VERY DIFFERENT CRUSTAL RESPONSE TO EXTREME EXTENSION IN THE SOUTHERN BASIN AND RANGE AND COLORADO PLATEAU TRANSITION

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ABSTRACT

Clustered about the southwest edge of the Colorado Plateau lie many highly extended terranes. Among these are metamorphic core complexes, distinguished by low-angle normal faults with sufficient offset to expose middle crustal rocks at higher elevation relative to the surrounding areas. About 150 km to the southwest, strong extension in the Salton Trough manifests itself very differently; high-angle normal faults form deep basins, with the strongest extension causing subsidence beneath sea level. We ask why strong extension takes such different forms, and, to help answer the question, we take advantage of seismic and gravity profiles that cross through the Salton Trough, metamorphic core complexes, and the Colorado Plateau. We propose that the relative rate of extension vs. intrusion of crust by magmatism and crustal flow controls the extensional style. We further show that conditions may have been ideal for core complex formation along the edges of the Colorado Plateau because its thick crust and high elevation provided a source of crustal flow and the pressure gradient to drive the flow.

INTRODUCTION

A persistent problem in tectonics is the very different strain response in the crust at different localities that results from similar regional stresses. In this paper we compare and contrast two zones of extreme extension, the Buckskin-Rawhide metamorphic core complex in southern Arizona and the Salton Trough of southern California (Figure 1). We ask the question: why did the crust of these two regions respond so differently to strong extensional forces? The two localities are nearby each other, southwest of the Colorado Plateau, and have experienced similar durations of activity and local magnitudes of extension, yet they responded very differently. The Salton Trough is a deep basin that has sunk beneath sea level, while the Buckskin and Rawhide core complexes have built small mountain ranges during the extension process (Figure 1, 2).

Tectonic Setting

The southern Basin and Range Province in the southwestern United States has been stretched and extended for at least the past 30 m.y. Within the province there is great variety in style and magnitude of extension. In different regions, estimates range from 10% to well over 100% extension. The earliest stages of extension began by latest Oligocene time in the southern parts of California and Arizona in the United States, and in Durango, Chihuahua, and Oaxaca, Mexico. By early Miocene time, strong extension had begun on major normal faults across much of Mexico (e.g., Henry and Aranda-Gomez, 1992), and metamorphic core complexes were forming along the Colorado River between California and Arizona (e.g., Howard and John, 1987) and along the southern edge of the Colorado Plateau in southern Arizona (e.

g., Rehrig and Reynolds, 1980). A narrow zone of extension between the southern Sierra Nevada and southern Colorado Plateau, sometimes called the central Basin and Range (e.g., Jones et al., 1992; Wernicke, 1992), became active during middle Miocene time (e.g., Duebendorfer and Wallin, 1991; Faulds et al., 1992), and some of the latest forming metamorphic core complexes are found in this zone (e.g., Axen et al., 1993; Faulds et al., 1995). The south central Basin and Range Province experienced a stress rotation and onset of oblique extension with a right-lateral component in the late Miocene (e.g., Zoback et al., 1981). Pliocene and Quaternary eruptions accompany incipient rifting in the Jalisco block that lies at the southern edge of the Sierra Madre Occidental in Mexico (Wallace at al., 1992), possibly indicating that the Basin and Range province is growing to the south. Large-magnitude earthquakes shake the Basin and Range province occasionally, and are distributed along its entire length, indicating that extension is widespread and ongoing.

The Colorado Plateau is a major tectonic and physiographic province in the southwestern United States (Figure 1) that has behaved as a relatively stable, coherent block during much of Phanerozoic time. A site of marine deposition during Cretaceous time, the Colorado Plateau now stands about 2 km above sea level, implying that nearly 2 km of uplift occurred during Cenozoic time. The greatest amount of uplift has apparently been along the southwestern margin of the Plateau, where elevations are often 0.5 km greater than in the center (e.g., Lucchitta, 1989). Study of vesicular basalts indicates that the southwest Colorado Plateau stood at least 1 km above sea level during Oligocene time (Sahagian and Proussevitch, 2000). The Colorado Plateau has apparently remained a relatively rigid block, resistant to faulting, a view reinforced by paleomagnetic studies that show coherent rotation of the plateau (e.g., Bryan and Gordon, 1986; Wells and Hillhouse, 1989). Given that the Colorado Plateau is in isostatic equilibrium now (the free air gravity anomaly is nearly zero; Thompson and Zoback, 1979), and assuming that it was in the past, then some growing mass deficiency at depth must have compensated for its uplift. Several mechanisms have been proposed to account for the most recent

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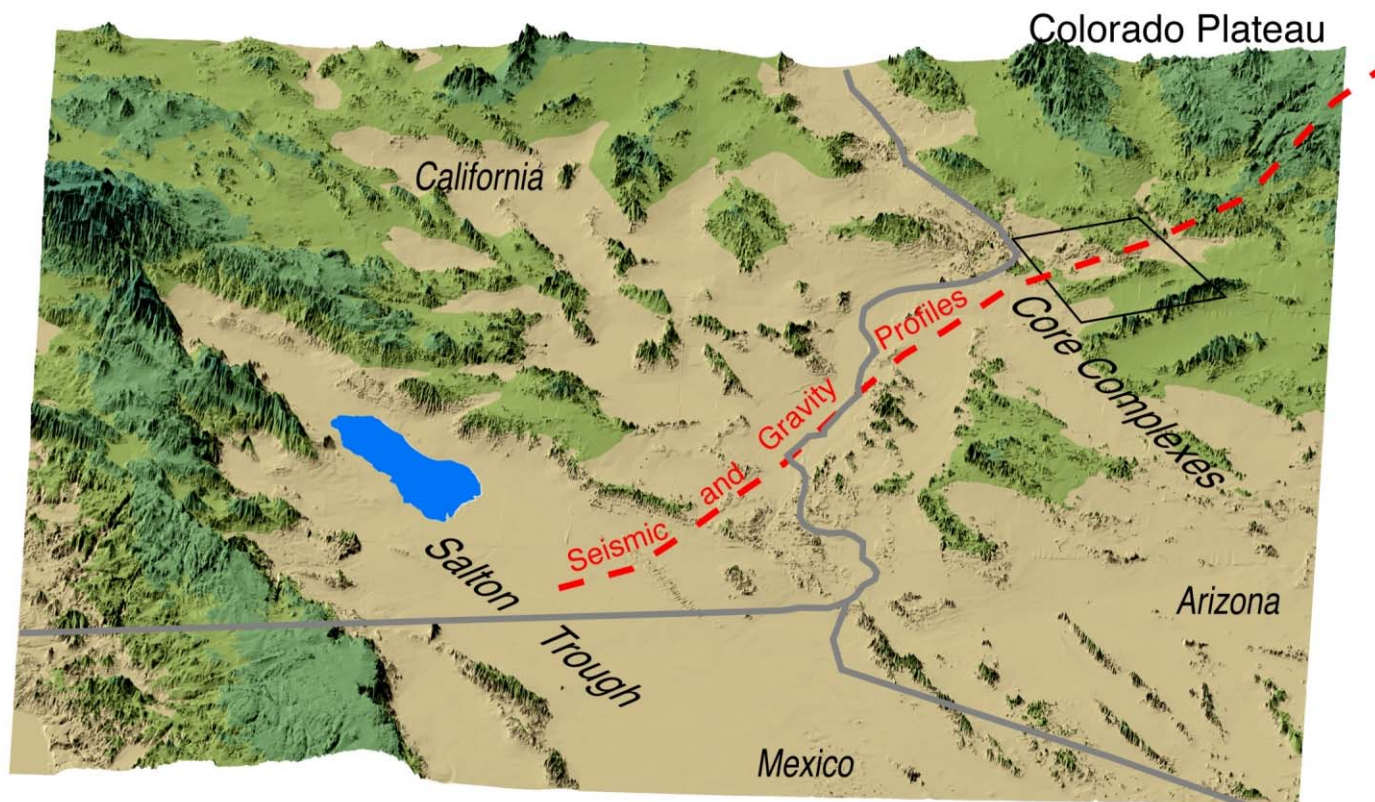[3]Department of Geophysics, Stanford University, CA, 94305

Figure 1. *Comparison of topographic setting of the Colorado Plateau, core complex belt, and the Salton Trough. The location of the seismic and gravity profiles used in this study is shown by the red dashed line. The black box in the core complex zone corresponds to the area shown in detail in Figure 2.*

phase of uplift, including thermal expansion, crustal thickening, and delamination of the lithosphere (e.g., Bird, 1979; Thompson and Zoback, 1979; McGetchin and others, 1980; Bird, 1984; Morgan and Swanberg, 1985; Spencer, 1996).

About 300 km southwest of the Colorado Plateau at the edge of the southern Basin and Range Province, the Salton Trough results from northward progression of the enlarging Gulf of California (e.g., Larson et al., 1968; Moore, 1968; Elders et al., 1972; Terres and Crowell, 1979; Crowell, 1989; Lonsdale, 1989; Larsen and Reilenger, 1991). The initial opening of the Gulf of California occurred about 12-10 Ma, shortly after subduction ceased along the continental margin of Mexico (e.g., Lonsdale, 1989; Stock and Hodges, 1989). The southernmost part of the active San Andreas fault extends northwest from the southeast corner of the Salton Sea. A palinspathic reconstruction indicates that displacement on the southern part of the San Andreas fault began about 10 Ma, with about 60 km of right lateral displacement occurring before 5 Ma and 240 km of right-slip occurring between 5 Ma and the present (Dillon and Ehlig, 1993). The Clemens Well fault, lying to the east of the San Andreas fault and the Orocopia Mountains, has been proposed as an early mid-Miocene strike-slip fault that accommodated up to 110 km of right-lateral displacement (Powell, 1993).

PHYSIOGRAPHIC COMPARISON: SALTON TROUGH VS. THE CORE COMPLEX BELT

The Salton Trough is a highly extended terrane at the northern extension of sea-floor spreading in the Gulf of California, and the Buckskin-Rawhide metamorphic core complex is one of several highly extended terranes draped about the southwest corner of the Colorado Plateau. The Buckskin-Rawhide metamorphic core complex is part of a larger structure known as the Harcuvar core complex that includes the parallel Harcuvar and Harquahala Mountains of the same age (Rehrig and Reynolds, 1980). We focus on the Buckskin-Rawhide Mountains here because they are crossed by our seismic and gravity transects.

The primary indication that the Salton Trough and metamorphic core complex belt responded to extensional stress so differently comes from a simple topographic comparison.
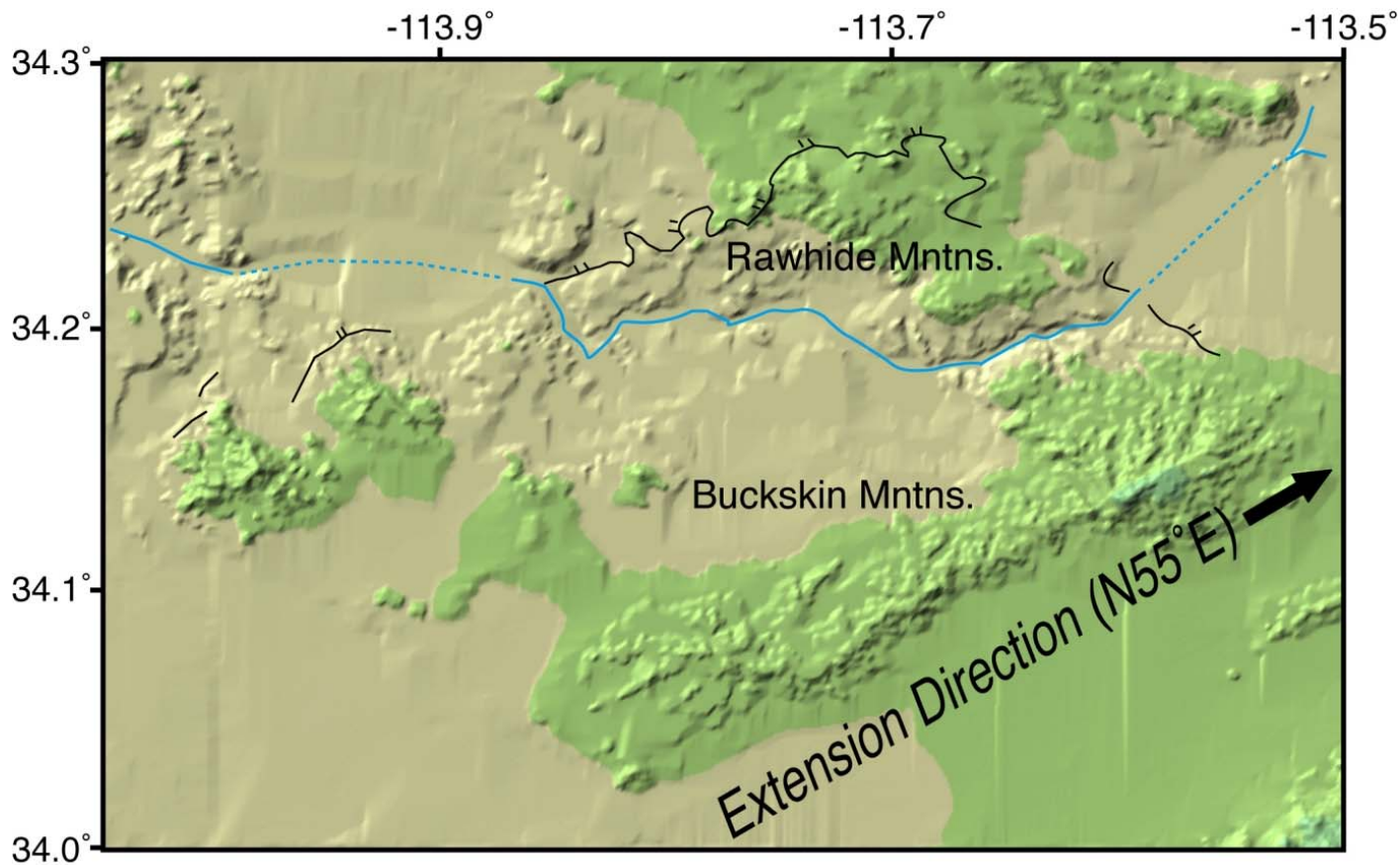
Figure 2. *Topography of the Buckskin-Rawhide metamorphic core complex. The footwall rocks are domed and arched, with axes parallel to the extension direction. The most denuded areas are found at the highest relative elevations. The location of this area is shown by a box on Figure 1.*
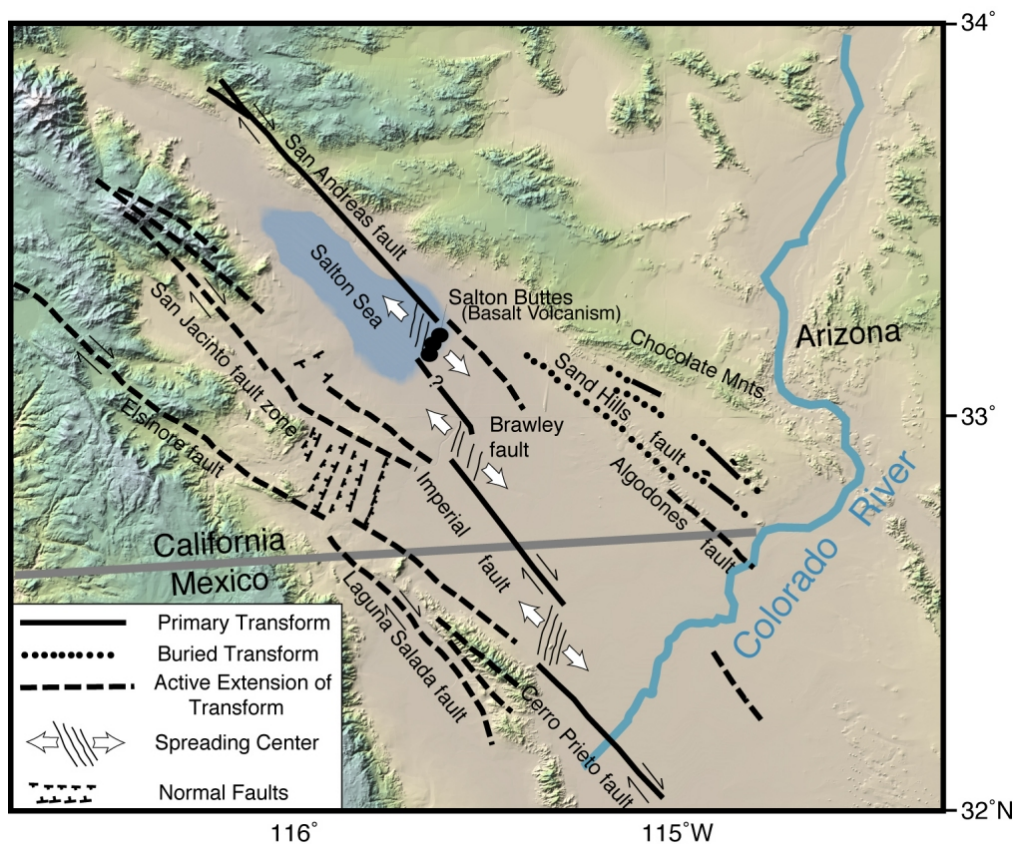

Figure 3. *Topography and tectonic features of the Salton Trough region. Extension occurs mostly between east-stepping right-lateral transform faults (Lonsdale, 1989). These structures are on-land analogs to the spreading occurring in the Gulf of California. In contrast with the core complexes, the most highly extended areas are found at the lowest elevations.*

Where the Salton Trough is a basin that locally lies below sea level, the Buckskin-Rawhide core complex belt is an average 700m above sea level. This observation alone is not very meaningful since much of the western Cordillera is raised well above sea level for reasons that may have little to do with local tectonics (e.g., Bird, 1984; Saltus and Thompson, 1996). More interesting is a comparison of the extensional faulting and local topography in the two regions, and a comparison between the relative elevations of highly extended crust and the surroundings.

The Buckskin and Rawhide Mountains are arched, or domed, with lower plate rocks foliated in concert with the arching (e.g., Rehrig and Reynolds, 1980) (Figure 2). There is about 1000 m of maximum relief between the highest parts of the ranges as compared with the surroundings. The low-angle, or detachment fault is corrugated, with axes trending about N55˚E, nearly parallel to mylonitic lineation, implying that folding of the detachment surface was related to extension (Spencer and Reynolds, 1991). The low-angle fault is cut by a later system of NW trending high-angle oblique faults; reconstruction of the detachment surface indicates it had an initial dip between 30˚ and 40˚ (Richard et al., 1990). Cooling data were interpreted and best fit to a 24˚ fault dip when denudation occurred (Scott et al., 1998).

In contrast to the core complex belt, the Salton Trough is a region of low relief (Figure 3) dominated by right-lateral strike-slip faulting of the San Andreas plate boundary. The growth of the Gulf of California has been characterized as a series of en echelon right transform faults that formed in response to Pacific-North American relative motion and were linked initially by pull-apart basins that matured into oceanic spreading centers (Lonsdale, 1989). The Salton Trough apparently represents a present-day on-shore analog to these Gulf-of-California evolving spreading centers (e.g., Elders et al., 1972). The Cerro Prieto, Imperial, Brawley, and San Andreas faults form an en echelon series of east-stepping right-lateral transforms linked by pull-aparts named the Cerro Prieto, Brawley, and Salton Buttes spreading centers by Elders et al., (1972) (Figure 3). These spreading centers have probably not been stable through time and have likely changed position more than once; for example the parallel Sand Hills and Algodones faults may represent fossil transforms or spreading centers parallel to, but ~45 km east of the Imperial fault (e.g., Lachenbruch et al., 1985; Lonsdale, 1989) (Figure 3). Farther northeast, smaller Late Cenozoic strike-slip faults are also known from surface exposures and these likely represent parts of the evolving transform system (R. Tosdal, personal communication, 1995).

The Salton Trough contains about a 10-km-thickness of sediment deposited as alluvial debris, thin marine beds, and deposits from the ancestral Colorado River (e.g., Crowell, 1989). A Basin and Range setting existed prior to the formation of the Trough that left Middle Miocene deposits in small basins; this period was followed by marine sedimentation during the formation of a proto Gulf of California ~8 Ma (Crowell and Baca, 1979). The present-day Salton Trough differs from its analogous structures south in the Gulf of California primarily because of large amounts of sediment deposited through growth of the Colorado River delta during the past 5 m.y. Thus sedimentation may play a strong role in reducing the apparent structural relief in the Salton Trough.

EXTENSION MAGNITUDE, EXTENSION RATE, AND MAGMATISM ACROSS THE CORE COMPLEX BELT AND SALTON TROUGH

A geological transect across the metamorphic core complex belt at the southwest corner of the Colorado Plateau indicates that an area once ~20 km wide is now closer to 100 km wide, with most of the extension occurring on the Buckskin-Rawhide detachment fault (Spencer and Reynolds, 1991). The initiation of extension at the Buckskin-Rawhide metamorphic core complex was about 27 Ma; the initial exposure of the core rocks was between 15 and 16 Ma, and extension ceased about 10 Ma (e.g., Scott et al., 1998). Study of $^{40}Ar/^{39}Ar$ and fission track cooling data from the lower plate shows a slip rate between 16 and 10 Ma of that ranges between 6.4 to 10.6 mm/yr (Scott et al., 1998). If the preferred fault dip of 24˚ (Scott et al., 1998) is used, then the rate of horizontal extension (lower plate relative to upper) is about 5.8 to 9.7 mm/yr. Alternatively, if the widening from 20 km to 100 km between 27 Ma and 10 Ma interpreted by Spencer and Reynolds (1991) is used, then a strain rate of about 30%/m.y. is attained.

Magmatism accompanied the initial phases of extension in the Buckskin-Rawhide metamorphic core complex, and persisted through to its end. The oldest approximately synextensional igneous rocks exposed in the region are 29.9 m.y. old granitoid rocks located between the Buckskin and Rawhide Mountains, and the youngest are 9-13 m.y. old basalts; the adjacent Harcuvar Mountains show relatively small volumes of near-surface magmatism (Spencer et al., 1995). While some surface evidence of magmatism is nearly always associated with extensional core complexes globally (e.g., Parsons, 1995), they quite commonly are not the areas where the most voluminous surface magmatism is observed. This is the case in southwest Arizona where regions south of the core complex belt show far greater volumes of igneous rocks intruded into the upper crust (Spencer et al., 1995).

Extension in the Salton Trough is more difficult to quantify than in the core complex belt because most of the structure is drowned by sediment from the Colorado River delta. Using heat flow constraints, Lachenbruch et al. (1985) modeled an average 20-50%/m.y. extensional strain rate which is comparable to the estimates for the Buckskin-Rawhide metamorphic core complex. If this rate was constant during the 5-6 m.y. since the Salton Trough started spreading (e.g., Lonsdale, 1989), then the magnitude of extension may range from 100-300%. However, this strain rate is an average for the entire Salton Trough region. If we examine the present-day configuration (Figure 3), it is evident that individual spreading centers act to accommodate much of the relative Pacific-North American plate motion (Larsen and Reilinger, 1991), concentrating very fast extension (~49 mm/yr; DeMets et al., 1987) across narrow zones. The loci of extension have mi-

grated in the Salton Trough, shifting across a 150-km-wide zone (10 times wider than the presently active zones) (Lachenbruch et al., 1985; Lonsdale, 1989; Larsen and Reilenger, 1991).

If we compare the most rapid extension in the Buckskin-Rawhide metamorphic core complex with that of the Salton Trough, we find that the spreading centers of the Salton Trough extend at rates from 5 times up to an order of magnitude faster. Extension in the metamorphic core complex belt was apparently concentrated at specific locations for longer times than in the Salton Trough, perhaps because of the interaction between Salton Trough spreading centers and the San Andreas fault system.

COMPARATIVE CRUSTAL STRUCTURE ACROSS THE SOUTHERN BASIN AND RANGE AND COLORADO PLATEAU TRANSITION

Seismic Refraction Models

From 1985 to 1992 the U.S. Geological Survey (USGS) collected seismic refraction and reflection profiles on a crustal transect across the southwestern U.S., which were dubbed the Pacific to Arizona Crustal Experiment (PACE). The PACE program focused first on the Whipple Mountain and Chemehuevi metamorphic core complexes (e.g., McCarthy et al., 1991; Wilson et al., 1991). In 1987, the PACE profiles were extended to the northeast from the Colorado River across the Buckskin-Rawhide metamorphic core complex and into the Arizona Transition Zone of the Colorado Plateau (e.g., Goodwin and McCarthy, 1990; McCarthy et al., 1991). In 1989, the PACE profiles were extended onto the Colorado Plateau (e.g., Wolf and Cipar, 1993; Parsons et al., 1996). The PACE 1992 data extended the main PACE transect to the southwest from the Colorado River to the San Andreas fault (Parsons and McCarthy, 1996), forming a continuous profile that is over 500 km long (Figure 4). These profiles were each analyzed independently and have never been presented and discussed as one continuous profile.

The crustal structure of the Salton Trough region has the following features (Figure 4): 1) a young (based on observation of velocities appropriate for unmetamorphosed sediments at depth), deep basin (~5-6 km) beneath the axis of the Salton Trough, 2) a regional deep crustal layer of 6.9 km/s velocity that is present beneath the Trough and extends ~65 km to the northeast where it pinches out beneath the Chocolate Mountains, 3) a generally thin ~20-22-km-thick crust beneath the Salton Trough that thickens gradually to ~27 km thick beneath the Chocolate Mountains, and 4) a low velocity (7.6-7.7 km/s) upper mantle that occurs beneath the Salton Trough and becomes faster (~8.0-8.1 km/s) northeast of the Chocolate Mountains. These observations consistently show significant changes at all levels in the crust and upper mantle across a boundary line marked by the Chocolate Mountains. The crust and upper mantle southwest of the Chocolate Mountains have anomalous velocities relative to the rest of the PACE transect,
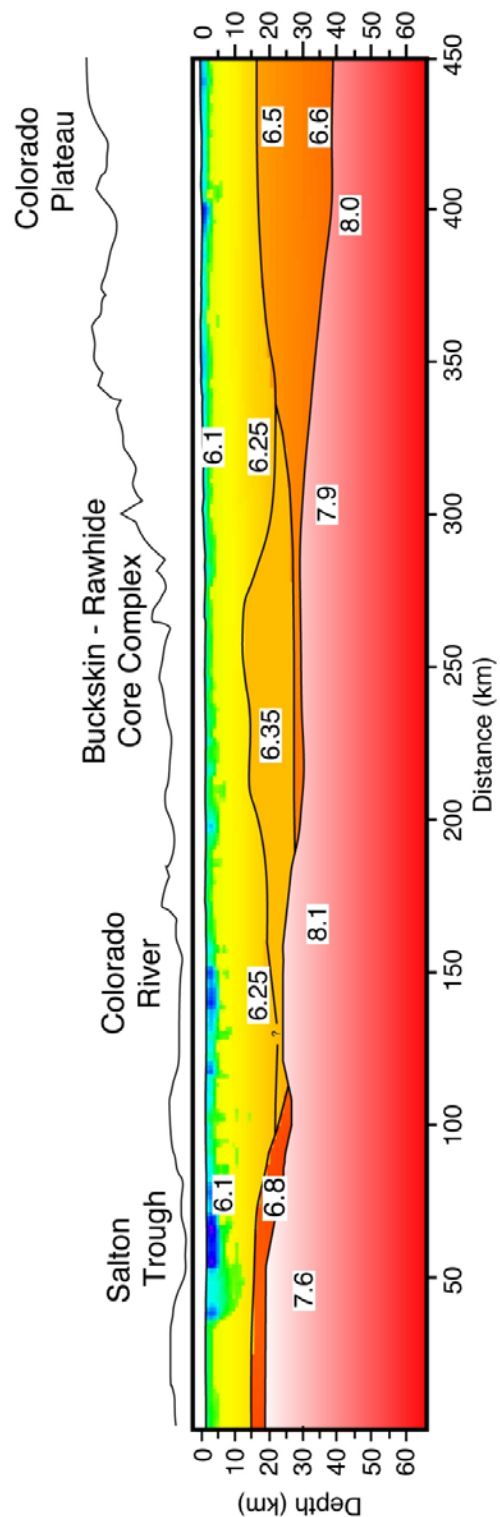

Figure 4. *Seismic velocity structure of southern California and southwest Arizona. The profile crosses the Salton Trough, metamorphic core complex belt, and the edge of the Colorado Plateau (Figure 1). The lower crustal structure beneath the Salton Trough has a seismic velocity most consistent with intrusion of mantle-derived basalt, whereas the crust beneath the core complexes is more consistent with a mix of intruded basalt and more silicic continental crust. Crustal thickness was maintained during core-complex extension, but not during extension of the Salton Trough.*

where lower crustal velocities are closer to 6.5-6.6 km/s, up-per mantle velocities are ~8.0-8.1 km/s, and no deep (> 2-3 km) upper-crustal basins are observed (e.g., McCarthy et al., 1991; Parsons et al., 1996) (Figure 4).

The most accepted explanation for the crustal structure of the Salton Trough is a combination of ocean-ridge style mag-matism forming the lower crust while concurrent faulting, sedimentation and metamorphism forms the upper crust (e.g., Fuis et al., 1984; Lachenbruch et al., 1985; Nicolas, 1985). Our velocity model localized to the Salton Trough supports this hypothesis. We observe a 6.9-km/s layer that may have had a magmatic origin. A velocity of 6.9 km/s falls in the middle of the reported range of laboratory velocity measure-ments on gabbros corrected for depths of 15-20 km and high temperature (e.g., Holbrook, 1988; Holbrook et al., 1992) and could be an indication of complete lower-crustal formation by gabbroic intrusion. Further support for the hypothesis of mid-ocean-ridge type intrusion beneath the Salton Trough comes from modeling of the coincident vertical-incidence seismic data by Larkin et al., (1996). Their reflection data show that

crustal reflectivity is limited to the outside edges of the 6.9-km/s lower-crustal layer, and they can model that reflectivity pattern with a series of vertical sheeted dikes forming the high-velocity layer and a small fraction (~5-20%) of intrusion of mafic sills just outside the high-velocity layer. In places where spreading centers may have been more ephemeral, the lower crust may have been less intruded and surface extension less recognizable. Thus a maximum estimate of mafic intru-sion beneath the Salton Trough is the entire 4-to-6-km thick, 6.9-km/s lower crustal layer.

The velocity structure beneath the metamorphic core complexes is significantly different than that beneath the Sal-ton Trough (Figure 4; McCarthy et al., 1991; Parsons et al., 1996). In the shallow crust there is no evidence for low-velocity basins associated with the Buckskin-Rawhide core complex as would be expected since middle-crustal rocks are denuded and exposed. From the surface to about 15 km depth, a mildly increasing crustal gradient from about 6.1 km/s to 6.25 km/s is comparable to the crust in the Colorado Plateau
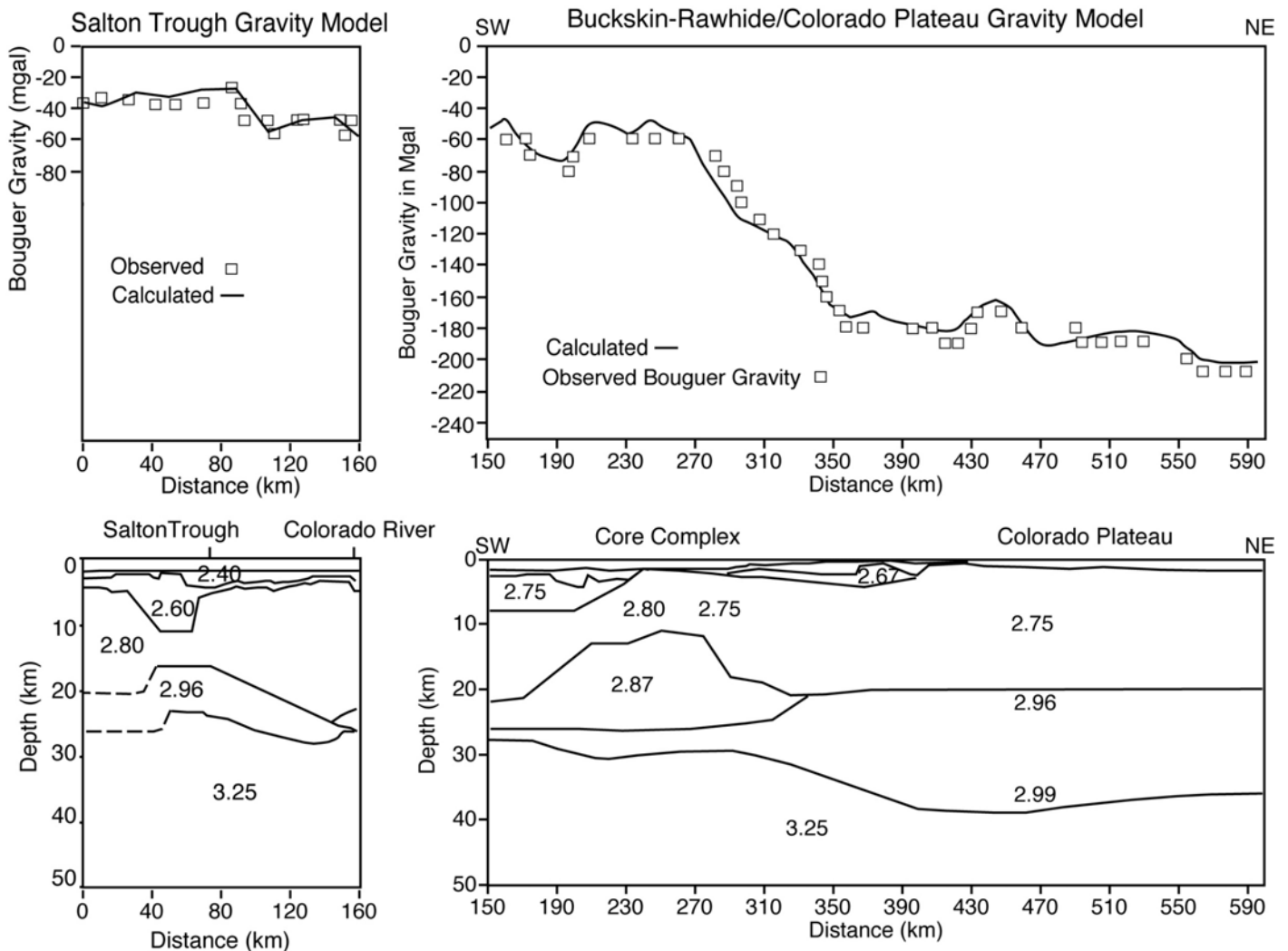

Figure 5. *Gravity data and models for the Colorado Plateau, core complexes, and Salton Trough. The gravity signature is simi-lar across both extended terranes, and neither has a strong anomaly compared with surrounding crust. Isostatic balance was achieved very differently as can be seen by examining the modeled density structure of the two terranes.*

transition. The most interesting feature beneath the core complexes (identified here and beneath the Whipple Mountains to the west; McCarthy et al., 1991) is a middle-crustal welt of rocks with velocity of 6.35 km/s. The 6.35 km/s velocity is intermediate between that of granite and gabbro and suggests a bulk composition of diorite. Actual rock types, however, may encompass a range of igneous and metamorphic compositions, including a mixture of silicic (granite) and mafic (gabbro) end members (McCarthy and Parsons, 1994). The mid-crustal layer pinches out in the direction of the Colorado Plateau transition to the north, and the Colorado River to the south (Figure 4), and thus appears to be associated with core-complex extension.

Although the velocity of the lower crust beneath the core complexes does not exceed 6.6 km/s and the average crustal velocity is low (6.2-6.3 km/s), there may have been intrusion of up to 8 km of mafic material into the crust along this highly extended portion of the transect. The intermediate 6.35 km/s velocity for the mid-crustal layer may represent a broad zone of gabbroic sills and sheets intruded and mixed with silicic host rock. Given that the middle crust is up to 14 km thick, a maximum of 6 km of this lens could consist of gabbroic additions to the crust if it were mixed with silicic country rock with a bulk velocity of 6.1 km/s. An additional 2 km of igneous rocks may have intruded the upper crust. Importantly, even if this maximum allowable amount of mafic material was intruded into the crust, and even if all of this were intruded during core-complex extension, the magmatic thickening still couldn't account for all the synextensional thickening necessary to maintain the 30-km crustal thickness, thereby implying that additional mechanisms have affected the evolution of the region (McCarthy and Parsons, 1994). The maximum thickness of mafic intrusion beneath the core complexes (8 km) exceeds that of the Salton Trough (4-6 km).

Gravity Data and Models

The crustal structure across the Salton Trough and the metamorphic core complexes is very different as evidenced by their physiography on the surface and subsurface velocity structure. However, the Bouguer gravity anomaly across these two regions is nearly the same, hovering between –20 to –40 mgal across the Salton Trough and between –40 and –60 mgal across the Buckskin-Rawhide metamorphic core complex (Figure 5). In both cases there is no Bouguer gravity signature of the highly extended terranes as compared with the surrounding crust, implying isostatic compensation for crust removed during the extension process (e.g., Thompson and McCarthy, 1990). The largest change in Bouguer gravity occurs at the edge of the Colorado Plateau, where the crust thickens to about 40 km and the Bouguer anomaly drops to a value between –180 and –200 mgal.

Comparison of the modeled density structure of the two highly extended terranes shows fundamental differences in how the isostatic balance was achieved. At the Salton Trough, rocks of strongly contrasting density are nearly immediately juxtaposed. Low-density sediment carried in by the Colorado River (=2.6) overlies dense (=2.96), intruded basalt/diabase with a thin, intervening metamorphosed layer (e.g., Fuis et al., 1984; Lachenbruch et al., 1985; Parsons and McCarthy, 1996; Larkin et al., 1996). This combination balances a relatively thin crust (~22 km) at, or slightly below, sea level. Presumably the pre-existing crust was attenuated to nearly zero thickness, and completely replaced during the extension process (e.g., Nicolas, 1985).

Density structure in the metamorphic core complex belt contrasts sharply with the structure beneath the Salton Trough. Rather than attenuation and collapse of the middle
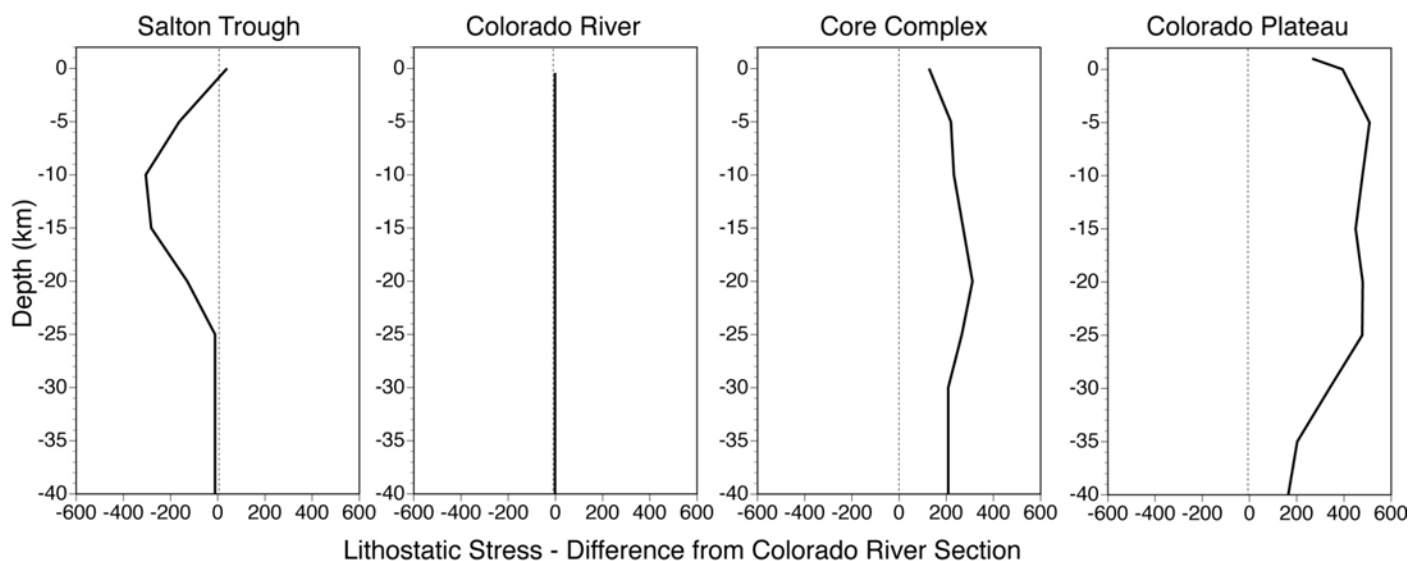

Figure 6. *Lithostatic pressure was calculated from the density models of Figure 5 for four locations, the Salton Trough, Colorado River, metamorphic core complex belt, and Colorado Plateau. The profiles were then differenced from the Colorado River section, which was chosen as a reference because less apparent tectonism has occurred there as compared with other places along this profile. A strong lateral push force away from the Colorado Plateau is expected because of its relatively higher topography.*

crust under extension, it was apparently forced upward by a growing lens of anomalous density rocks (=2.87), whose origin was described as a mixture of a ~6-km-thickness of mafic intrusive rocks with "normal" middle crust that flowed in from surrounding terranes (McCarthy and Parsons, 1994). Isostatic balance was achieved through this process, which resulted in a thicker (compared with the Salton Trough), but more homogeneous density crustal column after strong extension, that lies at about 700 m above sea level.

The gravity models enable the lithostatic pressure to be calculated along the profile from the Salton Trough into the Colorado Plateau. When the lithostatic stress is compared with a reference column (e.g., Crough, 1983), the relative lateral pressure along the profile can be examined. In Figure 6, we show the results of this calculation for four windows along the seismic and gravity transect; we chose the Colorado River region as the reference column and compared the relative lateral pressure between the Salton Trough, metamorphic core complex belt, and the Colorado Plateau (Figure 6). We find that there is a strong push in the middle crust from the Colorado Plateau into the core complex belt, driven by the higher topographic elevation of the Plateau. This force might have provided the driving mechanism for crustal flow into the core complexes during extension. Kruse et al. (1991), for example, fit the Bouguer anomaly to a model of ductile lower-crustal flow from beneath the unextended Colorado Plateau to the extended Lake Mead region of the central Basin and Range. In contrast, when the Salton Trough is compared with the Colorado River crust, despite the negative lateral force, crustal flow toward the Trough has been insufficient to maintain crustal thickness, or replace the crust thinned by extension. (Figure 6).

The magnitude of the pressure gradient for crustal flow from the Colorado Plateau into the core complex belt likely evolved with time. Prior to the onset of strong extension southwest of the Plateau in the early Miocene, sediments were carried from the southwest down onto the Plateau (e.g., Pierce et al., 1979). A reversal of drainage followed the onset of extension, and the previously higher regions southwest of the Plateau foundered (e.g., Lucchitta, 1989). Presumably the pressure gradient from the Colorado Plateau grew progressively larger as the crust in the core complex belt thinned relative to the Plateau.

Low-Angle vs. High-Angle Normal Faulting

Another distinction between how extension modified the crust at the Salton Trough and in the metamorphic core complexes is faulting style. The deep basins of the Salton Trough imply extension on mostly high-angle (~45°-60°) normal faults, which are the most commonly observed means by which the Earth's brittle crust extends (e.g., Olsen, 1995; Jackson, 1987). A potentially complicating factor in assessing extension in the Salton Trough is the role that strike-slip faults play in modifying crustal structure. In contrast, extension was accommodated on low-angle detachment faults in the Buckskin-Rawhide and other metamorphic core complexes (e.g., Rehrig and Reynolds, 1980; Spencer and Rey-

nolds, 1991). Why this should be so is fundamental to understanding the different response of the crust to extensional stress in the two regions.

Anderson's (1951) theory provides a general framework to describe faulting in relation to the ambient stress field in the Earth's crust. The theory predicts that when the vertical lithostatic load is the greatest principal stress, normal faulting ensues at an angle ~45° to 70° from vertical, when the difference between the horizontal least principal stress and vertical greatest principal stress exceeds the shear strength of the rocks. However, shallow dipping to horizontal fault planes are commonly observed, often with extreme normal displacements. Because these faults are shear failures that respond to the local stress field, apparently either the greatest principal stress direction deviates from the vertical (e.g., Bartley and Glazner, 1985; Bradshaw and Zoback, 1988; Melosh, 1990), or a steeply dipping fault plane rotates to a more shallow dip after displacement (e.g., Davis, 1983; Lavier et al., 1999). Reactivation along ancient low-angle fault planes is a less likely explanation because in most cases the shear strength of a plane of weakness improperly oriented to the principal stress axes exceeds that for a new fault in fresh rock along a more favored plane (Sibson, 1985). There is clear evidence that rotation followed by initiation of new fault planes occurs, as in the case at Yerington, Nevada (Proffett, 1977). However, structural reconstructions indicate that many detachment faults begin and propagate at low angles, including the Whipple Mountains (Yin and Dunn, 1992) and Chemehuevi Mountains of southern California (Miller and John, 1988), the Harcuvar Mountains of central Arizona (Reynolds and Spencer, 1985), and in the Mormon Mountains of Nevada (Wernicke et al., 1985).

The expected pattern for brittle extension with a vertical greatest principal stress is limited motion along steeply dipping fault planes, with a new plane forming when it is no longer efficient to continue motion along the first (much like the middle Miocene episode of block faulting in the Basin and Range province). Most earthquakes with normal focal mechanisms indicate steeply dipping fault planes (>40°) (e.g., Jackson, 1987). When lower angled faults occur, they tend to expose sharp divisions between brittle deformation in the upper plate and ductile deformation in the lower plate; this has invited the suggestion that the low-angle faults represent the brittle-ductile transition (e.g., Gans et al., 1985). Some models involving isostatic uplift ("rolling hinge") suggest that unloading caused by movement on a normal fault causes upwarp of the footwall, which rotates the initially steep fault plane towards the horizontal (e.g., Heiskanen and Vening Meinesz, 1958; Spencer, 1984; Wernicke and Axen, 1988). A rolling hinge model is a viable way to explain the doming of middle-crustal rocks, but a source of intruded rock, either igneous or crustal flow, is required to prolong slip on a single plane sufficient to denude the middle crust (e.g., Lavier et al., 1999).

The stress field and rheology of the upper crust may be influenced towards conditions favoring low-angle normal faulting by magmatism (e.g., Lister and Baldwin, 1993; Parsons and Thompson, 1993). Advected heat from intruded magma could raise the brittle-ductile transition temporarily,

and shear along the ductile zone (e.g., Melosh, 1990) or shear stresses imposed directly by the intrusion (Parsons and Thompson, 1993) might cause a rotation in the stress field favoring low-angle faulting. Any model for in-situ low-angle faulting must include some source of shear that drives the faulting, either gravitational as in the case of Gulf of Mexico faults (e.g., Bradshaw and Zoback, 1988), or some other source where topographic inclination is not likely to be a factor, such as in the metamorphic core complexes in the Basin and Range. Furthermore, models for metamorphic core complex development must be consistent with the following observations: (1) the crust beneath core complexes is often as thick as (or thicker than) the surrounding less extended terranes, (2) core complexes lack strong Bouguer gravity anomalies, thus regardless of its source, the material that maintains crustal thickness beneath the core complexes must be on average the same density as the whole-crustal average, and (3) the exposed core rocks are typically warped upwards into mountainous antiformal structures rather than buried beneath thick sedimentary basins.

DiSCUSSION: EXTENSION RATE VS. IN-TRUSION RATE

Did the crust of the metamorphic core complexes respond differently to extensional stress because low-angle normal faults formed, thus generating anomalous lower crust, or were deep crustal processes active that caused the low-angle faults? The answer to this 'chicken-and-egg' question is probably also the answer to the question: why did the crust of the Salton Trough and metamorphic core complex belt respond so differently to strong extensional forces? We propose here an explanation that involves interplay between extension rate and intrusion rate. We consider intrusion to be any source of rock from outside the region of extension, such as mantle-sourced magmatism and/or crustal flow from highstanding provinces such as the Colorado Plateau.

We suggest that the key differences between the core complex extensional belt and the Salton Trough is the rate of extension vs. supply of intruded rocks. Individual Salton Trough spreading centers likely extended at rates anywhere from 5 to 10 times faster than the estimated rate of extension for the Buckskin-Rawhide core complex. From the Salton Trough crustal structure it appears that magmatic intrusion and sedimentation rate balances the extension rate, much like a midocean ridge (e.g., Fuis et al., 1984; Nicolas, 1985; Parsons and McCarthy, 1996). In addition, a neighboring highstanding region like the Colorado Plateau with a strong lateral pressure gradient is less pronounced at the Salton Trough, with the adjacent, but narrower Peninsular Ranges having a ~20-30 km crustal thickness (Richards-Dinger and Shearer, 1997; Lewis et al., 2000), which could further limit the flow of crustal rocks into the extending zone.

In contrast, when strong extension occurred in the core complex belt, we suggest that magmatic activity had at least two roles in promoting low-angle faulting and metamorphic core complex development. First, if a pulse of magmatism intrudes crust that is extending at a moderate rate, then it is possible that the intrusion could expand, or maintain an already over-thickened crust despite the extension rate, leading to local magmatic overpressure and producing a stress state that enables sill intrusion and local uplift (e.g., McCarthy and Thompson, 1988; Parsons and Thompson, 1991; Holliger and Levander, 1994). Second, advected heat from magmatic intrusions can lower the yield strength of surrounding rocks, enabling them to flow into a strongly extended regime. This may have been particularly effective around the Colorado Plateau margins during the late stages of extension because of the high lateral pressure gradient in the crust at middle crustal levels (Figure 6). These two results of magmatism favor observations and models for low-angle faulting and core complexes: they supply a source of material (magmatic and flow intrusion) to enable a rolling hinge model to work, they raise the brittle ductile transition to shallower depths, and they can cause the doming of the footwall rocks commonly associated with extensional core complexes (Figure 7).

Beneath the more rapidly extending Salton Trough spreading centers, we suggest that intrusion rates have not been able to exceed extension rate, preventing the formation of metamorphic core complexes, and preventing the maintenance of crustal thickness (Figure 7). During very rapid extension, the available magma supply is taken up in the form of sheeted dikes that keep pace, or lag behind crustal stretching, causing necking of the lithosphere and subsidence. This is observed in the crustal structure of the Salton Trough (Figure 4), as is a more mafic lower crust when compared with the metamorphic core complexes. Since magmatic intrusion appears localized beneath the rifts, less broadly distributed intrusion occurs, limiting the amount of advected heat available to mobilize crustal flow. A significant reduction in regional crustal viscosity would be required so that middle crustal flow could keep pace with the higher extension rate. In addition, the Salton Trough lacks a neighboring highstanding region comparable to the Colorado Plateau, with a strong lateral pressure gradient and highly mobile middle crustal rocks necessary for strong crustal flow.

A complicating factor in the comparison between the core complex belt and the Salton trough is that the pre-extension thickness can only be estimated. If one of the regions were unstably overthickened, then gravitational collapse might have been an important factor during the initial stages of extension, and further, provide the necessary topographic head to initiate low-angle faulting. This has been argued by Spencer and Reynolds (1990), who suggested that Cretaceous crustal thickening in what is now the metamorphic core complex belt produced the isostatic forces that brought the core complexes to the surface. Such effects may well be important, but can only explain a return from overthickened to equilibrated crust.

We propose that the metamorphic core complex belt clusters around the southwest edge of the Colorado Plateau for two reasons: (1) the extension rate was slower than the rate of intrusion during pulses of mantle magmatism, and (2) advected heat and a high lateral pressure gradient from the adjacent highstanding Colorado Plateau enabled high rates of lateral crustal flow underneath the core complexes. This flux of material into the core complex belt can explain the observed features of the low-angle fault systems, the relatively thick
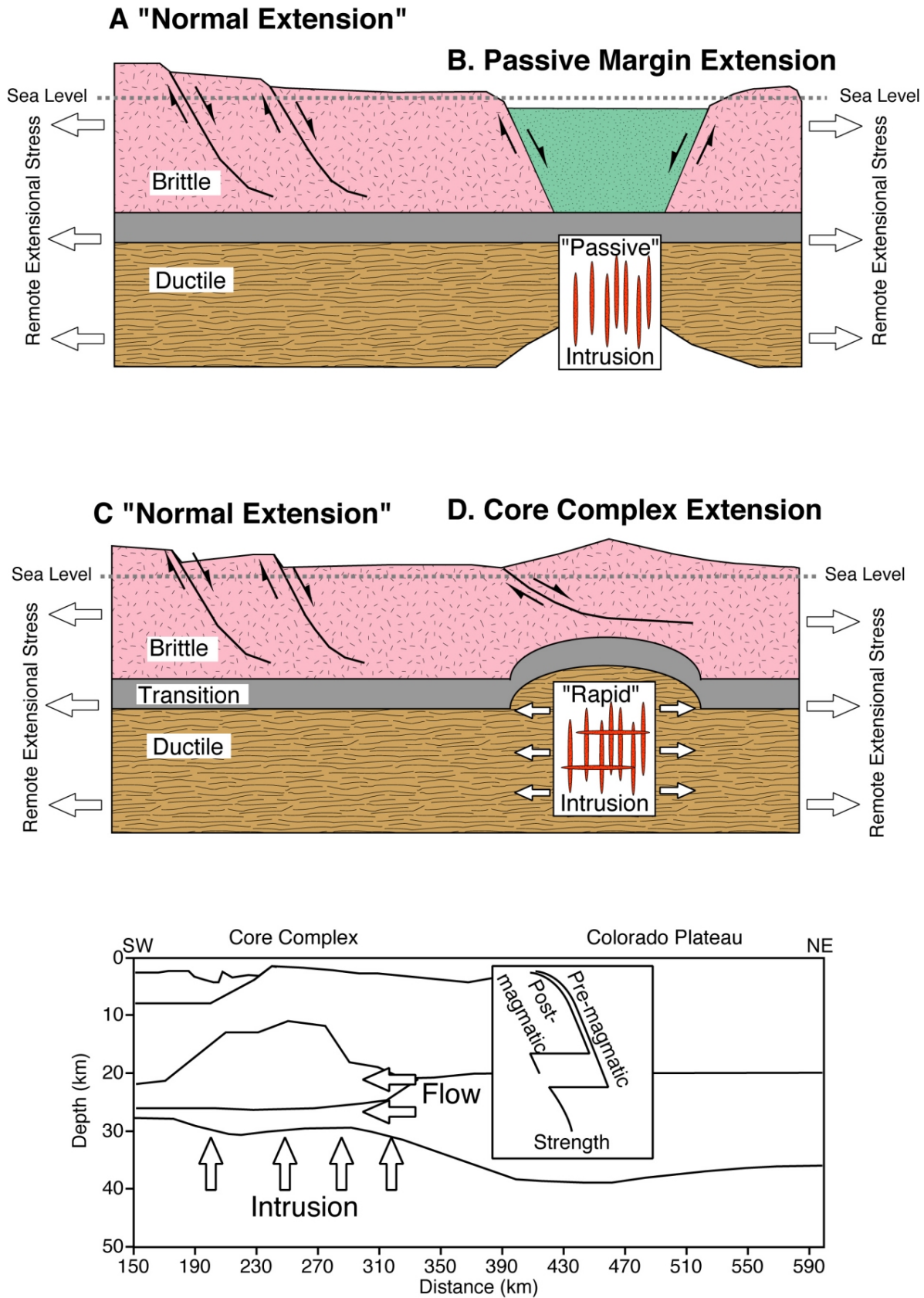
Figure 7*. A model for balance between extension and intrusion rates. Intrusion here is meant to be either magmatic or by crustal flow. When the extension rate exceeds intrusion rate, then we expect lithospheric necking, high-angle normal faults, subsidence, and basin formation. If intrusion rate can exceed extension rate over some duration, then low-angle normal faults with large off-set, uplift, and maintenance of crustal thickness by magmatism and crustal flow are expected.*

crust beneath them, and their associated relatively high topography. We suggest either that a higher extension rate at the Salton Trough, and/or slower intrusion rate prevents the necessary flux of crustal rock necessary to cause core complexes.

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