott and Rosendahl, 1989; Morley et al., 1990; Faulds and Varga, 1998; Schlische and Withjack, 2009). Here, the terminology of Faulds and Varga (1998) is used to avoid confusion with other terms in the literature.

Faulds and Varga (1998) define two primary ways to laterally terminate extensional domains: accommodation zones and transfer zones. Transfer zones are described as “discrete zones of strike-slip and oblique-slip faults that strike parallel or slightly oblique to the extension direction” (Faulds and Varga, 1998). These zones are an efficient means of transferring strain along offset extended domains. Accommodation zones are defined as “belts of overlapping fault terminations” and “accommodate the transfer of strain between overlapping … normal faults” (Faulds and Varga, 1998). Unlike transfer zones, the general trend of accommodation zones may not correlate with the extension direction.

The study of Higley Basin, located in a zone of accommodation, can serve to address several key questions regarding the growth and development of these features, such as: (1) how is strain accommodated in accommodation zones?, and (2) how will slip along individual faults and fault systems be modified approaching the accommodation zones? Finally, understanding how depocenters form within zones of accommodation and are subsequently filled can increase our understanding of the location of potential reservoir lithologies, both for groundwater and hydrocarbons, and the nature of structures affecting these reservoirs.
In this study, surficial geological observations are used in conjunction with recently acquired and vintage industry seismic reflection data, as well as gravimetric observations. Well-log and seismic data provide subsurface control of basin fill and structure. Gravitimetric observations are utilized to provide a means to extend subsurface interpretations along the basin axis, and provide a means to test our seismic interpretations. Finally, a new kinematic model is proposed, incorporating new geophysical observations, to address the geometry and timing of deformation within the accommodation zone.

2. Geologic Setting

Regional Geology

The Basin and Range Province of central Arizona has experienced dramatic extension (locally >100%) since the middle Tertiary (Spencer and Reynolds, 1989; Richard and Spencer, 1998) coupled with a coeval resurgence of magmatism (Spencer and Reynolds, 1989). Middle Tertiary extension and magmatism overprint Late Cretaceous – Early Tertiary magmatism and crustal thickening associated with contractional deformation (Spencer and Reynolds, 1989). However, the geometry and distribution of older contractional structures does not greatly influence subsequent extensional features. Generally northeast-southwest directed crustal extension during the Middle Tertiary was largely accommodated along low- to high-angle faults, many of which are known or suspected to sole into regional detachment faults (Spencer and Reynolds, 1989; Kruger and Johnson, 1994; Arca et al., manuscript in preparation, 2009). These detachment faults have several to tens of kilometers of displacement, and many exhume deep-crustal metamorphic rocks in their footwalls (e.g., Lister and Davis, 1989). The upper plates of these detachment systems are highly fractured, and multiple generations of upper-plate faults generally dip uniformly towards the direction of transport (Lister and Davis, 1989; Spencer and
During the Late Miocene, large-magnitude extension, largely along low-angle surfaces, was superseded by lower-magnitude extension accommodated along high-angle faults. This later east-west to west-northwest-east-southeast-directed deformation extended the crust an additional 10 to 20 percent (Menges and Pearthree, 1989). These later-stage faults clearly cut earlier low-angle faults and detachment surfaces and resulted in the development of the modern Basin and Range province in southern Arizona (Davis et al., 2004; Menges and Pearthree, 1989).

Large-magnitude extensional deformation along regional detachment surfaces, coupled with isostatic uplift of mid-crustal footwall rocks, is largely responsible for the exhumation of a belt of metamorphic core complexes through southern Arizona (e.g., Coney, 1980; Lister and Davis, 1989). Core complexes near Higley Basin, from northwest to southeast, include the White Tank, South, Picacho, Tortolita, and Catalina-Rincon Mountains (Figure 1A). Activity along these detachment surfaces occurred between 30-20 Ma (Eberly and Stanley, 1978; Reynolds and Rehrig, 1980; Dickinson, 1991). Detachment faults relating to the White Tank and South Mountains core complexes dip regionally to the northeast with associated top-to-the-northeast sense of shear (Kruger et al., 1998; Richards et al., 2000), whereas the Catalina detachment fault is shown to dip to the southwest with associated top-to-the-southwest sense of shear (Arca et al., manuscript in preparation, 2009).

**Superstition Mountains**

Higley Basin is bounded to the east and northeast by the Superstition Mountains (Figure 1A), which expose a thick sequence of Miocene extrusive rocks related to the formation of the Superstition cauldron complex (Stuckless and Sheridan, 1971), as well as minor exposures of Proterozoic sediments and metasediments (Richards et al., 2000). The Superstition volcanic sequence, approximately 2,000 meters of lava flows, volcanic breccias, and ash-flow deposits, is
dominated by the welded quartz-latite tuff referred to as the Superstition Tuff (Stuckless and Sheridan, 1971; Ferguson and Skotnicki, 1995). This sequence was largely deposited between 20-15 Ma, nonconformably overlying Proterozoic granitiods and metasediments; the majority of this sequence is inferred to have been deposited in the emerging, adjacent depocenter of Higley Basin (Stuckless and Sheridan, 1971; McIntosh and Ferguson, 1998). The readily identifiable Apache Leap Tuff member of the laterally extensive Superstition volcanic sequence extends across Higley Basin, roughly 45 km to the southwest, to the Santan Mountains (Stuckless and Sheridan, 1971; Ferguson and Skotnicki, 1995). Strata within the Superstition volcanic sequence are generally tilted southwest (Richard et al., 2007).

Tertiary volcanic deposits of the Superstition Mountains are cut by numerous north-south- to northwest-southeast-striking low- and high-angle normal faults (Richard et al., 2000), such as the Elephant Butte fault. The north-south-striking, west-side-down Elephant Butte fault, which partially defines the extreme eastern limit of Higley Basin, is inferred to offset volcanic strata by roughly 1 km. To the north, the fault turns towards the northwest and appears to divide into numerous branches (Ferguson and Skotnicki, 1995). No low-angle normal faults are observed near the basin margin (Ferguson and Skotnicki, 1995, Richards et al., 2000).

The Superstition Mountains are part of a larger northwest-southeast exposure of east-titled fault blocks of Proterozoic, Paleozoic, and Tertiary rocks extending over 100 km from the Goldfield Mountains in the northwest to Black Mountain in the southeast (Richard and Spencer, 1997, Richard et al., 2000). South of the Gila River, low-relief exposures of Proterozoic and Late Tertiary/Early Cretaceous granitic rocks bound the shallow Donnelly Wash basin. This small basin is bounded on its eastern margin by the Cochran fault zone, inferred to have been active prior to 17 Ma (Richard and Spencer, 1997). The Cochran fault cuts the older Walnut Canyon low-angle fault, which is inferred to be one of the major tilt-block-bounding faults.
(Richard and Spencer, 1997). The Cochran fault is one of several similarly trending, low-angle normal faults near Donnelly Wash basin that were active prior to the Basin and Range disturbance.

**Santan Mountains**

The Santan Mountains, which form the southern margin of Higley Basin, are conspicuous for lack of evidence for core-complex development within a belt of core complexes passing through the area. The range exposes Proterozoic and Cretaceous granitoids intruding the polydeformed Pinal Schist. Few Tertiary structures are clearly exposed in the range, and are frequently inferred from tilting of overlying strata. Both northeast- and southwest-dipping high-angle normal faults are observed within the range (Ferguson and Skotnicki, 1996). Southwest-tilted remnants of the Superstition volcanic sequence are exposed in places along the southwestern margin of the range (Ferguson and Skotnicki, 1996; Richard et al., 2000).

**3. Acquisition and Processing of Geophysical Data**

The reflection seismic data for this study were collected during the late 1970’s for the Anschutz Corporation using a Vibroseis® source; 19 lines were recently reprocessed at the University of Arizona using Promax™ seismic data processing software following common 2-D processing techniques. Generalized acquisition and processing steps are summarized in Table 1. Due to the complex structure and generally poor velocity control of the seismic profiles, the data shown are unmigrated. However, migrated sections were used as interpretational aids for several lines. Depth conversion of each profile was accomplished through a singular 1-D velocity field from averaged tomographic and stacking velocities from seismic data in Higley Basin. Although this may accumulate some error in depth conversion for lines increasingly distant from lines in
Higley Basin, this method was used to establish consistency for all seismic profiles. All seismic lines are displayed at a final datum elevation of 914 meters (3000 feet) above sea level.

Free-air gravity contours were drawn using 3026 free-air corrected gravimetric observations in the immediate vicinity of Higley Basin, obtained from the NGS U.S. Gravity Station database (Land and Marine Gravity, 1999; Figure 2). Irregularly sampled data were gridded and contoured using GMT (Wessel and Smith, 1991). Gridding and interpolation error, evaluated using repeated, random sub-sampling, is estimated to be less than one milligal.

4. Description and Interpretation of Data

Interpretation of seismic reflection profiles, coupled with gravimetric observations, serve to constrain the location and geometry of mid-Tertiary extensional features. For the purposes of this study, these features include the Cochran fault, the inferred southeastward extension of the Elephant Butte fault, and basin-bounding faults in Higley Basin and the Red Rock Basin area. The following three profiles document these structures and their variations along strike.

**Lines CX19/PW8**

Seismic lines CX19 and PW8 traverse the eastern arm of Higley Basin from the Santan Mountains to the Superstition Mountains (Figures 1 and 2). The two seismic lines are tied in a region of overlap to create a single profile; note there is ~ 2 kilometers of lateral separation. Interpreted and uninterpreted stacked sections are shown in Figure 4.

A thick package (~ 3000 m) of Tertiary and younger basin-fill sedimentary rocks overlie Proterozoic crystalline basement in Higley Basin. Two distinct packages of sedimentation, identified on the basis of reflection character, are correlated to the Power Ranches 1 (PR-1) well. This correlation is used only as a general guide due to the distance of this well from available seismic data (~ 17 km) and the incomplete sonic log for this well. However, gravity contours do
not suggest great variation along the axis of the basin across this distance (Figure 2), thus the sedimentary package encountered by the well is likely representative of that recorded by the seismic profile. The well tie to the seismic data is shown in Figure 3.

The earlier sequence of basin-fill rocks, characterized by medium- to high-amplitude, laterally coherent reflections, is composed of mixed volcanic and derived sedimentary strata inferred to be coeval with the nearby Superstition volcanic field based on age dating of cuttings from the PR-1 well; this sequence correlates with the lower ~1500 m of strata encountered by the well (Reynolds et al., 1986). The estimated thickness of this sequence is estimated to be ~ 1.5-2 km, similar to that observed in the nearby Superstition Mountains (Stuckless and Sheridan, 1971). Reflections associated with the strata of this unit are progressively rotated moving down section. Also, growth strata are evident in this unit along small-offset faults (< 300 m vertical offset) at km 16 and 17 along the profile.

Overlying the lower unit is a thick (~1 km), complex, heterogenous suite of sedimentary strata post-dating the Superstition volcanics, largely comprised of conglomerates, sandstones, siltstones, anhydrites, and gravels. This sequence is characterized by lower-amplitude, less-coherent reflections above ~1.5 seconds. This sequence appears to be relatively undeformed as compared to the lower unit, and overlies shoulders of Proterozoic basement rocks along the southwest and northeast margins of the basin. An unconformity separates these two sequences identified by the geometries of terminating reflections on the shoulders of Proterozoic basement at this level, similar to other basins in the area (e.g., Eberly and Stanley, 1978; Kruger et al., 1998) and showing geometries imaged in other basins in the extensional corridor (Johnson and Loy, 1992; Wagner and Johnson, 2006).

Rotated reflections of the lower unit terminate at the southwest margin of the basin along an inferred low-angle, northeast-dipping, apparently listric normal fault, hereafter referred to as
the Higley Fault. This major fault, which is not observed at the surface, is covered by several hundred meters of Plio-Pleistocene sedimentary rocks and is interpreted to project to the surface ~4 km from the northeastern flank of the Santan Mountains, or at ~5 km along the profile (Figure 4). Strike, as inferred from free-air gravity contours, is west-northwest. At shallow levels, the fault dip, as estimated by low-amplitude, dipping reflections and stratal terminations in the seismic data, is 35-40°. Weakly coherent reflections at 5-6 km depth, 10-16 km along the profile may represent the listric continuation of this fault in the subsurface. Vertical fault offset is inferred to be at least 3 km from horizontal restoration of rotated hanging-wall reflections, and slip of 10 km or more is possible. A shallow roll-over anticline geometry, imaged at 7-8 km along the profile, is suggestive of fault displacement at least as young as the strata at this level. Progressive rotation of early to middle Miocene strata terminating along this fault indicate the fault must have been active during this time interval. However, no maximum bound can be placed on the age of fault activity with the data currently available.

Three other smaller-offset normal faults, all dipping towards the southwest, are also imaged offsetting Tertiary strata at kilometers 16, 17 and 19 (Figure 4). These faults are identified on the basis of offset or terminating reflections at each location. Growth strata are clearly imaged above faults A and B. The offset along these faults is estimated to be 200-400 meters. Although presently imaged at a much steeper dip, these faults would have formed at dips similar to that of the Higley Fault assuming a similar amount of post-faulting rotation as the adjacent strata. Though not clearly imaged, it is assumed these faults terminate against the oppositely-vergent Higley Fault.

*Line PW16*
Line PW16, located approximately 30 km southeast of Lines CX19 and PW8, lies roughly perpendicular to the dominant extension orientation in the region (Spencer and Reynolds, 1989; Figure 1A). The northeast end of this profile begins at the eastern margin of Donnelly Wash basin near the Cochran and Walnut Canyon faults; the profile then proceeds across the basin, crosses low-relief hills composed of Middle Proterozoic granitic rocks, and terminates in a shallow basin in the Florence, Arizona area. This profile thus crosses two faults bounding separate tilt blocks, the Cochran fault and the inferred southern extension of the Elephant Butte fault (Figure 5).

Shallowly-dipping, high-frequency reflections from km 17.5 – 19 along the profile (Figure 5) are interpreted to be tilted crystalline basement beneath the shallow Donnelly Wash basin at 100-800 m depth. Though not clearly imaged at shallow levels, the Cochran fault, which is the main basin-bounding fault in the area, is interpreted to be the structure responsible for the vertical offset and rotation of these rocks. Vertical offset along the northwest-striking, southwest-dipping Cochran fault, as determined from the seismic data, is estimated to be ~ 800 m. Lower-frequency, high-amplitude reflections, imaged dipping towards the southwest, are interpreted to be the Cochran fault zone at depth. Assuming the seismic profile is approximately perpendicular to the overall strike of the fault, fault dip is at least 10 - 15 degrees at depth.

Moderately dipping, high-frequency reflections from km 7 - 8.5 along the profile are interpreted to be tilted Middle Proterozoic granitic rocks, rotated by the adjacent southern extension of the Elephant Butte fault. This fault, which juxtaposes Middle Proterozoic granitic rocks against Quaternary basin-fill deposits, should outcrop at about km 10 along the profile, although the fault may be buried by younger sediments. A lower-amplitude reflection, similar in dip to that of interpreted Proterozoic crystalline rocks, is imaged dipping to the southwest from 7.5 – 9 along the profile. Lower-frequency, higher-amplitude, dipping reflections from km 3 - 6
are interpreted to be from the deeper section of this fault. Similar to the Cochran fault, vertical offset along the inferred southern extension of the Elephant Butte fault is estimated to be less than 1 km.

**Lines D27/PW28**

Located approximately 20 km southeast of seismic line PW16, seismic lines D27 and PW28 obliquely cross the Red-Rock basin situated between the Picacho Mountains and the Tortolita Mountains, and terminate in Proterozoic exposures to the east of Donnelly Wash basin (Figure 1A). Given the good velocity control for line D27 and the better imaging of the complex structure of the basin fill, a time-migrated stack is shown in Figure 6, along with an unmigrated depth section (inset). Interpreted and uninterpreted stacked sections for Line PW28 are shown in Figure 7.

Similar to Higley Basin, two seismically-distinct sequences of basin fill are imaged in line D27 to the east of the Picacho Mountains. The lower sequence, cut by numerous normal faults, displays rotated growth strata thickening towards the northeast. The thickness of this sequence, estimated from the depth-converted seismic sections, may be up to 2,000 m. Overlying this sequence are a series of flat-lying to gently dipping, relatively undeformed high-frequency reflections of the interpreted upper sequence. Thickness of this sequence is estimated to be 1,500-2,000 m.

Two oppositely-dipping, basin-bounding faults are clearly imaged from km 0 - 6 and 12 - 20 along profile D27 (Figure 6). Gently northeast-dipping, laterally discontinuous reflections along km 6-12 are interpreted to represent the deeper continuation of the basin-bounding fault imaged at km 0-6 along the profile. These reflections, terminated against a series of southwest, moderately-dipping reflections, are interpreted to be the dominant normal fault in the area.
Vertical offset along this fault is estimated to be at least 3 km, and apparent dip is approximately 30 degrees.

The primary feature of line PW28 (Figure 7) is the centrally-located Donnelly Wash basin, imaged from km 14 – 20 along the profile. Low-frequency, gently northeast-dipping reflections are interpreted to be the top of crystalline basement underlying Tertiary and Quaternary basin fill. These reflections terminate against higher-amplitude, southwest-dipping reflections, interpreted to be the Cochran fault or its along-strike equivalent. Gently southwest-dipping reflections from 2-3 km at km 7-15 along the profile are interpreted to be the deeper sections of this fault. Vertical offset along this fault is estimated to be greater than 1,000 m.

5. Discussion

Interpretation of the seismic reflection and gravimetric data has important implications regarding the structural development of Higley Basin and the local accommodation of dramatic extension. Oppositely vergent Mid-Tertiary detachment domains must terminate within the vicinity of Higley Basin within a zone of accommodation (Figure 1B). The geometry of the zone has important implications for the development of the basin and adjacent structural culminations.

Kinematic Development of Higley Basin

Tilted and deformed growth strata within the basin, correlated to the Superstition volcanic sequence, suggest activity along the Higley Fault during 20-15 Ma. Minor faulting along faults A and B of seismic profile CX19-PW8 (Figure 4) also must have occurred during this interval. Interpretation of the northeast-dipping Higley Fault as the main basin-bounding fault forming the half-graben of Higley Basin is consistent with southwest-tilted Tertiary strata exposed within the Santan Mountains. This interpretation is also consistent with the sense of motion observed in the nearby South Mountains; it is possible, if not likely, that the Higley Fault
is linked to the South Mountains detachment fault. Rapid cooling of the South Mountains core complex is constrained to have occurred between 21-17 Ma (Fitzgerald et al., 1993), and is also consistent with the age of major fault activity within Higley Basin.

Faulting post-dating these Mid-Tertiary features, generally interpreted to be associated with the Basin and Range disturbance in central Arizona, is responsible for minor deformation relative to that of earlier structures. These Basin and Range structures, such as the Elephant Butte fault, are not observed to offset units more than 1 km, as compared to the ~ 10 km or more of slip inferred along the Higley Fault.

A schematic model for Higley Basin, compatible with available data, is presented in Figure 8. Higley Basin likely originated in a region of low relief in a region of exposed Proterozoic rocks post-dating early-Tertiary—Late-Cretaceous deformation. At the onset of mid-Tertiary deformation, extension was accommodated along generally low- to moderate angle, randomly-nucleated normal faults (Figure 8, Stage 1). Initially, various faults of differing dip across the landscape acted to accommodate strain in the region. However, a dominant fault system quickly developed. As deformation continued and individual faults were organized into fault systems, extensional domains were created as dominant faults of a particular dip shut off fault propagation along oppositely-dipping faults in regions of overlap. Extension continued to be accommodated preferentially along the dominant fault systems; in the case of Higley Basin, the Higley Fault developed as the dominant fault in the basin (Figure 8, Stage 2). This extension was coupled with voluminous magmatism, and volcanic material from the nearby Superstition volcanic complex filled the rapidly forming Higley Basin. Early units of volcanic fill were progressively rotated as slip continued on the Higley Fault, creating fanning sequences of interbedded volcanics and derived sedimentary rocks, tapering towards the northeast, away from the main depocenter.
As deformation waned in the Early to Middle Miocene, basin formation may have stagnated as an erosional surface, post-dating the volcanic sequence in Higley Basin, beveled the surface of the newly-formed basin (Figure 8, Stage 3). This may have occurred in response to minor isostatic rebound of unloaded regions (e.g., Kapp et al., 2008). Post dating this erosion, Basin and Range faulting gently deformed the basin (Stage 4), especially along the eastern margin. Basin and Range extension may have been accommodated partly by re-activation of pre-existing structures within the basin rather than through the formation of new structures.

Finally, passive basin deposition resulted in several hundred meters of Plio-Pleistocene sedimentary rocks that cover earlier structures (Figure 8, Stage 5). This subsidence produces the currently observed geometry of Higley Basin, most notably the locations of major basin-bound features several kilometers towards the axis of the basin from Tertiary and Proterozoic outcrops.

**Accommodation of Oppositely-Vergent Fault Domains**

Higley Basin is located between two oppositely-vergent detachment domains; each of the respective detachment domains must somehow terminate in the vicinity of Higley Basin in a zone of accommodation (Figure 1B). These zones of accommodation are recognized as a first order feature of extensional domains (regions of generally uniform fault dip), and are observed at all scales (Schlische and Withjack, 2009). Multiple geometries have been proposed for fault interaction and termination within zones of extensional accommodation (e.g., Scott and Rosendahl, 1989; Morley et al., 1990; Faulds and Varga, 1998); understanding these geometries is becoming increasingly important in the study of extended orogens and associated basins as interest in subsurface mineral, hydrocarbon, and water resources increases. To avoid confusion
with the evolving terminology within the literature, the classification and nomenclature of Faulds and Varga (1998) will be utilized exclusively.

Slip frequently is heterogeneously distributed along a fault, typically with maximum slip occurring near the middle of the fault and decreasing towards the fault tips. At the fault tips, strain often is transferred to other faults within the system (Faulds and Varga, 1998). Adjacent faults need not dip synthetically, and in such cases some feature must separate or accommodate fault domains of opposing dip. In zones of overlap, oppositely dipping, interfering faults will tend to stop propagating laterally (Schlische and Withjack, 2009).

Evaluation of geologic and seismic reflection data show that multiple fault systems branch or exhibit reduction in throw, from the northwest and towards Higley Basin. These include the Higley Fault, the Cochran fault, and other major basin-bounding faults along tilted fault blocks of Proterozoic, Paleozoic, and Tertiary rocks extending from the Goldfield Mountains to the Black Mountains (Figure 1). The fault systems that lose throw likely tip out within or approaching Higley Basin.

The Cochran fault, inferred to be the major bounding fault of Donnelly Wash basin, has its greatest slip along the southern portion of the basin, and appears to lose slip toward the north. As estimated from seismic line PW28, vertical offset along the fault is estimated to be greater than one kilometer. In seismic line PW16, offset is less, estimated to be ~ 800 m. The Cochran fault is also observed to lose slip towards the north of PW16 based on surface relationships (Richard and Spencer, 1998). Other major low-angle normal-fault systems predating the Basin and Range disturbance, such as the Grayback and Devils Canyon fault systems either tip-out or become obscured in Tertiary volcanic (Richard and Spencer 1997; Richard and Spencer, 1998; Richards et al., 2000; Figure 1). Major basin-bounding fault systems along the northeast margins of basins to the southeast of Higley Basin are also inferred to generally lose slip approaching
Higley Basin. Vertical offset along the major fault shown in seismic line D27 is estimated to be greater than 3 km. Throw along the southern extension of the Elephant Butte fault is considerably less, estimated to be less than 1 km. The northeast margin of Higley basin apparently is not bounded by major faults. Higley Fault, interpreted to be the main basin-bounding fault of Higley Basin, is also interpreted to progressively lose slip and tip-out near the southeast margin of the basin. Throw is inferred to progressively decrease along this fault as indicated by less negative free-air gravity values and outcropping Proterozoic basement between the Santan mountains and the North Butte area (Figure 2).

Within Higley Basin, as imaged by seismic Profile CX19/PW8, two oppositely dipping, low-angle fault systems, Higley Fault and faults A and B, must have been active approximately synchronously. Because these structures must have been active prior to the deposition of a 19.4 Ma ± 0.47 (Reynolds et al., 1986) welded tuff in the basin, it is inferred that both of these fault systems would have acted to accommodate extensional strain in the Middle Tertiary. However, the inferred Higley Fault emerged as the dominant fault and effectively stopped propagation along oppositely dipping faults. These overlapping, coeval mid-Tertiary fault geometries, which likely tip-out in the vicinity of Higley Basin, are partly responsible for accommodating two regional low-angle detachment systems of opposing vergence. The overlapping geometries of faults with the basin, without prominent synformal or antiformal folding of basin fill, indicate Higley Basin formed within a transverse antithetic accommodation zone located between the South Mountains and the Picacho Mountains core complexes. This zone is roughly aligned with the Mid-Tertiary extension direction (Spencer and Reynolds, 1989).

Implications
There remains a conspicuous lack of exposure of core-complex culminations along the zone of accommodation between the South Mountains and Picacho Mountains (Figure 1A and B). As detachment systems approach the zone of accommodation, individual faults must terminate and will likely progressively lose slip approaching their respective fault tips. Though the total upper-crustal extension may remain the same in the accommodation zone relative to the surrounding region (see discussion, below), the slip along a single feature is reduced, preventing the formation of local, large-offset detachment surfaces. This would prevent sufficient tectonic unloading to promote major local isostatic uplift of the lower plate in the detachment system (cf. Coney, 1980; Davis, 1980, Spencer and Reynolds, 1989), and may preclude the development of core complexes within the zone of accommodation.

Fault kinematics within the accommodation zone will also greatly influence patterns of deposition within the emerging and evolving depocenter. Basin deposition, especially during the early stages of basin development within a zone of accommodation, can be especially chaotic as multiple early-stage faults begin to variably deform the landscape. The basin rapidly fills as multiple structures act to create accommodation space, and facies changes may be abrupt and laterally discontinuous. As fault dominance is established and the accommodation zones cease to expand outwardly, deposition locally becomes more predictable as the number of active, large-displacement features decreases. Depositional patterns within the accommodation zone are likely to be unique compared to others along strike of the major fault systems.

One interesting feature of note is the relative depth of Higley Basin given its location within an extensional accommodation zone. Assuming faults lose slip approaching the basin, two options become apparent: either (1) the accommodation zone represents a region of minimal extension during the Mid-Tertiary, or (2) strain within the accommodation zone is accommodated on multiple structures, reducing the strain on any single feature. Further,
assuming that fault-reactivation of Mid-Tertiary structures during the Basin and Range disturbance was minor, the following speculation regarding detachment-involved accommodation zones is proposed. As detachment faults involved in the development of core complexes become increasingly back-rotated to shallower dips during exhumation of the core complex, extension is accommodated along gently dipping surfaces such that less accommodation space is created. Near the termination of these detachment systems, faults would be progressively less back-rotated and remain at steeper dips (see Kapp et al., 2008). Slip along these faults, though accommodating a lower percentage of regional extension, would therefore produce more local accommodation space.

6. Conclusions

Higley Basin represents a complicated half-graben which formed during the Middle Tertiary due to displacement along low-angle faults, largely along northeast-dipping faults bounding the Santan Mountains. The basin was concurrently filled with Middle Tertiary volcanic rocks from the nearby Superstition volcanic field.

Major fault systems lose throw approaching Higley basin, indicating Higley Basin should represent a region of minimal extension along low-angle faults. Nonetheless, Higley Basin may be one of the deepest basins in Southern Arizona, with more than 3,000 m of sedimentary and volcanic rocks overlying Proterozoic crystalline basement. This apparent contradiction may be explained by progressive decrease in fault rotation distant from uplifted core complexes.

Higley Basin represents part of a major accommodation zone between two oppositely vergent detachment systems in southern Arizona, as evidenced by overlapping, synchronous fault systems of the Middle Tertiary. Certainly, features other than those within the basin must also partly accommodate the opposing vergences of the two dominant detachment systems; thus,
the accommodation zone is inferred to extend either to the northeast buried beneath later volcanic rocks of the Superstition Mountains or to the southwest beneath young surficial deposits.
References


Figure 1 A: Geologic Map of Higley Basin and Vicinity. Inset detailing zone of accommodation. WT = White Tank Mountains; SM = South Mountains; SA = Sacaton Mountains; ST = Santan Mountains; GM = Goldfield Mountains; SP = Superstition Mountains; P = Picacho Mountains; T = Tortilita Mountains; SC = Santa Catalina Mountains; B = Black Mountain; DC = Devils Canyon Fault; GB = Grayback Fault; DWB = Donnelly Wash Basin. B: Detachment polarity and Mid-Tertiary strata tilt domains. From Richard and Spencer (1998) and Richards (2000). Tilt domains from Spencer and Reynolds (1989).
Figure 2 - Free Air Gravity Contours (in milligals) for Higley Basin. Note well location within basin axis, trending west-northwest.
Figure 3 A: Lithostratigraphic Column and Sonic Log from Power Ranches #1 Well. \(^1\)Age dates from Ar/Ar analysis of well cuttings; from Reynolds et al., 1986. Note the 39.4 Ma age is considered unreliable; no tuffs of this age are known around Higley Basin. B: Well tie to Seismic line CX19. Averaged stacking velocities from seismic data were used 0-5400 ft (0-1646 m) TD (region of no data within Sonic Log).
Figure 4 - Seismic Profile CX19-PW8, Depth Section; Above – uninterpreted, lower – Preferred interpretation. Approximate TWT (two-way traveltime) shown along right axis. Interpretation correlated to cuttings from well PR-1 (Figure 3). The fanning, rotated synfaulting strata of the lower sequence indicate majority of fault activity during the deposition of this sequence. Though initially active roughly synchronously, slip along the Higley Fault continued after faults A and B ceased activity. Displacement along faults A and B, along with other deformation below the resolution of this dataset, serve to accommodate deformation within the hanging wall (see Gibbs, 1984).
Figure 5 - Seismic Line PW16, Depth Section; Above – uninterpreted, lower – Preferred interpretation. Approximate TWT (two-way traveltime) shown along right axis. The inferred southern extension of the Elephant Butte fault (left) was active during the Basin and Range disturbance, though may have been active previously. The Cochran fault (right), similar in geometry to that of the Elephant Butte fault, is was active prior to 17 Ma (Richard and Spencer, 1997).
Figure 6 - Seismic Line D27 (Time migrated), with TWT (two-way traveltime) along the vertical axis; Above – uninterpreted, lower – Preferred interpretation of the Red Rock Basin. Inset: Unmigrated depth section. Major deformation is accommodated by a SW dipping normal fault along the NE margin of the Red Rock Basin. Basin fill consists of two major sequences, a faulted and rotated lower sequence, and a much less deformed upper sequence. Unconformities are present near the boundary between the two sequences.
Figure 7 - Seismic line PW28, Depth Section; Above – uninterpreted, lower – Preferred interpretation. Approximate TWT (two-way traveltime) shown along right axis. The major fault in the center of the profile is the Cochran fault. Compare offset to that imaged in seismic line PW16 (Figure 5).
Figure 8 - Higley Basin Kinematic Model. (1) Onset of mid-Tertiary deformation, low- to moderate-angle faults nucleate at random. (2) Higley Fault develops as the dominant fault in the basin, forming a half-graben. Continued slip along this fault buries older faults, which have now stopped propagating. (3) Sub-aerial exposure and minor erosion of the basin, perhaps due to mild isostatic rebound. (4) Basin and Range faulting gently deforms basin. (5) Passive deposition covers older basin fill and structures, extending the width of the basin and producing the currently observed geometry of Higley Basin.
<table>
<thead>
<tr>
<th>Acquisition Parameters</th>
<th>Processing Steps and Parameters</th>
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<tbody>
<tr>
<td><strong>Source</strong>: Vibroseis® 14-56 Hz, 18 s</td>
<td><strong>Vibroseis correlation</strong></td>
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<td><strong>Source interval</strong>: 67 m</td>
<td><strong>Elevation statics</strong>: floating datum</td>
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<td><strong>Receiver interval</strong>: 67 m</td>
<td><strong>Short-wavelength refraction statics</strong> (when available)</td>
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<td><strong>CDP interval</strong>: 33.5 m</td>
<td><strong>Bandpass filter</strong>: (8-12-35-40 Hz), or time-variant spectral whitening</td>
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<td><strong>Channel array</strong>: 48; off-end or split-spread</td>
<td><strong>First break mute</strong></td>
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<td><strong>Maximum offset</strong>: 3.5 km</td>
<td><strong>Ensemble spiking deconvolution</strong></td>
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<td><strong>Nominal fold</strong>: 24</td>
<td><strong>Automatic gain control</strong>: 500 or 750 ms</td>
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<td><strong>Nominal data length</strong>: 6 s</td>
<td><strong>Normal move-out (NMO) correction</strong>:</td>
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<td><strong>Recording length</strong>: 24 s</td>
<td>Velocity Analysis every 15 or 25 CDP</td>
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<td><strong>Sample rate</strong>: 4 ms</td>
<td><strong>Alpha-trimmed CDP stack at final datum</strong>:</td>
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<td>3000 ft/ 914 m</td>
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<td><strong>Depth conversion</strong>: 1D velocity field from tomography and RMS velocity</td>
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<td><strong>Kirchhoff time migration</strong>: using stacking velocity (Line D27)</td>
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Table 1. Seismic reflection profile acquisition and processing parameters