STRUCTURAL RECONSTRUCTION AND REINTERPRETATION OF THE AREA NEAR HAPPY VALLEY, LITTLE RINCON MOUNTAINS, SOUTHEASTERN ARIZONA

by

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Abstract

Structural reconstruction and mapping of select areas north and east of Happy Valley in the Little Rincon Mountains show multiple generations of Tertiary normal faults that have caused significant extension and tilting of rocks in the area, overturning (rotating through horizontal) certain early normal faults and yet older Laramide reverse faults. The tectonic history of southeastern Arizona includes contractional deformation during the Late Cretaceous and subsequent extensional deformation during the middle to late Tertiary, producing complicated map patterns with widely differing interpretations of their origin. Southern Arizona has only a thin section of Proterozoic to Mesozoic sedimentary rocks that serve as the best structural markers. The area near Happy Valley, however, is a prime location to attempt structural reconstructions because Laramide contraction duplicated the structural section prior to extension, thereby providing a much thicker sedimentary sequence to use for structural control.

The geology northeast of the Happy Valley area is composed of Precambrian basement intruded by Proterozoic granites and diabase sheets, overlain by Proterozoic, Paleozoic, and Mesozoic strata. The area contains at least five generations of approximately north-south striking normal faults, with both easterly and westerly dips. The biggest of these has approximately 3 km of slip. These faults are responsible for 50% of extension east of the San Pedro Valley and as much as 190% in parts of the western side of the region. Additionally, the faults have combined to expose the entire stratigraphic section from Precambrian granites to the west near the Rincon Mountains to Tertiary sediments east of the San Pedro Valley. The mid-Tertiary Mineta Formation presently dips 50-90° to the east, which is a measure of the net tilting of the area.

Reconstructions show that an early generation of normal faults crop out as low-angle, east-dipping, overturned normal faults and have been previously mapped as the San Pedro

detachment faults. By reconstructing the Mineta Formation to horizontal, this generation of normal faults upon inception would have originally dipped 50-60° to the west. The Laramide reverse faults on the west side of the San Pedro Valley, which presently dip eastward, restore to westward dips of 20-50°. These attitudes are consistent with the vergence of Laramide faults and presence of Laramide foreland clastic rocks in the eastern side of the study region. The balanced reconstruction of this area begs reevaluation of the detachment model as it has been applied to the area near Happy Valley and provides new insights into post-Laramide geology as of the mid-Tertiary paleosurface.

Introduction

The Catalina core complex, which includes the Rincon, Santa Catalina, and Tortolita Mountains, is a major geologic feature in southeastern Arizona, with a complicated geologic history (Davis, 1980; Dickinson, 1991; Force, 1997). The tectonic evolution of southeastern Arizona includes contractional deformation during the Late Cretaceous to early Tertiary or Laramide time (Davis, 1979) and subsequent extensional deformation during the middle to late Tertiary (Dickinson, 1991). The relative lack of exposure of upper plate rocks around the core complex has hindered the understanding of Paleozoic, Mesozoic, and early Tertiary structures developed before and during the onset of extension and core complex formation in the Miocene.

The chronology and geometry of normal faulting in the Catalina core complex and its environs has been the subject of considerable previous work (e.g., Lingrey, 1982; Davis, 1987a; Naruk and Bykerk-Kauffman, 1990; Dickinson, 1991; Force, 1997; Davis et al., 2004) and is the main point of interest for this study. Extension during the mid to late Tertiary was accommodated by several generations of normal faults, as supported by the presence of several ages of syn-extensional Tertiary sedimentary rocks in the area. The clasts in these sedimentary rocks commonly were derived from rocks exposed nearby, including earlier Tertiary rocks, pre-Tertiary sedimentary strata, and crystalline basement rocks. Growth sequences within the sedimentary accumulations record the time of movement on graben-bounding faults (Dickinson, 1991). Yet, several Tertiary sedimentary members have poorly constrained ages and thus provide only loose constraints on the chronology of normal faulting. Furthermore, the areas where certain faults should intersect are not exposed because of burial by late Tertiary and younger basin fill; hence, crosscutting relationships are not necessarily available to definitively determine the relative ages of certain faults.

The geologic mapping of the Catalina core complex has been extensive and has yielded complicated geologic map patterns. Formation of the core complex began in late Oligocene to early Miocene time and has been characterized by low-angle faulting and a mylonitic fabric on the western flanks of the Santa Catalina and Rincon Mountains (e.g., Davis, 1975, 1987a; Bykerk-Kauffman and Janecke, 1987; Naruk and Bykerk-Kauffman, 1990). Previous workers have attributed much of the extension and core complex formation to movement on a single detachment fault (Davis, 1980; Lister and Davis, 1989) that places pre-Tertiary cover rock on highly metamorphosed and ductilely deformed granitic basement. This fault is known by two names: the Catalina detachment fault on the western side of the complex and the San Pedro fault on the eastern side of the complex (Dickinson, 1991). Although the mapping has been thorough, the cross sections produced have failed to reflect the kind of detail and complexity found in map pattern. Moreover, no attempts at rigorous fault reconstructions have yielded balanced or viable results.

The geometric style of the Laramide orogeny has been a point of controversy in southeastern Arizona for the past three decades, and in this area the Tertiary extensional deformation must first be palinspastically removed before addressing the geometry of Laramide contractional deformation. Some workers have advocated a classic “basement-cored uplift” model for the style of contractional deformation (Davis, 1979; Krantz, 1989), while others have argued in favor of megathrust stacking for the mode of shortening (Drewes, 1974, 1978). Likewise, the propagation or vergence of the Laramide thrust belt in the region is also in contention. Whereas most reverse faults mapped on the eastern side of the San Pedro Valley show a top-to-the-northeast geometry interpreted as indicating a northeast vergence (Grover, 1982; Dickinson, 1986; Goodlin and Mark, 1987; Waldrip, 2008), other faults, exposed on the western side of the valley, were mapped and interpreted as having a southwest vergence (Drewes, 1976; Lingrey, 1982).

The region chosen for this study to address these problems is an area of approximately 100 km^2 that lies just northeast of Happy Valley, spanning the San Pedro Valley to include the eastern flanks of the Galiuro Mountains. This study area was chosen due to great exposures of Paleozoic and Mesozoic strata. These strata provide geologic markers to help determine the amount and direction of fault-related slip, and their orientations also help define areas of folding and/or fault-related tilting. Furthermore, outcrops of low-angle faults, many of which have been previously interpreted as detachment faults (in the sense of Lister and Davis, 1987), and moderate- and high-angle faults are preserved on both sides of the San Pedro River. These faults commonly accommodate syn-extensional Tertiary sedimentary rocks in their half-grabens, which are critical to unraveling the history of normal faulting in the region. Evidence for Laramide shortening is also present in this area in the form of reverse faults, which exhibit older-on-younger relationships, and overturned bedding in proximal sedimentary units. These exposures provide an opportunity to assess the role of normal faults in producing Tertiary extension in the Catalina core complex, as well as to assess the nature of Laramide contractional deformation in the study area.

Inside of this larger region a smaller area (~15 km^2) was chosen for detailed mapping. This area was not mapped in detail (1:48,000) by Drewes (1974). Yet, it is fairly complex, including the largest exposures of Proterozoic diabase and sedimentary sequence of the region, which both serve as important structural marker. The diabase, intruded in sill-like sheets across the region during the late Proterozoic, can be used as a key structural indicator in plutonic rocks where other such features are absent. This locale is adjacent to areas mapped in detail by Lingrey

(1982) and Trever (1983) to the north and thus was a logical area to extend existing geologic mapping to the south.

Syn-extensional Tertiary sedimentary rocks, as well as key crosscutting relationships recorded in the geologic mapping of the study area, point to at least five generations of Tertiary normal faults. Three sets of these faults currently dip to the east, while the other two dip to the west. There is sufficient evidence to believe that each generation of faults initiated at high angles of 60-70°. As each generation of faults slipped, younger generations rotated older generations of faults to lower angles. A few segments of these early generations of faults are currently overturned. Likewise, Laramide age reverse faults are locally overturned in areas of largest amount of extension. After restoration of movement on Tertiary normal faults, the orientations of the reverse faults support an east-verging thrust system, as they are largely concordant with the orientation of faults mapped in the eastern part of the study area as well as the foreland-type sedimentary rocks exposed there.

It is the goal of this study to supplement previously mapped regions with new mapping of an area to the south, as well as contributing a regional compilation map. Three regional cross sections are presented utilizing the compiled geology of the region. Rigorous reconstructions of the cross sections provide an interpretation of the post-Laramide/mid-Tertiary paleosurface and the underlying geology.

Geologic Framework

The Laramide orogenic events in southeastern Arizona manifested themselves in the form of arc magmatism, as well as reverse faulting and folding during the Late Cretaceous and early Tertiary time and are interpreted as a response to the flattening of the subducting oceanic slab beneath the subjacent lithosphere (Heidrick and Titley, 1982). Geologic events following the

Laramide time period, including erosion, Eocene intrusions, and mid- to late Tertiary extensional deformation, have worked to alter and obscure the geometric nature of Laramide tectonism. Thus, the geometry of faulting, width of the thrust belt, and amount of shortening in southeastern Arizona have been topics of controversy for many decades.

The style of contractional deformation during the Laramide is perhaps the most contentious issue among workers in southeastern Arizona. Two of the most notable opposing models for the style of Laramide deformation are the overthrust model and the basement-cored uplift model, both of which are succinctly juxtaposed by Krantz (1989). The overthrust model proposed by Drewes (1976, 1978, 1981) suggests that contraction was accommodated by the stacking of regional-scale thrust plates, which have caused an estimated 100 km of shortening in the region. In the Happy Valley area, Drewes (1974, 1976) has interpreted many low-angle features dipping gently to the east as exposures of a local underthrusting plate, which dips beneath the San Pedro Valley and is a result of the break up of a regional-scale allochthon into two northeast-verging thrust lobes.

The competing basement-cored uplift model suggests a near-vertical reverse faulting as the mode of shortening during Laramide time in southeastern Arizona (Davis, 1979). Davis concludes that the high-angle reverse faults exploited pre-Laramide zones of weakness and perhaps were a response to a later Cretaceous pulse of contraction. He discounts low-angle reverse faults as atypical features, citing block faulting earlier in the Mesozoic as a major hindrance to the mechanics that would have been responsible for the emplacement of a large overthrust sheet. Furthermore, Davis (1979) suggests that observations of structural relationships of low-angle reverse faults used as evidence for overthrusting by Thorman (1977) and Drewes (1976, 1978, 1981) fail to take into account the effects that regional tilting, intrusion, and metamorphism associated with middle to late Tertiary extension would have had on the present-day orientation of Laramide structures.

The vergence of the Laramide thrust belt in southeastern Arizona is another major point of interest in the literature. Drewes' overthrust model, as previously mentioned, predicts an overall top-to-the-northeast sense of displacement of the thrust belt. In the region of study, previous workers have documented both northeast- and southwest-dipping reverse faults. The best evidence in favor of an east-verging thrust system is found on the eastern side of the San Pedro Valley between Hot Springs Canyon and Teran Basin. Here, a reverse fault dipping gently to the southwest places basement rocks of the Johnny Lyon Granodiorite on Cretaceous Bisbee Group (Grover, 1982). Further north, Cretaceous Cascabel Formation, which only appears on the western flanks of the Galiuro Mountains, has been interpreted as a foreland-type sedimentary deposit (Goodlin and Mark, 1987) and, consequently, suggests proximity to the toe of the thrust system. The Cascabel Formation is in turn cut by a reverse fault of small displacement, which dips ~25° to the southwest, with the Bisbee Group in its hanging wall (Dickinson et al., 1987; Waldrip, 2008?).

In contrast to the eastern side of the San Pedro Valley, the western side has many documented east-dipping reverse faults interpreted as having westward transport kinematics (Drewes, 1974; Lingrey, 1982; Trever, 1983; Dickinson, 1987, 1998). In Happy Valley, a reverse fault dipping gently to the southeast places Johnny Lyon Granodiorite on top of sedimentary rocks of the Bisbee Group (Drewes, 1974; Dickinson, 1998). Likewise, a reverse fault several miles to the north of Happy Valley dipping 50-70° to the east, which can be traced for several miles along the western flank of Banco Ridge, exhibits a similar geologic relationship (Lingrey, 1982).

On the northeastern margin of the Catalina Mountains (a few miles northwest of the study region), east-dipping ductile structural features and metamorphic fabric have been interpreted as Laramide compressional features overprinted by Tertiary metamorphism during core complex formation. Lineations in this area show an east-directed sense of shear and, although faults exhibit younger-on-older relationships, evidence of strong tilting in the area suggests that these were once northeast-verging reverse faults active during the early Tertiary and perhaps as late as 50-44 Ma (Bykerk-Kauffman and Janecke, 1987). A possible analog to these features exists in a less tilted terrain of the Little Rincon Mountains. Here, the Little Rincon thrust dips moderately to the southwest and places Proterozoic Continental Granodiorite on Paleozoic metasedimentary rocks with kinematics in the upper-plate mylonite exhibiting top-to-the-northeast transport (Smith, 1989). Zircon age dates and crosscutting relationships of intrusions proximal to the fault suggest that it was active between 66±10 and 51±2 Ma (Gehrels and Smith, 1991).

Laramide arc magmatism in southeastern Arizona occurred roughly between 80 and 55 Ma and manifested itself in the form of metaluminous and peraluminous suites of intrusions, as well as andesitic to rhyolitic volcanism (Titley, 1981; Damon et al., 1981; Keith, 1982). These magmatic events were directly related to low angle subduction beneath much of Arizona (Coney, 1980). In and around the Santa Catalina core complex, a range of mineralized and unmineralized plutons of Laramide age crop out, many of which are part of the classic suite of Laramide hornblende- and biotite-bearing metaluminous intrusions in Arizona that are related to the porphyry copper deposits (Titley, 1982; Lang and Titley, 1998). Examples of such Laramide orebodies include the San Manuel and Kalamazoo porphyry copper deposits located just north of the Catalina core complex between the towns of Oracle and Mammoth (Creasey, 1965; Lowell, 1968; Sandbak and Alexander, 1995). These subvolcanic intrusions have been spatially and temporally correlated with others in and around the core complex and have provided an analogous model for associating Laramide volcanic rocks with corresponding intrusive stocks (Creasey, 1965; Dickinson, 1991).

The Wilderness suite of granites which form a large part of the Catalina-Rincon core complex are distinct from the Laramide porphyries. Some of these peraluminous, felsic-intermediate granitoids have been dated at 48-44 Ma (Shakel, 1978; Keith et al., 1980; Reynolds et al., 1986), which would place them in an interval following most Laramide intrusions and preceding mid-Tertiary magmatism. Yet, other work suggests that a series of such Wilderness-type plutons could have intruded in pulses between 65 and 25 Ma (Gehrels and Smith, 1991; Dickinson, 1991). This age spread highlights the complexity and uncertainty regarding the events that may have transpired between the last gasp of Laramide contractional tectonics and the onset of mid-Tertiary extension.

Extension in southern Arizona began during mid- to late Oligocene and was accompanied by magmatism that swept from east to west across the region. The westward migration of magmatism occurred in response to the rollback and eventual break-off of the subducting Farallon plate (Dickinson, 1991). A crustal profile overthickened by Laramide orogenic events and a geothermal gradient elevated regionally by advective heating from magmatism contributed to rapid extension rates in the mid-Tertiary across southern Arizona (Davis, 1979; Davis, 1980; Shafiqullah et al., 1980; Lipman, 1981; Coney and Harms, 1984; Coney, 1987).

The response to the high extension rates manifested itself in one of the largest physiographic extensional feature in southeastern Arizona. The Catalina metamorphic core complex represents a string of such similar aged extensional phenomena found along the length of the North American Cordillera from southern British Columbia to northern Sonora (Crittenden et al., 1980; Armstrong, 1982; Dickinson, 2002). Although, Cordilleran metamorphic core complexes were initially interpreted as contractional features (Misch, 1960; Drewes, 1976, 1978), today, they are widely recognized as results of extension (e.g., Dickinson, 2002). Perhaps the most distinctive feature of metamorphic core complexes is the decollement zone typically formed by a one or more low-angle faults (usually referred to as detachment faults), which flanks one or two sides of a core complex and juxtaposes an upper plate carapace against deep crustal, mylonitized granitoids or otherwise ductilely deformed sedimentary or volcanic rocks (Davis and Coney, 1979; Davis, 1980; Crittenden et al., 1980; Armstrong, 1982).

Extension in and around the Catalina core complex evolved in two phases. Major extension in the late Oligocene to early Miocene time produced brittle to ductile shear zones that are expressed now in the form of low-angle ("detachment") faults. These and related faults caused substantial denudation and exhumation of rocks at the mid-crustal levels. This episode of extension was followed by a slower extension rate manifested by several generations of high-angle normal faults, the oldest of which were progressively tilted and rotated to flatter orientations by incipient sets. There exists a considerable debate about whether or not the first or oldest generation of high-angle normal faults were, in fact, detachment faults which have been rotated to their present orientations by subsequent generations of normal faults initiating at similar angles. Much of previous work suggests that the Catalina detachment fault system, as well as many others, initiated and were active at low angles (Wernicke, 1981; Lister and Davis, 1989). Many cross sections and models across the Catalina-Rincon core complex portray low-angle detachment continuous over tens of kilometers. Yet, this low-angle master-fault model has its competitors in the form of tilt-block models and multiple generations of normal faults initiating at high angles responsible for the mode of extension (Davis, 1983, 1987b; Gans and Miller, 1983; Jackson, 1987; Seedorff, 2006, 2007).

Multiple generations of normal faulting in the study region were first recognized in part due to the array of mid to late Tertiary sedimentary assemblages and volcanics found in the region. Sedimentary packages often filled half-grabens produced by a series of active faults and were largely composed of conglomeratic clasts of Paleozoic and Mesozoic sedimentary rocks as well as Precambrian basement derived from fault scarps and tilt blocks. Sedimentation in these half-grabens was largely syn-tectonic, producing fanning dips of sedimentary strata in response to fault movement and block tilting. The oldest of these syn-extensional sedimentary units, the Mineta Formation, roughly reflects the age of the first generation of normal faults, which in turn were coeval with detachment faulting. The Galiuro Volcanics, resulting from a late Oligocene ignimbrite flare up, soon covered much of this first generation of sediments. The basins formed by these early sediments and volcanic rocks were in turn cut and tilted by later generations of normal faults creating new half-grabens to be filled locally by younger sedimentary sequences of the Pantano, Cloudburst and San Manuel Formations (Dickinson, 1991).

The youngest generation of normal faults is of mid-late Miocene age and is often referred to as Basin and Range style of extension. The effects of Basin and Range normal faulting are seen today in the physiographic and topographic landscape of southern Arizona and much of southwestern North America. This type of range-front faults may be responsible for the final exhumation of the Catalina-Rincon core complex as it is seen today. Total extension across the whole of Catalina-Rincon core complex and its environs has been estimated at 20-30 km (Dickinson, 1991; Davis et al., 2004).

Methods

Excursions to select areas throughout the Rincon, Santa Catalina, and Galiuro Mountains were integral to the understanding of regional geology for the purposes of this study. Detailed geologic mapping was conducted at 1:12,000 scale in a 15 km^2 area just northeast of Happy Valley bound by Gardner Mountain ridge to the east, Driscoll Mountain to the west and Bald Mountain to the south. Additionally, several smaller areas in the overall region of study, which were particularly relevant to a regional structural synthesis were visited, some remapped and reinterpreted. In all cases, key geologic contacts, rock types, and orientations were observed and recorded in detail. The total time spent mapping was approximately two months.

A regional geologic map was compiled at a 1:24,000 scale (Figure 3) based on previous mapping from Trever (1983), Lingrey (1982), Dickinson (1986, 1991, 1998), Dickinson and Olivares (1987),Waldrip (2008), and Spencer and others (2008a, 2008b) and incorporating new interpretations based on the field excursions and mapping. Regionally, this map encompasses an area of four, 7.5”-quadrangles: Soza Canyon, Soza Mesa, Wildhorse Mountain, and Happy Valley (clockwise from northwest to southwest, respectively). This map served as the base for a fault compilation overlay map (Figure 4) depicting several generations of faults along with their spatial and temporal relation to each other. Three regional cross sections through the study region were prepared using the data depicted on the geologic map compilation, fault overlay map, and supplemental mapping of select areas. These cross sections were rigorously restored fault by fault, beginning with the youngest faults and working backward in time, implementing balanced fault reconstructions to depict a mid-Tertiary paleosurface.

Results

Detailed Field Study

The area mapped in detail for this project lies on the eastern flanks of the Rincon Mountains, just east of Happy Valley in the rolling and, in places, cliffy desert landscape of the Little Rincon Mountains (Figure 1). This area displays geologic complexity largely reflective of the greater Catalina core complex and its environs (Figure 2). The terrain exhibits a significant amount of outcrop, which, in large scale, displays two distinct geologic domains. The cliffy peaks of Gardner Mountain ridge south to Eagle Peak are composed of upper Paleozoic sedimentary strata largely made up of limestones, whereas the rolling foothills and drainages flanking these topographic highs are predominantly lower Paleozoic quartzites, sandstones, and siltstones all underlain by Proterozoic quartzite. This Proterozoic-Paleozoic sedimentary sequence is tilted regionally 30-50° to the east, is largely undeformed, and unconformably overlies lower Proterozoic Johnny Lyon Granodiorite (Figure 2).

The geology described above depicts a Proterozoic-Paleozoic sequence that has been thoroughly documented across southeastern Arizona (Bryant, 1968; Beus, 1989; Blakey and Knepp, 1989). Within my field area, an area of comparatively straightforward geology abuts an area exhibiting a high degree of geologic complexity (Figure 2). These two contrasting domains are separated by a low-angle, ductile fault striking roughly north and dipping very gently to the east near the Hells Gate canyon, wrapping around and dipping under the undeformed Proterozoic and Paleozoic strata surrounding Eagle Peak to a more eastern orientation. South of this low-angle feature and just south of the field area, the rugged peaks of the Little Rincon Mountains are composed of Proterozoic crystalline rocks of the Continental granodiorite, Pinal Schist and Johnny Lyon Granodiorite, respectively, from west to east. To the west of Hells Gate canyon, the rocks are metamorphosed and penetratively deformed. A large body of metamorphosed Johnny Lyon Granodiorite lies to the south of Driscoll Mountain, which is separated by an east-west striking fault from exposures of Pinal Schist to the north, which is largely intruded out by a dark green, fine-grained diabase of Middle Proterozoic age (~1.1 Ga; Wrucke, 1989). Bordering the western side of the low-angle fault separating the metamorphosed rocks from the Proterozoic and Paleozoic strata lies a thin veneer of highly deformed and attenuated layer of quartzites, slates, and marbles. The units overly and locally cap topographically high exposures of Johnny Lyon Granodiorite, Pinal Schist, and the fine-grained diabase. These metamorphosed sedimentary rocks are likely derived from the sequence of Proterozoic and Paleozoic rocks; commonly are observed as ductilely folded and presumably later dissected by brittle faults, both of which complicate the understanding of their structural orientation, even on a regional scale.

The faulting in this area, alluded to previously, is highly varied and complex. Ductile normal faulting of a similar nature to the afore-mentioned low-angle feature is present throughout the metamorphosed domain of the field area. These faults, commonly dipping at low angles and intermittently exposed along strike, cut and displace north-striking reverse faults, which locally place crystalline and metamorphic basement on Proterozoic and Paleozoic sedimentary strata. In turn, these low-angle, ductile normal faults are cut and displaced by numerous, higher angle normal faults in various locations throughout the metamorphic and underformed domains of the field area. Furthermore, evidence of intraformational faults (i.e., faults with the same stratigraphic unit in both the hanging wall and footwall of a given exposure) is present, localized largely in the unmetamorphosed Paleozoic units of the Gardner Mountain ridge and Eagle Peak area (Figure 2).

Regional Study

Regionally, and in large part, the geology of the four 7.5”-quadrangles hugging the flanks of the San Pedro Valley is analogous to and equally complicated as the field area mapped in detail east of Happy Valley chosen for detailed mapping (Figure 3). In the Little Rincon Mountains and vicinity on the western side of the valley, crystalline and metamorphic Proterozoic rocks and overlying Paleozoic, Mesozoic, and Tertiary sedimentary strata are separated by a northwest-striking, gently east-dipping normal fault from ductilely deformed sedimentary rocks overlying similar basement rocks. Conversely, Tertiary sedimentary and volcanic rocks on the eastern flank of the San Pedro Valley and adjacent Galiuro Mountains cap large exposures of Mesozoic sedimentary rocks, which are locally deformed.

Geologic Units

Basement geology of the regional study area is composed of a series of Precambrian granitic plutons intruding the ~1.7 Ga Pinal Schist (Copeland and Condie, 1986; Reynolds et al., 1986a). Johnny Lyon Granodiorite (Cooper and Silver, 1964) intrudes the Pinal Schist both in the southeastern and southwestern portions of the regional map area. Flanking the eastern parts of the Rincon Mountains is a large body of Continental granodiorite (similar in age, ~1.4 Ga, to the Oracle Granite (Keith et al, 1980) north of the study area), which intrudes both the Pinal Schist and the Johnny Lyon Granodiorite. All three Precambrian intrusions are locally cut by the Middle Proterozoic fine-grained diabase, which is voluminous around Driscoll Mountain (Figure 2), but is also intraformationally present in the middle Proterozoic sedimentary strata in the southeastern portion of the regional study area. The Precambrian sedimentary sequence is composed largely of the sedimentary rocks of the Apache Group, especially the Dripping Spring Quartzite (Wrucke, 1989). These thinly bedded, dark red quartzites consistently strike north-

northwest on both sides of the San Pedro Valley, dipping from ~30° east near Eagle Peak (Figure: 2) to 55° southeast of Kelsey Canyon. (Figure 3).

The Paleozoic sedimentary sequence is largely conformable with the underlying Precambrian sedimentary strata. Unmetamorphosed exposures of Paleozoic sediments are relegated in large part to the southern half of the regional study area and, where exposed, the sequence is structurally akin to that of the underlying units. In the western portion of the regional map area, near Happy Valley, Carboniferous strata dip ~50° to the east, whereas in the east, south of Kelsey Canyon, the same strata exhibit more northwesterly strikes with dips of 50-60° to the northeast. The metamorphosed Paleozoic section is exposed as a relatively thin veneer of highly attenuated and tectonized quartzites and marbles covering a large area in the center of the study area, west of the San Pedro Valley. Although regionally folded, the marbles of this section west of Paige Canyon exhibit a ductile foliation trending roughly north and plunging east at around 40°. In contrast, east of Paige Canyon the foliation swings from northwest trends in the northern exposures to northeast trends in southern exposures. The foliation in both the northern and southern localities plunges 30-50° to the east (Figure 3).

Mesozoic rocks occur predominantly in the northern half of the study area, with large exposures in the northeast near Soza Mesa and a few outcrops west and south of Banco Ridge on the western side of the San Pedro Valley (Figure 3). The thickness and regional extent of the late Jurassic-Early Cretaceous rift sediments of the Bisbee Group are poorly constrained. Locally, those strata, which exhibit few marker beds, are highly folded. Near Soza Mesa, the lower part of the Bisbee Group as well as the younger Muleshoe Volcanics and Cascabel Formation are regionally folded from north to south with fold axes trending west-southwest. On the northern end, Cretaceous rocks strike north to northwest and dip regionally ~45° to the west (Figure 3).

South of Hot Springs Canyon, the same strata dip 30-60° to the northeast. Near Banco Ridge (Figure 3), sedimentary rocks of the Bisbee Group generally strike northwest and dip ~55° to the northeast, although bedding attitudes are locally highly variable. To the north of Happy Valley (Figure 3), limited exposures of the Bisbee Group exhibit dips of ~50° to the southeast. Almost no exposures of the Late Jurassic portion of the Bisbee Group are found within the region of study, with exception of the extreme eastern locality southeast of Kelsey Canyon where both Late Jurassic and Early Cretaceous strata are east-northeast dipping at ~40° (Figure: 3).

A variety of Cenozoic age rocks including intrusions, volcanic rocks, and sedimentary strata are exposed throughout the regional study area and comprise, perhaps, the largest fraction of all rocks exposed. Tertiary sedimentary deposits in the study region occupy a range of localities and are roughly composed of two age groups of sediments. The oldest of these are the conglomeratic red beds and lacustrine limestones and siltstones of the Mineta Formation (Chew, 1962; Grover, 1984), a sedimentary growth sequence, the dates of which have been bracketed at ~35-27 Ma (Dickinson, and Shafiqullah, 1989; Dickinson, 1991). In the study region, these sedimentary deposits crop out mostly in the northern half of the area on both sides of the San Pedro Valley. West of Banco Ridge (Figure 3), beds of the Mineta Formation stretch for more than 10 km along strike from northwest to southeast and rest unconformably on crystalline and metamorphic basement rocks. In the northern part of the exposure, northwest of Banco Ridge, the basal conglomerates dip 40-65° to the northeast. On the southern end west of Paige Canyon, the beds adjacent to the unconformity dip ~80° and in places approach verticality.

To the eastern side of the San Pedro Valley, near Kelsey Canyon (Figure 3), large outcrops of the Mineta Formation lie unconformably on sedimentary rocks of the Cretaceous Bisbee Group and dip ~50-65° to the northeast. Two other, smaller series of exposures of Mineta

Formation are found within the regional study area. One, scattered along the west side of the San Pedro River, is intermittently exposed overlying metamorphosed Paleozoic strata, exhibiting similar strikes to those already mentioned but dipping shallower at ~40°. At the other locality, located just north of Happy Valley, conglomerates and sandstones of the Mineta Formation rest on upper Paleozoic limestone and dip ~45° to the northeast. Near Banco Ridge, the Mineta Formation is conformably overlain by andesitic to latitic lavas of the Galiuro Volcanics, which in the study region are otherwise relegated largely to the Galiuro Mountains. Here, the lava flows strike north-northwest and dip ~25-35° to the east. Limited exposures of the Galiuro Volcanics appear on the western side of the San Pedro Valley near Banco Ridge (Figure 3), where the structural orientation of the flows is poorly constrained but appears to be similar to those on the eastern side of the valley.

The second group of Tertiary sedimentary rocks exposed in the regional study area are three facies of the San Manuel Formation (Heindl, 1963; Dickinson, 1991), which unconformably rest on the Galiuro Volcanics and pre-Tertiary rocks. None of the three facies is well dated and may be only bracketed by the latest Oligocene and beginning of the middle Miocene boundary (24-16 Ma). The Soza Canyon facies of the San Manuel Formation crops out on the western side of the San Pedro Valley, east of Banco Ridge. This alluvial fan deposit, containing clasts of Galiuro Volcanics, dips ~30-40° to the southwest. Deposits of the second facies, known as the Paige Canyon Facies, are found just south of the Soza Canyon facies, contain metamorphic clasts derived from the tectonized Paleozoic strata of the surrounding area, and dip ~20-35° to the east. The third facies of the San Manuel Formation, known as the Kelsey Canyon Facies, crops out on the eastern side of the San Pedro Valley flanking the Galiuro Mountains, with significant exposures between Hot Springs and Kelsey Canyons. The Kelsey

Canyon strata contain granite clasts and have variable bedding orientations that dips gently to the east on the northern end and gently to moderately west on the southern end (Figure: 3).

Tertiary intrusive rocks of the study area are located on the extreme western and southern sides of the regional map area, flanking the Rincon Mountains and as rugged peaks southeast of Happy Valley, respectively. In the western portion, leucogranites of the Wilderness Suite intrude Continental Granodiorite, whereas on the southern end the same granites also intrude Pinal Schist. Additionally, a small body of Turkey Track porphyry of mid-Tertiary age intrudes Pinal Schist and metamorphosed Paleozoic sedimentary rocks a few kilometers north of Hells Gate (Figure: 3).

Alteration of an unknown age (or ages) has affected the Johnny Lyon Granodiorite pluton all along the extreme southern end of the study area. In the south-central part of the regional map, the pluton features fine-grained, polycrystalline "shreddy" biotites after hornblende sites in hand sample. In the southeastern corner of the regional study area, the same intrusion contains chlorite and epidote in veins and replacing original minerals in the rock. This type of alteration also was observed in Rincon Valley, outside the study area west of the Rincon Mountains.

Faults in the regional study area are pervasive on the regional scale and exhibit complicated geometries and crosscutting relations. The density of faults appears to increase on the western side of the San Pedro Valley approaching the Santa Catalina core complex. There, multiple sets of normal faults are present, with older faults cutting and segmenting younger faults. The various segments of faults are commonly difficult to correlate with one another. On the eastern side of the valley, the degree of faulting is lower, but crosscutting relationships are likewise complex. To help ease the correlation and grouping of various sets of normal faults, a map showing only faults was generated from the regional study map. The fault map (Figure 4) assigns individual faults to fault sets, based on similarities in descriptive characteristics of individual faults (e.g., strike and dip), crosscutting relationships between faults, and relationship between faults and sedimentary units (Figure: 4). To the extent that definitive crosscutting relationships have been observed, each progressive fault sets thus likewise represents a different temporal generation of faults.

No faults were observed that appear to control deposition of the Late Jurassic to Lower Cretaceous Bisbee Formation. The oldest faults, shown in red on the regional fault map (Figure 4), are reverse faults as evidenced by older over younger relationships. These faults are cut by all other faults in the region and presumably are of Laramide or Sevier age (Krantz, 1989). On the western and northern side of the San Pedro Valley, the Roble Spring Fault strikes northwest and dips moderately to the northeast, placing crystalline/metamorphic basement on sedimentary rocks of the Cretaceous Bisbee Group. In the south (near Happy Valley), faults displaying a similar geologic relationship trend to the northeast and dip moderately to the southeast. Conversely, on the eastern side of the valley the Soza Mesa fault places Bisbee Group over Upper Cretaceous Cascabel Formation and dips regionally at ~35° to the west-southwest. Southeast of Kelsey Canyon, strands of east-dipping faults place Precambrian rocks on Jurassic and Cretaceous strata (Figure: 4; Figure: 3; Table: 1).

The purple faults on the regional fault map (Figure 4) are a complex set of ductile shear and shear zone normal faults, which apparently have been folded and dissected by younger geologic events. They appear to be concentrated at or near the base of the metamorphosed Paleozoic strata, commonly appearing intraformationally in Cambrian and Devonian strata. The attitudes of this set of faults are extremely variable over the regional study area but are overall north to northwest trending, dipping very gently to the east. The age of this ductile set of faults is not well constrained. They appear to be intruded by the Turkey Track Porphyry (~24-27 Ma) north of Hells Gate and may postdate Eocene suite of Wilderness granites. In this study, they are regarded as the first generation of normal faults (Figures 3, 4; Table: 1).

Light blue colored faults in the study area cut and offset the ductile shear faults and are thus considered the second generation of normal faults. To the west and north of the San Pedro Valley, the San Pedro fault dips ~40° to the northeast, whereas in the south its counterpart dips slightly shallower to the southeast. Across the valley, the Teran Basin fault exhibits similar trends, but dips gently to the southwest at ~35°. The importance of this fault set across both sides of the valley is that these faults appear to be responsible for the formation of the earliest set of Tertiary sedimentary basins, which now house the growth sequence of the Mineta Formation. This sedimentary correlation places the age of these faults to be at around 30-35 Ma based on age dating of rhyolitic ignimbrite at the base of the Mineta Formation and sedimentation rates of analogous syn-extensional Tertiary strata elsewhere in the region (Dickinson, 1991; Figures 3, 4; Table: 1).

Both the dark and light green colored normal fault sets in the study area are age-bracketed based on crosscutting relationships between the light blue faults, which control sedimentation in the Mineta Formation, and the youngest, Basin-and-Range faults. Both sets are roughly north striking and display dips of 35-65° to the west and appear, with some exceptions, to be roughly coeval. These third- and fourth generations of normal faults appear to either cut or control sedimentation of the various facies of the San Manuel Formation, which places the age for their inception no earlier than 20-22 Ma. The youngest, dark blue colored set of normal faults crosscut all other sets of faults and contributes to the present day physiographic appearance of the landscape. Regionally, these faults strike north and consistently dip steeply to the east, with the exception of the Banco Ridge Fault, which has a more northwesterly strike. This youngest generation of faults appears to cut the ~15 Ma lacustrine and floodplain sediments of the Quiburis Formation (Heindl, 1963), yet are often buried beneath younger Quaternary gravels and basin fill (Figures 3, 4; Table: 1).

Interpretations

Cross Sections

Three regional cross sections were prepared using the regional geologic and fault overlay maps to capture the complexity of the subsurface geology of the regional study area (Figure 5). The cross sections transect the structural grain of the regional geology, which is trending predominantly north-northwest, from west to east (Figure 3). Cross Section 1 runs east-northeast from the eastern flank of the Rincon Mountains southwest of Banco Ridge, across the San Pedro Valley, to the southern end of the Galiuro Mountains. Cross Section 2 trends more northeasterly beginning on the southwest side from the northern margin of Happy Valley, then parallels Kelsey Canyon, and extends northeasterly to the southern end of the Galiuro Mountains. Cross Section 3 stretches from Hell's Gate in the west to the northern end of the Johnny Lyon Hills in the east.

In all three cross sections, the regional tilt of Paleozoic, Mesozoic, and Tertiary strata is approximately 30-85° to the east-northeast, which has exposed lower crustal igneous and metamorphic rocks in the west and Cretaceous and Tertiary sedimentary rocks in the east.

In Cross Section 1 (Figure 5) exposures of the mid-Tertiary unconformity are tilted ~80° in the west and 30-60° in the east, based on the dips of the Mineta Formation at the base of the unconformity. Beds of the Paige Canyon facies of the San Manuel Formation are tilted ~30° to the east, dipping into the footwall of the Paige Canyon fault and its subsidiary fault directly to the east. In contrast, the Kelsey Canyon facies of the same formation appears to have lapped onto the footwall of the Teran Wash fault that dips to the west. Subsurface down-plunge projections from outcrops to the south of Cross Section 1 indicate that pre-Tertiary sedimentary strata are tilted ~50° to the east. In Cross Section 1, these pre-Tertiary rocks and beds in the overlying Mineta Formation appear to be tilted into the footwalls of faults of the second generation, which dip gently to the west on the eastern side of the San Pedro Valley but are overturned (i.e., rotated to gently east dips) in the west. Faults of the third and fourth generation dip moderately west on both sides of the valley, whereas faults of the youngest generation dip steeply to the east.

Cross Section 2 (Figure 5) transects a large swath of metamorphosed Paleozoic rocks in the center of the regional study area. Here, the metamorphic foliation dips 30-50° to the east even as the whole sedimentary package is folded with axes plunging to the east-northeast. The cross section parallels the axis of a syncline, which plunges gently east-northeast. As in Section 1, in Cross Section 2 beds of Mineta Formation near the mid-Tertiary unconformity dip east at 35-55° on both sides of the San Pedro Valley, and the pre-Tertiary sediments are likewise east-tilted ~50°. Generations of normal faults are progressively more tilted with age, with the oldest ductile faults dipping gently to the east (overturned from original steep westerly dips), whereas the youngest faults dip moderately to steeply to the west, while those of the second generation appear at sub-horizontal attitudes.

Cross Section 3 (Figure 5) runs along the southern side of the regional study area, intersecting several repeated sections of the undeformed Paleozoic sedimentary sequence through this complexly faulted terrain. The Paleozoic sequence is repeated at least three times from west to east in this area and in most cases dips steeply to the east. Repetition of this section is attributed to two reverse faults, which presently dip steeply to the east and appear to be cut off by the San Pedro fault in the subsurface. The San Pedro fault underlies the repeated Paleozoic sequences and appears to be overturned dipping gently to the east. Sparse outcrops of the Mineta Formation suggest that the locally buried mid-Tertiary unconformity dips ~40° to the east into the footwall of the San Pedro fault. Folded and metamorphosed Paleozoic sedimentary rocks underlie the San Pedro fault and, as regionally, dip gently to moderately to the east. Late generations of normal faults segment and rotate the San Pedro fault and the underlying deformed sedimentary rocks to their present orientations. There is little control on subsurface geology below the metamorphosed Paleozoic sedimentary rocks, but rocks expected to be present in the crystalline basement would be Pinal Schist, Johnny Lyon Granodiorite and Continental Granodiorite, locally intruded by diabase.

Slip on major faults in the regional study area (Table 2), measured and averaged on all three cross sections, indicate that the second and third generations of normal faults accommodated a significant percentage of extension in the area. As an example, the San Pedro and Teran Basin faults had more slip than all the other major faults combined. Both faults accommodated approximately 3 km of slip each transporting their hanging wall geology to the west-southwest (Figure 1). Major faults of the third and fourth generation produced slip of 0.5-2.4 km directing their upper plate geology predominantly to the west (Figure 1). Finally, faults of the fifth generation produced minimal slip of ~0.4-0.9 km, this time with easterly slip indicators (Figure 1).

Reconstructions

All three cross sections were rigorously reconstructed assuming rigid behavior and slip in the plane of the cross sections. Figure 6 shows the reconstructions for mid-Tertiary time to portray the paleosurface prior to deposition of the Mineta Formation and inception of movement on the second generation of normal faults. As an illustration of how the fault-by-fault reconstructions are developed, Figure 7 shows the sequential reconstruction of each generation of normal faults, beginning with the present day cross section and ending with the inception of the fifth and final fault generation.

The reconstruction (Figure 7) begins with the restoration of the youngest, fifth-generation of normal faults, by aligning the corresponding geologic units that previously were displaced by movement on these faults. Faults were thus restored stepwise, from youngest to oldest generations. After each step of fault generation restoration the net rotation of the section was removed by rotating the entire section back to horizontal, based on the paleosurface at the inception of movement on a particular generation of faults. The sedimentary rocks that were deposited contemporaneous with movement of a particular fault set determine the paleosurface for each time frame.

Two-dimensional reconstructions of regional cross sections are challenged by the difficulty in accounting for the on-strike curvature of faults whose overall geometry seems to be spoon- or shovel-shaped. For example, Cross Section 1 probably is oriented subparallel to the slip direction of the San Pedro fault, but in the vicinity of this section, the fault has an important component of dip into the plane of the section. Hence, this geometry then creates the appearance of a poor fit in the resulting reconstruction. Furthermore, the amount of slip changes along strike, because of factors such as scissor-type movement along any individual fault and transfer of slip between adjacent or en echelon faults of the same generation (e.g., Faulds and Varga, 1998). Consequently, the two-dimensional reconstructions depicted here do not convey the full complexity of three-dimensional relationships, but they do convey the preferred interpretation of the structural architecture and evolution of the region.

The net tilting of each crustal block on each cross section is largely determined by the present day dip of the mid-Tertiary unconformity exposed on or projected into each of the sections. Thus, in a view to the north, the western side, near Banco Ridge, appears to have been tilted as much as 90° clockwise from its original orientation, whereas the eastern side, north of Kelsey Canyon, was only tilted 40-60°. In Cross Section 2 the net rotation accommodated appears to have been only ~40° since mid-Tertiary time. Poor controls on geology in Section 3 make it difficult to constrain a precise amount of tilting, but sparse outcrops of the Mineta Formation, presumably near the base of the mid-Tertiary unconformity, suggest a maximum of ~50° of net eastward tilting.

In the western part of the region, across the San Pedro Valley, up to 50° of tilting occurred between 34 – 24 Ma (according to the time span for deposition of the Mineta Formation and overlying Galiuro Volcanics), the majority of which occurred during movement on the second generation of normal faults. This is evident by the angular unconformity observed between the Mineta Formation and overlying facies of the San Manuel Formation (24-16 Ma) (Dickinson, 1991). Faults controlling sedimentation of the Kelsey Canyon facies of the San Manuel Formation cut the Mineta Formation, bracketing the upper age for the tilting. In the northwest portion of the study region (Figure 3), where up to 85° of tilt has occurred, third and fourth generation faults such as the Teran Wash and Paige Canyon faults (Figure FM) contributed to the rest of the rotation after 24 Ma. Conversely, in the east, almost all of the rotation was accommodated on the second generation of normal faults, as evident by the fact that the area is largely not deformed by late generations of normal faults.

The amount of extension of each regional cross section is calculated by locating and measuring the distance between two geologic contact points on the present day section, subtracting the distance between the same points on the reconstruction, dividing the result by the distance found in the reconstruction. This fraction is converted to a percentage by and multiplying by one hundred. The area transected by Cross Section 1 appears to have been extended by 150-190%, while in Section 2 only 70-80% of net extension occurred. The difference in amounts of extension can be attributed to the apparent increase in displacement and number of faults in the north of the regional study area. This is evident by exposures of the Cretaceous Bisbee Group on both sides of the San Pedro Valley indicating a large amount of extension necessary in order to stretch this stratigraphic marker over such a large area. The amount of extension in Cross Section 3 is difficult to calculate owing in part to poor geologic constraints on the eastern side of the San Pedro Valley. Based on depth of exposure and repetition of the stratigraphic section from the eastern flanks of the Rincon Mountains to the San Pedro Valley, the amount of extension is estimated to be similar to that found in Cross Section 1, i.e., ~150-190%.

From the step-by-step reconstruction of Cross Section 2 (Figure: 7), the original inception angle of faults is easily observed. The youngest set of faults, belonging to the fifth generation of normal faults, appears to have initiated at steep angles of 70-85°, which is largely concordant with high-angle Basin-and-Range normal faulting. Faults of the third and fourth generation initiated at angles ranging from 50 to 85°, whereas normal faults of the second generation initiated at ~65°, akin to classic models of normal fault formation.

The reconstructions also are useful for assessing the original orientation and vergence of Laramide reverse faults. Laramide reverse faults in the region in the mid-Tertiary were approximately north-northwest striking, with variable westerly dips ranging from 10° to 65°. Reconstructions of Cross Sections 1 and 2 (Figure: 6) suggest that reverse faults of major displacement were predominantly east verging with westerly dips of 20-50°. Furthermore, major reverse faults place Precambrian crystalline rocks on Cretaceous Bisbee Group sediments in effect repeating >4 km of stratigraphic section.

Discussion

Structure of Proterozoic Diabase and Low-Angle Ductile Faults

The area mapped in detail represents, on a smaller scale, the great geologic complexity of the regional study area. The geologic relationships found there are integral to the understanding of the nature of key contacts and trends in the surrounding region. In previous studies of the area many of the geologic contacts were misinterpreted, specifically in the case of Drewes (1974) where almost all low angle faults of the area were mapped as reverse faults. Furthermore, metamorphism in the Johnny Lyon granodiorite and the Paleozoic sedimentary units was not properly recognized or categorized, nor was the intrusive nature of the diabase well understood. Despite a more detailed geologic synthesis, many issues within the study area still remain unresolved.

Exposures of Proterozoic Dripping Spring Quartzite, largely absent in the regional study area, indicate that there is no significant angular unconformity between the Precambrian and Paleozoic sedimentary sequences. A large body of Proterozoic diabase intrudes the Dripping Springs Quartzite in sill-like sheets and serves as a great structural marker within older igneous bodies of the region. The detailed study area is separated into two distinct domains by a low angle, ductile fault dipping gently (15-20°) to the east. The fault separates largely undeformed

Proterozoic and Paleozoic sediments in its hanging wall from ductilely deformed and attenuated Proterozoic crystalline rocks and overlying Paleozoic strata.

The tilt of the Paleozoic sedimentary sequence is locally analogous to the regional tilt of the same strata and has thus served as a great example for study to the rest of the region. Likewise, low-angle, semi-ductile faults within the detailed study area are largely representative of many such faults in the region and have been integral in aiding the interpretation of many others like it. Although, strictly speaking, the nature of the low-angle fault in the detailed study area and its relationship to the metamorphism of the rocks in its footwall is not understood. Future studies need to address the issue of the apparent absence of the Proterozoic sedimentary sequence along strike throughout the rest of the region. As shown by Barton et al. (2007) and Maher (2008) the attitudes of diabase sheets in crystalline rocks can aid in the interpretation of the amount of tilting in localities with no sedimentary stratigraphy.

Geometry of extensional faults and possible relationship to Catalina core complex

Extension in southern Arizona is attributed to the rollback of the subducting Farallon plate in the Oligocene, which left behind an orogenically thickened, unstable crustal column built up during Laramide contraction (Davis, 1980; Coney, 1987). The high extension rates that followed throughout the mid-Tertiary time contributed to the formation of a series of metamorphic core complexes within the Basin and Range province (Crittenden et al., 1980). Metamorphic core complexes commonly exhibit exposures of highly deformed and attenuated rocks of the mid-crust, which are hypothesized to have been exhumed by a detachment fault. Previous studies suggest various explanations for the formation of a detachment fault system. Some suggest that a low-angle normal fault or a series of such faults that merge at depth into a master low-angle detachment are solely responsible for net extension and exhumation of a core complex (Wernicke, 1981; Lister and Davis, 1989). Other workers argue for a progression of high-angle normal faults soling into a sub-horizontal decollement near the brittle-ductile transition (Davis, 1983; Gans and Miller, 1983; Jackson, 1987), while still others reject the detachment model altogether for a core complex formation model favoring multiple generations of high angle normal faults (Seedorff, 2006; 2007).

In the area studied extension appears to have been generated by five generations of normal faults, which initiated at high angles, and were tilted and rotated to lower angles by later generations of faults. This is evident in part due to crosscutting relationships observed in the field, as well as timing and relationship of faults with regard to Tertiary sedimentation. These observations and inferences are similar to those of Maher (2008) in a regionally extensive study north of the Catalina-Rincon-Tortolita complex. Sedimentary rocks are regionally tilted and rotated 50-85°, which is difficult to attribute to motion on a single fault or fault set. Two of the five sets of faults dip to the east, while the three others dip to the west and appear to be responsible for the majority of extension as evident by the mid-lower crustal exposures in the west. The first two generations of normal faults are currently overturned on the west side of the San Pedro Valley, which indicates that a substantial amount of extension and rotation must have occurred after these faults ceased slipping. Regionally, the magnitude of extension varies, with as much as 150-190% in the west, on the margins of the Catalina-Rincon core complex and as little as 50% in the east, near the Galiuro Mountains. The second generation of faults appears to have been responsible for the majority of the overall extension, accommodating as much as 3.3 km of westward-directed slip on each of the two major faults of that generation.

The findings of this study suggest that the current model for core complex formation is at best incomplete. Although, the Catalina core complex was not the focus of this study, geology on its margins shine light on the complexity surrounding it. Multiple generations of normal faults responsible for the extension of much of the upper plate east of the core complex since the mid-Tertiary contrasts with the detachment fault model of Wernicke (1981) and Lister and Davis, (1989). A recent study of the Sierra Mazatán core complex in Sonora, Mexico, suggests that core complex formation can result from slip on initially high angle faults, which are rotated to lower angles by a concert of subsidiary faults and need not involve a detachment-type mechanism (Wong and Gans, 2008). Their finding suggest that total slip on the fault responsible for the formation of the Sierra Mazatán core complex was 15-20 km. The results of the present study imply that extension and core complex formation can result from a relatively small amount of slip distributed among several generations of normal faults, which do not necessarily need to feed slip into a master decollement. Any model for core complex formation must take into account such multiple generations of normal faults and the amount of slip observed on any one fault.

Laramide vs. Sevier-style Shortening in Southeastern Arizona

Contraction during the late Cretaceous, early Tertiary time occurred in part as a result of a progressively flattening subducting slab below southern Arizona (Heidrick and Titley, 1982). Tectonics of the Tertiary time period, especially mid-late Tertiary extension, have obscured the original nature of Laramide events sparking a controversy over the style of deformation active during this time. Two competing contractional styles, the overthrust model (Drewes, 1976; 1978; 1981) and the basement-cored uplift model (Davis, 1979), attempt to make sense of the complexity of Laramide features observed in southeastern Arizona. Drewes (1978) suggested that a continuous thrust belt, exhibiting a thin-skinned, Sevier style deformation, stretched from Alaska to Mexico in a fairly uninterrupted fashion and was responsible for ~100 km of shortening in southeastern Arizona. In contrast, Davis (1979) believed that a high-angle, basement-cored uplift style of contraction, akin to that which is found in the classic Laramide-style regions of the Rockies of Colorado and Wyoming, was prevalent in southeastern Arizona.

Reconstructions of cross sections tentatively support an east-verging thrust system in the region of study. Overturned reverse faults on the west side of the San Pedro Valley, previously mapped (Drewes, 1974; Lingrey, 1982) as west-verging, restore to westerly dips with major faults dipping at 20-50° with a few higher angle exceptions of minimal displacement. The presence of foreland-type sedimentary rocks on the eastern side of the San Pedro Valley, as well as a regionally decreasing amounts of slip found on reverse faults of that area, imply that in the region of study the toe of the thrust belt may have been active during the Laramide. When restored to mid Tertiary time major reverse faults appear to cut out up to and perhaps more than 4 km of stratigraphic section on both sides of the San Pedro Valley.

The amount of stratigraphic section that has been duplicated by the reverse faults, as well as some evidence for high-angle faulting, suggests that the basement-cored uplift model is a likely mode of contraction in the region. However, the presence and close proximity of relatively low-angle thrust faults together with higher angle ones, suggests that a ramp-flat thrust geometry may be a possible explanation for the method of shortening. Likewise, the presence of a foreland-type system is suggestive of lower angle fault propagation and thus, a sub-horizontal contractional style. In summation, it is difficult at this point to establish unequivocally which method of shortening was responsible for contraction in southeastern Arizona. Perhaps southeastern Arizona may have the intersection of the Sevier and Laramide styles of contraction in which both may have been active contemporaneously or that shortening had occurred in alternating pulses of the two.

Intrusions, alteration, and structure: Implications for mineral exploration

Laramide intrusions, interpreted to be the result from an eastward sweep of magmatism as a result of flattening of the subducting slab (Coney, 1980), are prevalent throughout the regions surrounding the Catalina core complex. Although porphyry copper systems of Jurassic age are known in the province, most of the economically important intrusions are Laramide age, hornblende- and biotite-bearing porphyry stocks emplaced at hypabyssal levels in the crust (Lang and Titley, 1998). Post-mineral structural dismemberment and tilting causes variable levels of the crust to be exposed at the surface and disrupts the original zoning of alteration and mineralization patterns compared to those in upright, intact systems (Wilkins and Heidrick, 1995; Seedorff et al., 2005, 2008; Maher, 2008) and in important to searching for new deposits or structural fragments of known deposits, especially in subsurface (e.g., Lowell, 1968, 1991; Maher, 2008).

Alteration of an unknown age has affected the Johnny Lyon Granodiorite pluton all along the extreme southern end of the study area. Tilting of strata (typically ~50° to the east) of Proterozoic to Tertiary ages in the vicinity of the pluton indicate that the Johnny Lyon Pluton is tilted and dismembered by normal faulting. In the south-central part of the regional map, the pluton features secondary ("shreddy") biotite replacing hornblende in hand sample. These rocks were not studied in detail, but they appear to be typical of a biotitic type of potassic alteration, commonly formed at moderate to high temperatures in porphyry copper systems (e.g., Seedorff et al., 2005). If they are related to a porphyry copper system, their seemingly copper-poor character suggests that they are either distal to a mineralized center or related to a largely barren system. The age of alteration could be either Proterozoic (i.e., related to emplacement of phases of the Johnny Lyon Granodiorite) or considerably younger, related to unexposed or unrecognized

Laramide intrusions. In the southeastern corner of the regional study area, the same intrusion contains chloritic and epidote in veins and replacement of wall rock, with local pyrite and specular hematite. These minerals could have formed at somewhat lower temperatures that the biotitically altered rocks, in a hydrolytic (or locally propylitic) geochemical environment of a porphyry copper system (e.g., Seedorff et al., 2005), likely during the Laramide or perhaps in the Proterozoic. Alternatively, the epidote-chlorite rocks could be part of an iron-oxide copper-gold system (e.g., Barton and Johnson, 2000; Williams et al., 2005), perhaps of Tertiary age and analogous to deposits found in western Arizona (e.g., Spencer and Welty, 1986; Wilkins et al., 1986).

In combination with a good understanding for the zoning of alteration, a better synthesis of extension via multiple generations of high-angle normal faults will aid greatly in the discovery of new mineralized districts and new deposits that represent structural fragments of existing ones.

Conclusion

Results of this study begotten from structural reconstructions of the area near Happy Valley suggest an alternative method of extension of the region as well as some new insights into the mid-Tertiary paleosurface with regard to late Cretaceous – early Tertiary contraction. Extension in the region of study proceeded with five generations of high angle normal faults. Each generation accommodated a relatively moderate amount of slip and extension, the largest having ~3.3 km, but collectively the five generations were responsible for 50% extension in the east of the region and as much as 190% in the west. Furthermore, these normal faults have tilted the stratigraphic section from 50° in the east to nearly 90° in the west, exposing the entire section from west to east, with the majority of this rotation coming from the second generation of faults.

Models for core complex formation need to take into account extension via multiple generations of normal faults.

Structural reconstructions suggest that the geometry of reverse faults in southeastern Arizona was highly varied. Reverse faults restore to westerly dips of 20-50° with a few outliers at lower and higher angles. Foreland-type clastic sedimentary rocks in the east of the region coupled with exposures of deep-seated rocks in the west suggest an east vergent thrust belt was active during shortening, which may represent a Sevier style mode of contraction. Yet, high angle reverse faults present in the area, which cut out >4 km of stratigraphic section, imply a different mechanism for contraction in the region. Future work needs to tackle structural reconstructions of more areas in southeastern Arizona in order to extend understanding of core complex formation and complete the Laramide contractional picture.

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Tables

Table 1. Fault set grouping with major faults for examples and approximate fault set attitudes.

Fault Set	**Example** (Fault name)	**Attitudes** (Approx. strike, dip)
Purple	N/A	North-northwest, very gently east
Light Blue	San Pedro Fault	315°– 030°, 20 – 45°E; 150°, 35°SW
Light Green	Teran Wash Fault	165°, 40°WSW; 345°, 45°ENE
Green	Paige Canyon Fault	0°, 65°W
Blue	Banco Ridge Fault	320°– 0°, 60 – 80°E
Red	Roble Spring Fault	320°– 050°, 45 – 65°E; 340°, 35°NNE

Table 2. Major faults, their attitudes, magnitude of slip, and slip direction.

Fault	**Fault Set**	**Attitudes (Approx. strike, dip)**	**Magnitude of Slip (m)**	**Slip Direction**
San Pedro	Light Blue	315°– 030°, 20 – 45°E (overturned)	3300	WSW
Teran Basin	Light Blue	150°, 35°SW	3000	WSW
Teran Wash	Light Green	165°, 40°WSW	2400	WSW
Paige Canyon	Green	0°, 65°W	~1200	W
County Line	Green	0°, 62°W	~500	W
Banco Ridge	Blue	320°, 65°NE	~900	NE
Soza Ranch	Blue	355°, 70°E	~300	E
River Front	Blue	0°, 76°E	~400	E
Roble Spring	Red	320°, 50°NE (overturned)	N/A	ENE
Soza Mesa	Red	340°, 35°NNE	N/A	NNE

Figure Captions

Figure 1. Photo of Happy Valley (view to the northwest; Rincon Mountains in the background)

Figure 2. Detailed field study map.

Figure 3. Regional study area geologic map. Compiled from Lingrey (1982), Trever (1983), Dickinson (1986, 1991, 1998), Dickinson and Olivares (1987), Waldrip (2008), and Spencer and others (2008a, 2008b).

Figure 4. Fault map overlay of the regional study area showing fault generations.

Figure 5. Regional cross sections (1-1’, 2-2’, 3-3’).

Figure 6. Regional cross section reconstructions (1a-1a’, 2a-2a’, 3a-3a’).

Figure 7. Schematic reconstruction of cross section 2-2’.

Step 1: 4th generation normal faults restored.

Step 2: 3rd generation normal faults restored.

Step 3: 2nd generation normal faults restored.

Step 4: 1st generation normal faults restored showing the Mid-Tertiary/Pre-Mineta Formation paleosurface.

(All figures are attached separately).

Figure 1

Figure 2

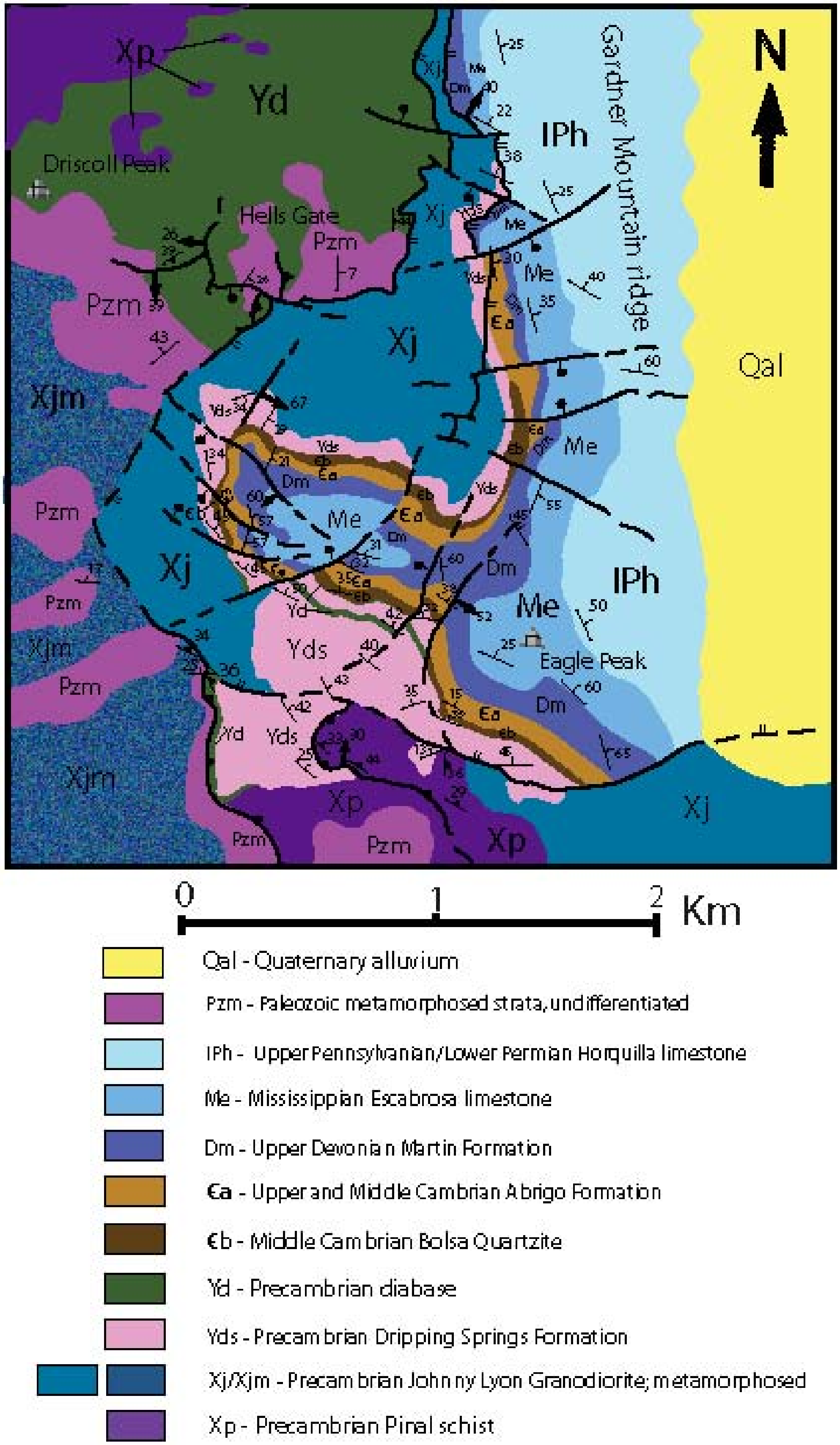

Xp
Yd
Driscoll Peak
Hells Gate
Pzm
Xj
IPh
Gardner Mountain ridge
N
Qal
Xjm
Me
Dm
Ɛa
Ɛb
Yds
Eagle Peak
0
1
2
Km
Qal - Quaternary alluvium
Pzm - Paleozoic metamorphosed strata, undifferentiated
IPh - Upper Pennsylvanian/Lower Permian Horquilla limestone
Me - Mississippian Escabrosa limestone
Dm - Upper Devonian Martin Formation
Ɛa - Upper and Middle Cambrian Abrigo Formation
Ɛb - Middle Cambrian Bolsa Quartzite
Yd - Precambrian diabase
Yds - Precambrian Dripping Springs Formation
Xj/Xjm - Precambrian Johnny Lyon Granodiorite; metamorphosed
Xp - Precambrian Pinal schist

Figure 3.

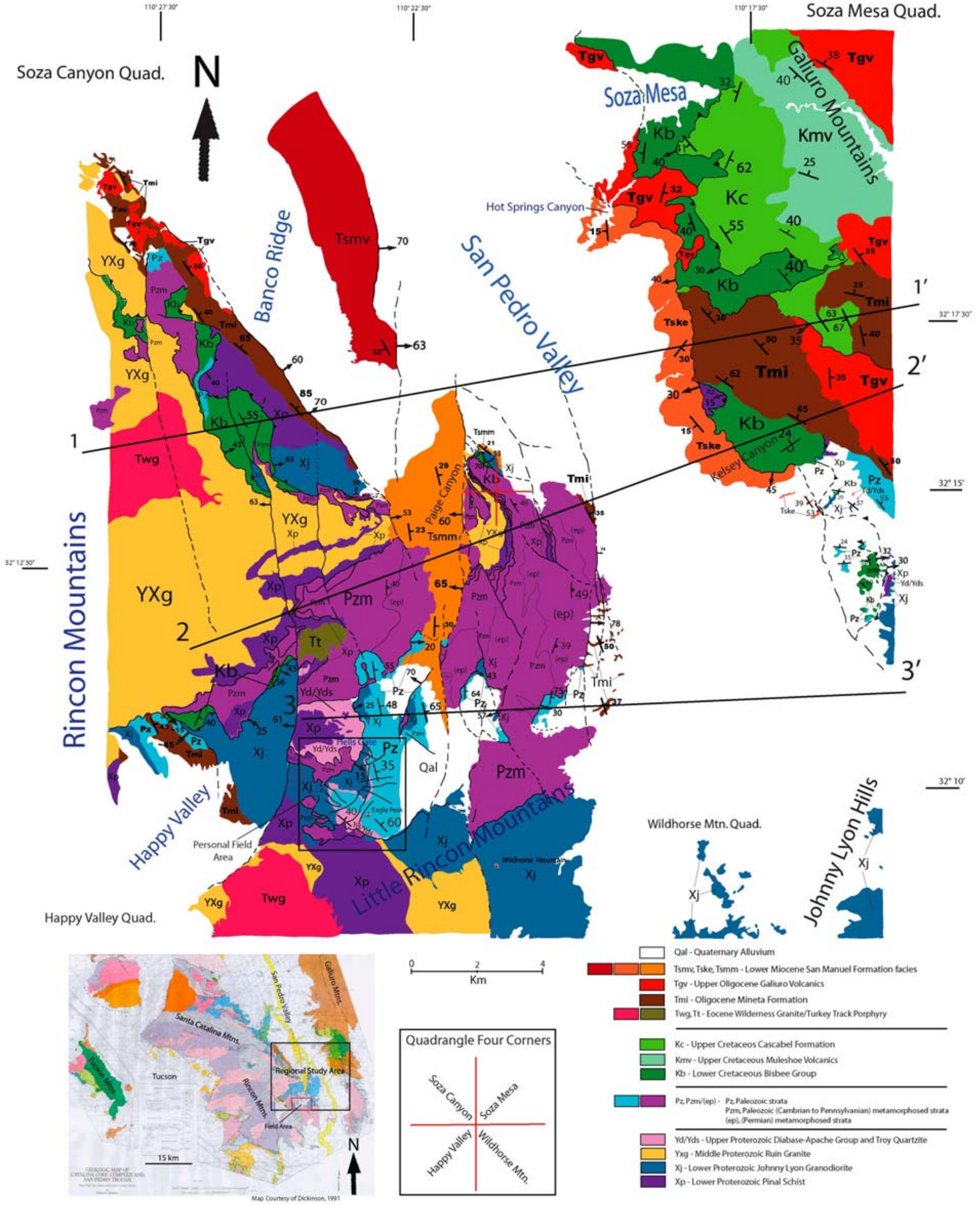
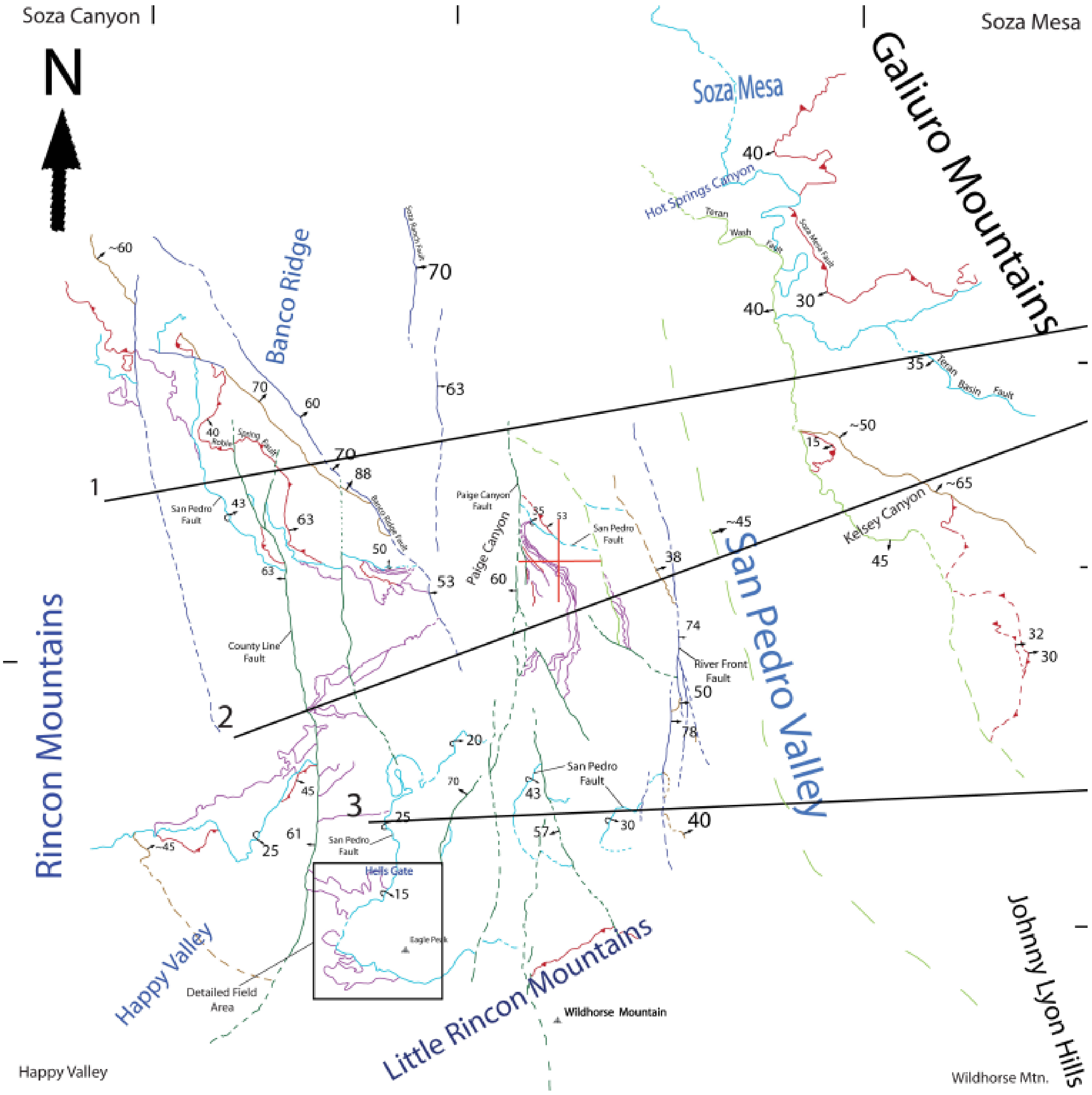

Soza Canyon Quad.
Soza Mesa Quad.
Happy Valley Quad.
Wildhorse Mtn. Quad.
110° 27' 30"
110° 22' 30"
110° 17' 30"
32° 17' 30"
32° 15'
32° 12' 30"
32° 10'
N
Soza Mesa
Galiuro Mountains
Hot Springs Canyon
Banco Ridge
San Pedro Valley
Rincon Mountains
Paige Canyon
Kelsey Canyon
Happy Valley
Little Rincon Mountains
Johnny Lyon Hills
Hells Gate
Eagle Peak
Wildhorse Mountain
Personal Field Area
1
1'
2
2'
3
3'
Tgv
Tmi
Tsmv
Tske
Tsmm
Twg
Tt
Kc
Kmv
Kb
Pz
Pzm
(ep)
Yd/Yds
YXg
Xj
Xp
Qal
0
2
4
Km
Qal - Quaternary Alluvium
Tsmv, Tske, Tsmm - Lower Miocene San Manuel Formation facies
Tgv - Upper Oligocene Galiuro Volcanics
Tmi - Oligocene Mineta Formation
Twg, Tt - Eocene Wilderness Granite/Turkey Track Porphyry
Kc - Upper Cretaceos Cascabel Formation
Kmv - Upper Cretaceous Muleshoe Volcanics
Kb - Lower Cretaceous Bisbee Group
Pz, Pzm/(ep) - Pz, Paleozoic strata
Pzm, Paleozoic (Cambrian to Pennsylvanian) metamorphosed strata
(ep), (Permian) metamorphosed strata
Yd/Yds - Upper Proterozoic Diabase-Apache Group and Troy Quartzite
Yxg - Middle Proterozoic Ruin Granite
Xj - Lower Proterozoic Johnny Lyon Granodiorite
Xp - Lower Proterozoic Pinal Schist
Quadrangle Four Corners
Soza Canyon
Soza Mesa
Happy Valley
Wildhorse Mtn.
Galiuro Mtns.
San Pedro Valley
Santa Catalina Mtns.
Tucson Mtn.
Tucson
Rincon Mtns.
Regional Study Area
Field Area
15 km
N
Map Courtesy of Dickinson, 1991

Figure 4.


Soza Canyon
Soza Mesa
N
Galiuro Mountains
Soza Mesa
Hot Springs Canyon
Teran Wash Fault
Soza Mesa Fault
Soza Ranch Fault
Banco Ridge
Banco Ridge Fault
Robles Spring Fault
San Pedro Fault
County Line Fault
Paige Canyon Fault
Paige Canyon
San Pedro Fault
Teran Basin Fault
Kelsey Canyon
San Pedro Valley
River Front Fault
Rincon Mountains
San Pedro Fault
San Pedro Fault
Hells Gate
Eagle Peak
Detailed Field Area
Happy Valley
Little Rincon Mountains
Wildhorse Mountain
Johnny Lyon Hills
Happy Valley
Wildhorse Mtn.
1
2
3
~60
70
60
70
88
40
43
63
63
50
53
60
35
53
38
~45
74
50
78
40
30
70
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40
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35
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57
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25
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61
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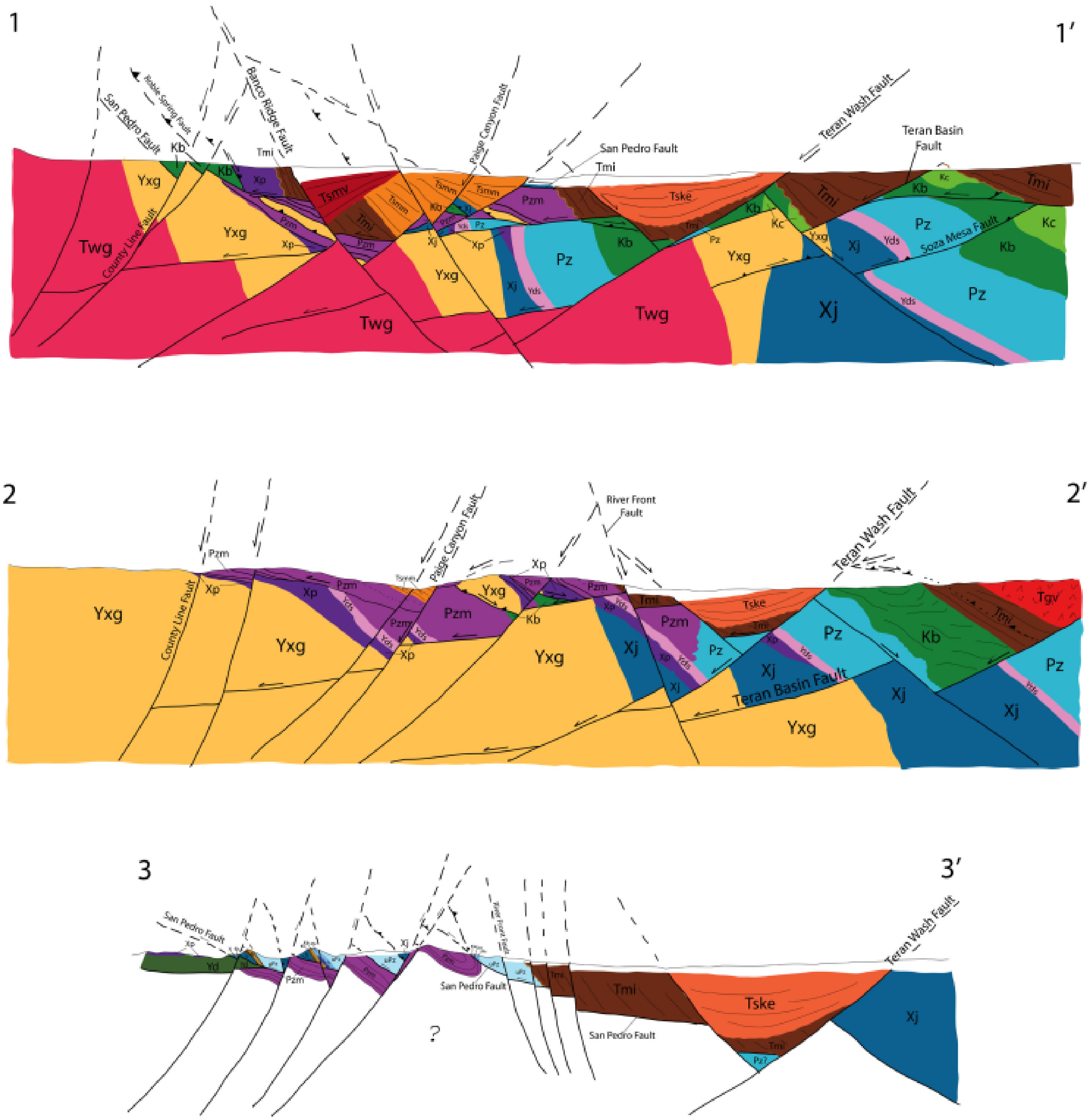
~45
15

Figure 5.



1
1′
Rimble Spring Fault
San Pedro Fault
Banco Ridge Fault
Paige Canyon Fault
San Pedro Fault
Teran Wash Fault
Teran Basin Fault
Soza Mesa Fault
County Line Fault
Kb
Tmi
Yxg
Xp
Pzm
Tsmv
Tsmm
Xj
Yds
Pz
Tske
Kc
Twg
2
2′
Pzm
Xp
Yxg
County Line Fault
Paige Canyon Fault
Tsmm
River Front Fault
Teran Wash Fault
Teran Basin Fault
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Tske
Pz
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Yds
3
3′
San Pedro Fault
Xp
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Pzm
Xj
River Front Fault
San Pedro Fault
Tmi
Tske
Pz?
?
Teran Wash Fault

Figure 6.

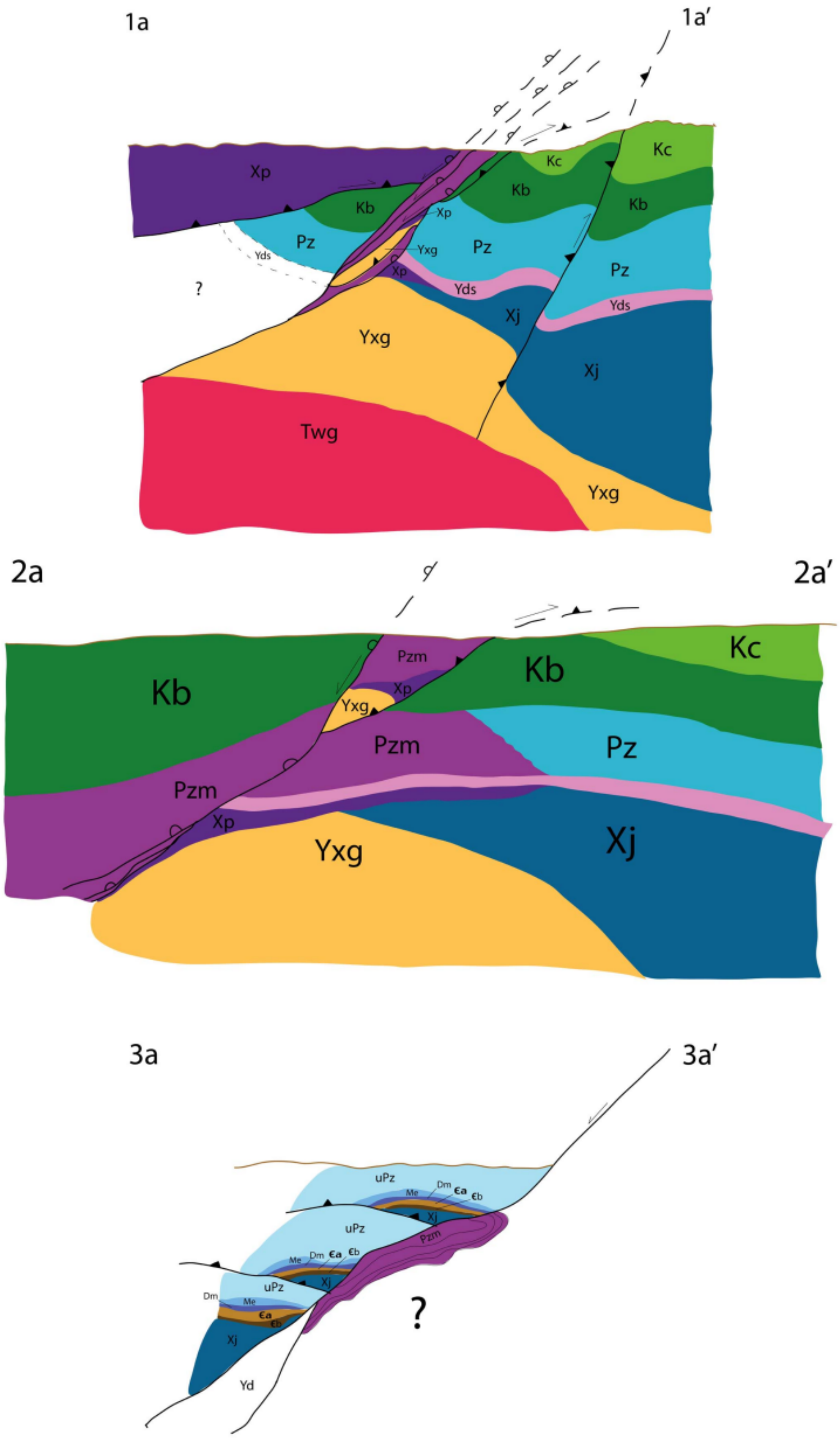
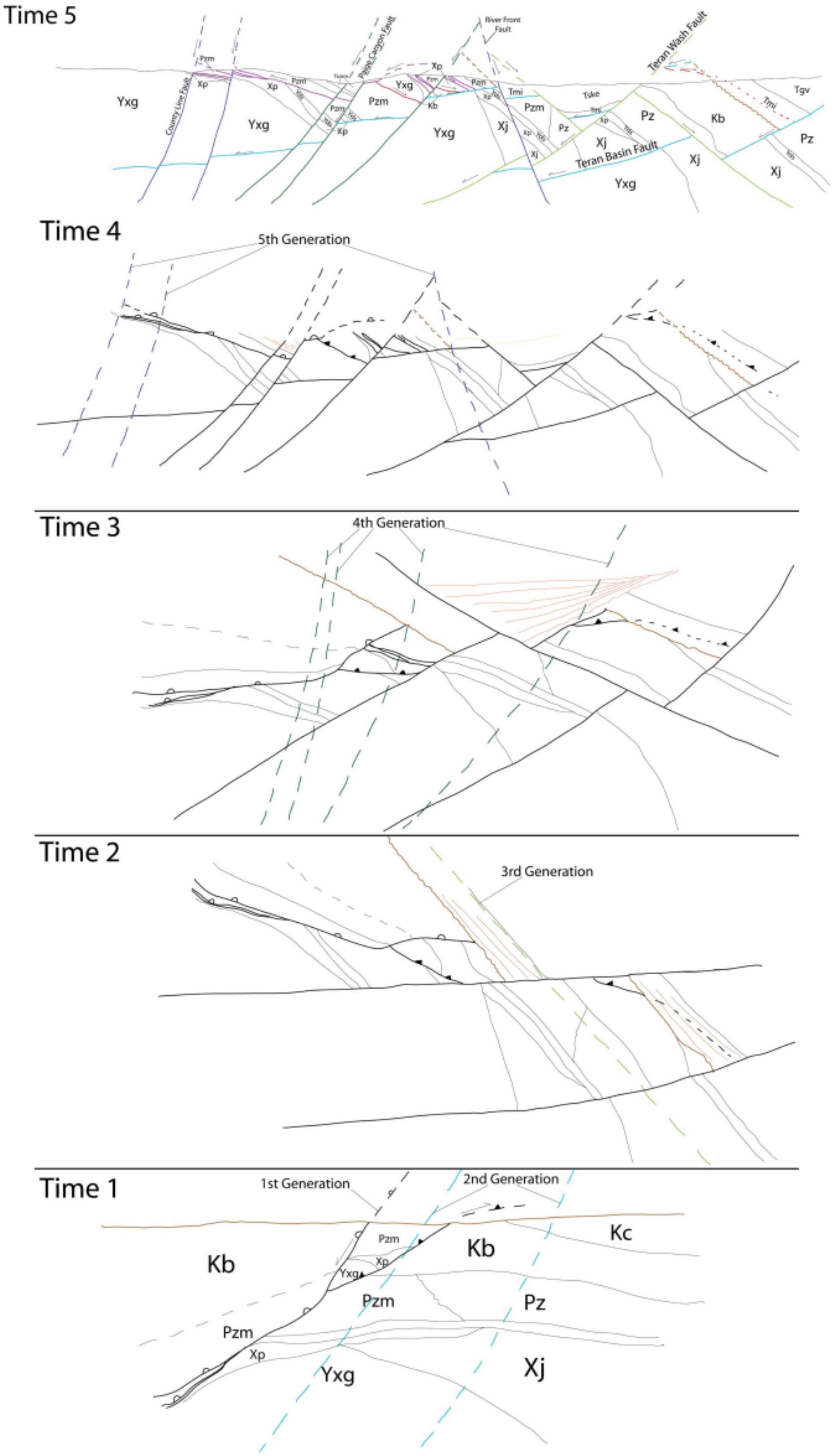

1a
1a′
Xp
Kb
Kc
Kc
Kb
Kb
Xp
Pz
Pz
Pz
Yds
Yxg
Xp
Yds
Yds
?
Xj
Yxg
Xj
Twg
Yxg
2a
2a′
Kb
Pzm
Xp
Yxg
Kb
Kc
Pzm
Pz
Pzm
Xp
Yxg
Xj
3a
3a′
uPz
Me
Dm
Єa
Єb
Xj
uPz
Pzm
Me
Dm
Єa
Єb
Xj
uPz
Dm
Me
Єa
Єb
Xj
?
Yd

Figure 7.



Time 5
Pzm
Xp
County Line Fault
Yxg
Xp
Pzm
Yxg
Tsce
Paige Canyon Fault
Pzm
Xp
Pzm
Xp
Yxg
Kb
Pzm
River Front Fault
Pzm
Tmi
Yxg
Xj
Xp
Pzm
Tske
Pz
Xj
Xj
Xp
Pz
Teran Wash Fault
Teran Basin Fault
Kb
Tmi
Tgv
Pz
Xj
Xj
Yxg
Time 4
5th Generation
Time 3
4th Generation
Time 2
3rd Generation
Time 1
1st Generation
2nd Generation
Kb
Pzm
Xp
Yxg
Kb
Kc
Pzm
Pz
Pzm
Xp
Yxg
Xj