Controlling Factors on Mesozoic and Cenozoic Metamorphism and Deformation in the Maria Fold and Thrust Belt and Colorado River Extensional Corridor, Southeastern California and Western Arizona

by

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Abstract

The Maria Fold and Thrust Belt (MFTB) and Colorado River Extensional Corridor (CREC) were the sites of atypically extreme compression in Mesozoic time and extension in Cenozoic time, respectively. The orientations of these deformational structures are at odds with the Sevier and Laramide thrust belts and the Basin and Range Extensional Province surrounding these areas, a fact that remains largely unexplained. Data pertaining to metamorphic grade, deformational structures, and plutonism are compiled and reported in order to characterize compression and metamorphism. Field data on the 18.6 Ma Peach Spring Tuff are collected and presented and data on cooling ages are compiled in order to characterize extension. It is suggested that high metamorphic temperatures and ductile compressional structures are related to Late Cretaceous S-type plutonism; furthermore, it is suggested that later extension is related to earlier metamorphism and compression. It is demonstrated that the spread in attitudes of the Peach Spring Tuff correlates well with the degree of post-18.6 Ma extension. Finally, a favored model is presented for the Mesozoic-Cenozoic evolution of the MFTB and CREC.

Introduction

Overview

The Maria Fold and Thrust Belt (MFTB) of the eastern Mojave Desert, in southeastern California and west-central Arizona, is a poorly understood piece of the larger puzzle of the Western Cordillera. Paleozoic stratigraphic units correlated with the undeformed Grand Canyon sequence are commonly seen in the MFTB as upper-amphibolite facies metamorphic rocks, isoclinally folded on the scale of mountain ranges and attenuated to as little as 1% of the thickness of the correlative Grand Canyon units (Stone et al 1993, Salem 2009). However, in certain areas this high-grade metamorphism and deformation is juxtaposed with the nearby presence of the same
stratigraphic sequence, but relatively unmetamorphosed and undeformed (compare the Ship and Old Woman Mountains in Figure 2, below).

The aims of this thesis are 1) to examine the relationship between metamorphic gradients, cooling histories, plutons, and pre- and post-metamorphic structures in the eastern Mojave Desert, 2) to examine the relationship between the Mesozoic compressional structures of the MFTB and the Tertiary extensional structures of the Colorado River Extensional Corridor (CREC), and 3) to suggest plausible scenarios resulting in the observed patterns in the aforementioned data compatible with the accepted geological timeline of the southern Cordillera. Towards these ends, a field excursion was made to gather measurements of the Peach Spring Tuff, a widespread 18.6 Ma sanidine-bearing tuff (Glazner et al 1986), in an attempt to temporally constrain deformational and metamorphic events. All other data reported are the result of an exhaustive literature compilation, including several years of unpublished data from the Massachusetts Institute of Technology undergraduate course Field Geology II, for which I was a contributor to the 2014 Piute Mountains data.

Geologic Setting

Proterozoic Era – Passive margin sedimentation and failed rifting

The oldest exposed rocks of the eastern Mojave Desert area consist of Archean to Middle Proterozoic age crystalline rocks, largely mafic paragneisses and later granitic dikes (Burchfiel et al 1992, Hoffman 1988). There were several periods of extension near 1000 Ma (Burchfiel and Davis 1972, Burchfiel et al 1992), which created basins in which a Middle-Late Proterozoic sediment bed was deposited. These sediments eventually became the mafic paragneiss we see as the basement rock in the Mojave area today. Another extensional event, lasting from the Late Proterozoic to the Late Devonian, initiated the development of the Cordilleran miogeocline (Stewart 1972). At this time the western continental margin constituted a passive margin. The lack of motion along the plate boundaries allowed a miogeocline to slowly form. Today, broadly
speaking, the terrane from the Mojave and westwards is miogeoclinal marine sediments, and the terrane to the east is largely cratonal metaigneous rock, and so the eastern edge of the Mojave, where field efforts were focused, is likely in a transitional zone between miogeoclinal and cratonal assemblages (Stone et al. 1983).

In the final stages of the Proterozoic, several failed rift zones were established in the continental plate, resulting in a large topographically low area that later filled in with a paleo-sea, which in the subsequent Paleozoic era allowed marine rock deposition as far inland as the Grand Canyon area (Burchfiel et al. 1992, McMechan and Price 1982).

**Paleozoic Era – Pacific spreading center and active margin thrusting**

In the Paleozoic era a new rift zone opened up to the west of the failed Proterozoic rift zones, near what would become the west coast of North America, and succeeded in creating a major spreading center that gradually migrated west over time (Poole et al. 1992, Burchfiel et al. 1992, Burchfiel and Davis 1972), driving subduction of oceanic plate underneath the continent and thus changing the formerly passive margin to an active margin. The spreading center migration is recorded by the collision of the Antler island arc with the main continent in mid-Paleozoic times. In the literature there are conflicting opinions on whether east- or west-dipping subduction first occurred. One theory suggests (Dickinson et al. 1983) that the Antler rocks were an offshore arc on a small piece of continental crust, and the small piece of oceanic lithosphere between North America and the Antler arc subducted west underneath the Antler arc, which dragged the arc against the continent through retrograde slab motion. Another theory (Burchfiel and Davis 1972) suggests that east-dipping subduction dominated, with the Antler arc having been dragged against the continent by typical plate convergence. Once the arc had been accreted, both schools of thought agree that the oceanic plate behind it began to subduct eastwards underneath the continent. Retrograde slab motion caused the Antler arc and the accretionary prism to thrust 200 km eastwards to their final resting place atop earlier miogeoclinal rocks. A later theory, proposed by Burchfiel and Royden (1991), requires no arc-continent collision at all but instead proposes
inactivation and subsidence of the arc before thrusting, resulting in only the youngest part of the arc being obducted.

By the Devonian period, east-dipping subduction was firmly entrenched, and an associated volcanic arc had developed on the continent running approximately north-south. In the Carboniferous, an increased convergence rate at the subduction zone began the uplift of the Ancestral Rocky Mountains (Kluth and Coney 1981). The orogenic crustal shortening was accommodated at least in part along reactivated Proterozoic thrust faults (Ye et al 1996).

In latest Paleozoic times, a large transform fault trending northwest-southeast to the southwest of our field area is thought to have removed the southernmost parts of the Proterozoic miogeocline and the Antler belt, carrying them into northern Mexico. A small sliver of Antler assemblage found in the northwest Mojave desert is interpreted as a sliver left behind en route to Mexico as the fault terminated and began another parallel transform fault (Burchfiel et al 1992).

Key to this study is a sequence of Paleozoic sedimentary rocks which were later variably deformed and metamorphosed; these rocks are currently exposed in several mountain ranges in the study area at differing grades of metamorphism and degrees of deformation. These rocks are correlative with the well-known Grand Canyon sequence rocks to the northeast (Stone et al 1983), but unlike the Grand Canyon rocks did not regionally escape Mesozoic deformation events. The variable pattern of metamorphism and deformation has not been well explained, and compilation and analysis of this data is a central component of this thesis.

Mesozoic Era – Continued thrusting and Sevier orogeny

Near the Permian-Triassic boundary, Andean-style convergent tectonics dominated in the southern Cordillera, while the Sonoma orogeny dominated in the north (Burchfiel et al 1992). Subduction continued as normal in the southern section, while the northern Sonoma orogeny is thought to have been similar to the earlier Antler orogeny: a magmatic arc lay off of the western margin and upon accretion to the continent the
sedimentary sequence of the closed marine basin was obducted onto the continent (Burchfiel and Davis 1972, 1975). However, there have been no observations of oceanic crust fragments in the Sonoma allochton. This lack of oceanic material led Speed (1979) to present a similar model to Dickinson's interpretation of the earlier Antler thrust, which involved west-dipping subduction of the marine basin plate underneath the offshore arc, which caused earlier decoupling of the oceanic plate and sedimentary sequence, increasing the likelihood that no oceanic plate was obducted. As with the Antler orogeny, neither explanation is clearly favorable, but Speed's model enjoys the slight benefit of the lack of observed oceanic plate.

The Maria Fold and Thrust Belt (MFTB), a region of ductile compression structures overlain by brittle thrusting, developed in a narrow east-west trending belt in the present day Mojave and Sonoran Deserts at the extreme southern end of the Cordillera. In defiance of the convergent plate boundary causing east-west compressional stress to the north, its structures appear to record roughly north-south compression. Geographically, the MFTB's east-west oriented landforms are an abrupt change from the east-west compression in the north, which created orogenic features running north-south (see Figure 1 below). South of the MFTB area, the perceived direction of major Mesozoic compression gently shifts back towards east-west.

At a similar time as the MFTB developed, in the Late Cretaceous just before the Cenozoic boundary (~67 Ma), increased subduction rates of the Farallon oceanic plate (DeCelles 2004) initiated the Sevier orogeny in which the east-west compression created thrust faults along the weak bedding planes of Paleozoic and Mesozoic sedimentary layers. A volcanic arc developed to the east in the North American craton, generally causing synconvergent extension to the east of the compressional terrane (Burchfiel et al 1992). The forearc basin of the Sevier orogeny is today the Great Valley of California. The southernmost extent of the Sevier belt is not well known, but could have extended as far south as the northern end of our field area (Hoisch et al 1988, Fletcher et al 1995). In the Latest Cretaceous, much of the southwestern Cordillera underwent post-compressional extension, likely related to gravitational collapse of overthickened crust (Wells et al 2005, Hodges and Walker 1990).
The MFTB is of particular interest to this study due to its atypical and poorly-understood deviations in stress direction and magnitude of deformation. The MFTB is unique from most of the Cordillera in Mesozoic time in that the deformation was thick-skinned, involving ductile thrusting and folding of the deep Proterozoic basement rocks and Paleozoic strata. Furthermore, the MFTB records a shift in compression direction from east-west to north-south, and is accordingly positioned in a transitional zone between north-south trending mountain belts to the north and east and east-west trending mountain belts to the south and west. Later Cenozoic extension exposed deep Mesozoic ductile structures in Paleozoic rocks near the centerline of our field area in the Old Woman, Big Maria, Riverside, and surrounding ranges, while it emplaced metamorphic core complexes farther east in the Chemehuevi, Whipple, and Sacramento mountain ranges. (Salem 2009, Knapp and Heizler 1990, Spencer and Reynolds 1990).

**Cenozoic Era** – Laramide orogeny and magmatic gap, initiation of transform margin

In the latest Cretaceous period to the early Cenozoic era, increased convergence rates and subduction of the Farallon oceanic plate initiated the Laramide Rocky Mountain orogeny along reactivated Ancestral Rockies structures, which were by now unusually far from the plate boundary for such a large mountain-building event to occur there. This orogeny was achieved by the atypical subduction of the Farallon plate, which in the southern area is thought to have not sunk into the mantle as deeply with distance as is normally expected for oceanic plates; the cause of this anomaly is not well understood (Coney and Reynolds 1977, Decelles 2004, Saleeby 2003). This flatness of subduction terminated the Sevier volcanism through the Farallon plate isolating the volcanic arc from the mantle, which created the Laramide Magmatic Gap (see Figure 1 below, Armstrong and Ward 1991). The Farallon subduction also initiated new back-arc magmatism further east in Montana and Colorado (Stern and Wyllie 1981, Chen and Moore 1982), which in turn caused east-west contraction in the formerly extended Sevier back-arc region. The Laramide orogeny reactivated thrust faults of the Ancestral
Rockies orogeny as well as former Proterozoic faults (Burchfiel et al 1991). The general topography of the orogenic belt was shaped before the massive uplift of the Colorado Plateau, which occurred gradually throughout the era and continued to occur after major thrusting events ceased, but had subsided by Miocene time (Young 2009).

Following the Laramide orogeny was a long period of no major recorded tectonic events, until at roughly 25 Ma, the boundary between the Pacific and Farallon oceanic plates was totally subducted underneath the continent at roughly the latitude of our field area (Burchfiel et al 1991). The resulting pair of triple plate junctions spread with time and soon had changed the western margin of the United States to a transform fault system. At approximately this time the Laramide Magmatic Gap closed, restoring magmatism to our field area (Armstrong and Ward 1991).

In the Miocene, the present-day Colorado Plateau region of the Cordillera was still undergoing compressional orogeny, but large-scale east-west extensional stress began to exhibit itself as the Basin and Range extensional province to the west, north, and south of the Mojave area (Hileman et al 1990). The extension was possibly related to a segment of the subducted Farallon plate breaking off into the mantle, allowing hot mantle convection to occur in contact with the continental lithosphere much further west than during the Laramide orogeny, which created a rift-zone-like extensional environment (Sigloch and Mihalynuk 2013). In the Mojave, this extension was accommodated in part in the Central Mojave Extensional Complex (CMEC) to the west, but largely in the Colorado River Extensional Corridor (CREC) to the east, where today we see a well-studied system of detachment faults and metamorphic core complexes, the typical example of which is found in the Whipple Mountains. I will later refer to this belt of metamorphic core complexes as the Colorado River Core Complex Belt (CRCCB), and it should be thought of as coincident with but more narrow than the CREC.

At 18.6 Ma the Peach Spring Tuff, a regionally extensive volcanic tuff layer first recognized by Young and Brennan in 1973, was deposited as far west as Barstow, California from a supervolcano thought to have been located at the present-day junction between the California, Arizona, and Nevada state lines (Ferguson et al 2012,
Since the Peach Spring Tuff is fairly recent and well-recognized throughout the area, it proves very useful in temporally constraining deformation. The relative timing of Cenozoic faulting and uplift is not well understood in the eastern Mojave, and so this study ultimately attempts to relate metamorphic gradients of Paleozoic rock to Mesozoic and Cenozoic tectonic features using basic field observations of the Peach Spring Tuff and structural, metamorphic, and thermochronologic data compiled from existing literature.

Figure 1: Overview Map. Shows the western US and key features discussed in text. The Maria Fold and Thrust Belt (MFTB), in red, is the same as the MFTB drawn in later figures. The Central/Western Mojave Block contains the E-W trending Central Mojave Extensional Corridor (CMEC). Blue lines bound the area where core complexes have been observed, and are larger in extent than the Colorado River Core Complex Belt (CRCCB) shown in blue in subsequent figures. The thick arrows of the Laramide Magmatic Gap indicate where magmatism was blocked starting at roughly 55 Ma. Of particular note is the apparent coincidence of the 90° bend in the MFTB with a similar bend in the edge of the Colorado Plateau. See Appendix for citations.

Data
Metamorphic grade, compressional deformation, and plutonism

Figure 2: Metamorphic Grade, Compressional Structures, and Mesozoic Plutonism. The abbreviations of mountain range names are color coded to peak metamorphic temperatures as indicated by the key to center right. Certain colors are outlined in white for visibility only. Black text indicates areas of no Paleozoic exposure and makes no implication on metamorphic grade. The major observed sense of compression is given with double black arrows. Plutons and the MFTB are outlined as in the key to the upper right. Of particular note is the coincidence of Late Cretaceous plutons (pink) with the highest peak metamorphic temperatures (deep red). Furthermore, major compressional senses are generally oriented roughly NW-SE in the northern MFTB, and NE-SW in the southern MFTB. Finally, ranges recording no major compression also record low peak metamorphic temperatures (dark green and cyan). Mountain range abbreviations are as follows: Ma = Marble Mtns, Cl = Clipper Mtns, Sh = Ship Mtns, Pi = Piute Mtns, LP = Little Piute Mtns, OW = Old Woman Mtns, K = Kilbeck Hills, Ir = Iron Mtns, Gr = Granite Mtns, Sa = Sacramento Mtns, St = Stepladder Mtns, T = Turtle Mtns, A = Arica Mtns, LM = Little Maria Mtns, Pa = Palen Mtns, Mc = McCoy Mtns, Ch = Chemehuevi Mtns, W = Whipple Mtns, R = Riverside Mtns, BM = Big Maria Mtns, Mo = Moon Mtns, DR = Dome Rock Mtns, Mh = Mohave Mtns, Pl = Plomosa Mtns, GW = Granite Wash Mtns, H = Harquahala Mtns. See Appendix for citations.

Figure 2 is a generalized map reporting compiled data on peak metamorphic temperatures, the major observed sense of compressional stress, and locations of
exposed Jurassic to Cretaceous-age plutons. Outlined in red dashed lines is the approximate area where MFTB-style deep-skinned compressional deformation structures have been observed, after Karlstrom et al (1993), Spencer and Reynolds (1990), and Fletcher and Karlstrom (1990). The main markers used in characterizing the deformation and the metamorphic grade were the Paleozoic miogeoclinal strata. As the Paleozoic strata pinch out towards the east, the ages of compressional structures and metamorphism become more uncertain towards the east, as in the Whipple and Chemehuevi Mountains, and in areas where only Mesozoic plutonic rocks and Tertiary igneous and sedimentary rocks have been reported, as in the Iron Mountains. Black double arrows indicate the most recent sense of compression, which is largely perpendicular to the axes of major folds. Although not reported on Figure 2, the Jurassic plutons are generally metaluminous I-type granitic rocks while the Late Cretaceous plutons are generally peraluminous S-type granitic rocks (for example, Miller and Bradfish 1980, Miller and Wooden 1994).

Metamorphism-deformation relation

The first notable observation of this dataset is an apparent relation between higher peak metamorphic temperatures and the presence of ductile compressional structures. The Piute, Old Woman, Big Maria, and Harquahala Mountains are good examples of high-grade metamorphism coinciding with widespread tight-to-isoclinal ductile folding. The currently exposed structural levels in Ship, Clipper, and Marble Mountains have apparently undergone no ductile deformation since pre-Cambrian times, as Paleozoic miogeoclinal strata are unfolded in this area (Miller et al 1982). This area also indicates very low-grade peak metamorphic temperatures and so serves to reinforce the deformation-metamorphism relation. However, this relation is not absolute. For example, in the Arica and Riverside Mountains, metamorphism of Paleozoic strata has been rather low-grade (mid-greenschist), yet clear evidence of ductile deformation has been reported (by Rachel Baltz, in print, MIT Riversides undergraduate field camp, 2011). Additionally, even the undeformed strata in the Ship and Clipper Mountains have

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been metamorphosed to low greenschist-grade (Miller et al 1982, Howard et al 1995). Several researchers have suggested a regional greenschist-grade metamorphic event sometime prior to the Cretaceous (for example, Knapp 1989, Salem 2009, Stone et al 1983), which is convenient supporting evidence for the reality of the deformation-metamorphism relation.

Plutonism-metamorphism relation

The second observation to note is the spatial coincidence of Late Cretaceous plutons (shown in pink on Figure 2) with higher peak metamorphic temperatures. This relation is most clearly observed in the northern limb of the MFTB, in the Piute and Old Woman Mountains. There, peak metamorphic temperatures are the highest reported in the entire MFTB, exceeding 650°C in both ranges (Foster et al 1992). Detailed metamorphic isograd mapping reveals that peak metamorphic temperatures increase with proximity to Late Cretaceous plutons (Foster et al 1992). Furthermore, studies of higher-grade metamorphism in the entire region indicate high-temperature, low-pressure conditions (Hoisch 1987, Hoisch et al 1988, Foster et al 1992), suggestive of metamorphism by the added heat of intrusive magma bodies. Note that in the Ship and Clipper Mountains there are no exposed Late Cretaceous plutons and metamorphism is of low greenschist grade. This metamorphism without adjacent plutonism serves as further evidence of a regional greenschist-grade metamorphic event.

A glaring exception to the plutonism-metamorphism relation is found in the Turtle and Stepladder Mountains, where Late Cretaceous plutons are exposed over relatively small areas but metamorphic grade is only low-mid greenschist. This spatial coincidence of low metamorphic grade with Late Cretaceous plutonism could mean that these plutons were emplaced in much cooler country rock, or were much smaller in total magma volume, than in those areas where plutons are related to higher-grade metamorphism, cooling quickly enough to not induce temperatures higher than those of the regional metamorphic event. This exception is discussed in detail in the Discussion section below.
Since Late Cretaceous plutons appear to be related to high-grade metamorphism, it seems natural to ask whether Early Cretaceous and Jurassic plutons (shown in light and dark purple respectively on Figure 2) follow a similar relation. Jurassic plutons are present over large areas of the Marble and Ship Mountains, yet metamorphic grade is no higher than that of the presumed regional greenschist grade (Stone et al 1983, Howard et al 1995). In the Big Maria Mountains area, significant Jurassic pluton exposure is present alongside lower amphibolite-grade metamorphism, yet metamorphic isograds are not clearly related to proximity to Jurassic plutons (Hoisch 1987). Thus it seems unlikely that Jurassic plutonism is meaningfully related with metamorphic grade, which likely means that Jurassic plutons were emplaced at shallow depths relative to the Late Cretaceous plutons. Hoisch proposes that the higher-grade metamorphism in the Big Marias was the result of large hydrothermal fluid fluxes from deeper in the crust, supported by the presence of wollastonite (1987). He considers the possibility that this fluid was heated by deep magmatic intrusions and propagated upwards by fracture networks. Since he mentions that the metamorphic event was Late Cretaceous in age, it seems likely that in the Big Maria Mountains area metamorphic grade is again related to Late Cretaceous plutonism. In a later paper, Hoisch mentions that metamorphic grade within the Big Marias is higher in areas with higher concentrations of Late Cretaceous dikes, which are possibly related to a large unexposed pluton underneath the Big Maria area (Hoisch et al 1988).

Early Cretaceous plutons are few in the area, and so it is difficult to suggest any relation with metamorphic grade. The sole instance where Early Cretaceous plutons are found alongside MFTB compressional structures is in the Riverside Mountains, where peak metamorphic temperatures were roughly 100° C above the presumed regional metamorphic event (Hamilton, in print, and Lyle, in print). Based on this single piece of evidence, a slight correlation between Early Cretaceous plutonism and peak metamorphic temperatures can be tentatively suggested. If this is indeed a valid correlation, it is suggestive of the depth at which Early Cretaceous plutons were emplaced falling in between those of the Jurassic and Late Cretaceous plutons.
Compression directions

Finally, it should be noted that sense of compression in the MFTB is generally near perpendicular to the MFTB boundary and that fold axes have almost universally subhorizontal to shallow dips. Notable exceptions occur in the Arica Mountains, where the sense of compression lies roughly parallel to the boundary and fold axes dip approximately 50° to the southwest, and in the Moon and Plomosa Mountains, where the sense of compression is oblique to the boundary. In the southern limb of the MFTB, it appears that the presence of Jurassic plutons is related to compression being roughly northeast-southwest trending, while Late Cretaceous plutons are related to compression being northwest-southeast trending. The anomalous northeast-southwest trending compressional structures in the McCoy and Big Maria Mountains area are thought by Salem (2009), Laubach et al (1980) and Knapp (1989) to be Late Cretaceous in age, and in their interpretations it is hard to see how Jurassic plutonism could be related to differences in Cretaceous compressional sense. However, Harding et al (1980) believe the major deformational structures preserved in the McCoy Mountains to be Jurassic in age, and Boettcher et al (2002, in print) infer southeast-vergent Jurassic compression and southwest-vergent Cretaceous compression in the Dome Rock Mountains. Thus the possibility must be considered that the ages of reported compression in the southern area of the MFTB are actually Jurassic, at ~90° to later Cretaceous shortening.

Extensional deformation and metamorphic core complexes

Figure 3 below overlays on Figure 2 the location of the belt of metamorphic core complexes (in blue), indicative of extreme extension, and directions of Tertiary extensional transport direction (dark blue arrows). This belt of metamorphic core complexes is part of a Laramide hinterland core complex belt extending from Arizona to Alaska (for example, Armstrong & Ward 1991, Coney 1980). Note the similarities in the shapes of the MFTB and what I will call the Colorado River Core Complex Belt (hereafter referred to as the CRCCB). Both belts exhibit an unusual change in direction
around the latitude of the Iron and Whipple Mountains, and generally trend in the same direction at any given latitude within the bounds of Figure 3. The two differences between the belts are that the CRCCB is offset roughly 50 km to the northeast with respect to the MFTB and that the CRCCB appears to bend somewhat less than the MFTB.

**Figure 3: Core Complexes and Tertiary Extension.** Mountain range abbreviations and colors indicating peak metamorphic temperatures are the same as in Figure 2, as are compression directions and pluton locations. Added is the outline of the CRCCB in dashed blue lines and directions of Late Tertiary extension as blue arrows. Key observations are the similarities in shape of the MFTB and the CRCCB and the variations in differences in Mesozoic compression and Tertiary extension directions between mountain ranges. See Appendix for citations.

Next, compare the directions of the major compressional senses (dark gray arrows) with the directions of Tertiary extension. Tertiary extension is almost always oriented to the northeast, with the exception of the Old Woman-Piute Mountains area.
where extension has been inferred to occur in a roughly eastern direction (Foster et al 1992, Hileman et al 1990). However, the Old Woman and Piute Mountains themselves are likely relatively unextended, with a north-south trending breakaway fault presumed just to the east between the Piute and Little Piute Mountains (Spencer and Reynolds 1990, Foster et al 1991). In most ranges where major extension overlaps with the MFTB, the compression and extension directions are broadly similar (e.g. Plomosa, Harquahala, Riverside Mountains). Notable exceptions are the Moon and Granite Wash Mountains, where extension was observed to occur nearly perpendicular to the major compression direction (Knapp 1989). Whether this upset in the compression-extension correlation is due to difficulties in temporally constraining compressional episodes or reflects a true offset in stress regimes from the surrounding ranges is unclear.
Figure 4: Cooling Ages from *Ar/Ar* and Apatite Fission Dates. Two cooling ages (given in Ma = million years ago) are reported below mountain range abbreviations where the data were available. The top number in each range is an *Ar/Ar* date of K-feldspar closure, occurring at roughly 250° C. The bottom number is an apatite fission date, occurring at roughly 120° C. Question marks indicate inconclusive or unavailable data. Abbreviations are the same as in figure 2 with the addition of: Bu = Buckskin Mtns, Ha = Harcuvar Mtns. Key observations are the general decrease in cooling ages towards the NW in the CRCCB, the younger cooling ages in the northern MFTB compared to areas directly west and east, and the young cooling ages near the intersection of the MFTB and CRCCB in the southeast of the map. See Appendix for citations.

K-feldspar *Ar/Ar* closure dates and apatite fission ages are the main data reported in Figure 4. Difficulties arose in this data compilation due to the variance in closure and fission temperatures based on cooling rates, total transport distance, and original structural depth, but honest attempts were made to report data at a similar level for all. Within the belt of core complexes, cooling ages seem to weakly decrease.
towards the north. Ranges in the northern outside of the core complex belt clearly cooled through K-feldspar closure much earlier than ranges in the core complex belt, and ranges in the MFTB underwent final apatite-fission cooling much later than ranges not within either the MFTB or the Colorado River Extensional Corridor (CREC). Ranges in the northern part of the MFTB appear to have cooled through K-feldspar closure much earlier than ranges near the southern overlap of the core complex belt and the MFTB. Ranges near the overlap area of the core complex belt and the MFTB all cooled at anomalously late ages. Finally, cross-referencing with Figures 2 and 3, note that mountain ranges that passed through K-feldspar closure temperatures prior to roughly 73 Ma universally are of low metamorphic grade and record no compressional structures or core complex emplacements.
The 18.6 Ma Peach Spring Tuff and Cenozoic vertical-axis rotations

Figure 5: Peach Spring Tuff Attitudes and Paleomagnetic Declination Anomalies. Strike/dip symbols are of the Peach Spring Tuff, with numbers reporting the paleomagnetic declination from that of the Peach Spring found on the Colorado Plateau from data of Well and Hillhouse (1989). Paleomagnetic declination anomalies are taken as indicative of post-18.6 Ma vertical-axis rotations. Clockwise rotations are positive, counterclockwise rotations negative. Dip is represented by color: the shallowest dips are most blue and the steepest dips are the most black. Stereonets given are 1% contour. The key observation is the coincidence of higher rotations and more chaotic attitudes with the CRCCB area of most extreme extension. See Appendix for complete citations.

Figure 5 summarizes paleomagnetic data of the Peach Spring Tuff from Well and Hillhouse (1989) as well as field measurements from my own excursion and the 2014 Massachusetts Institute of Technology undergraduate field camp in the Piute Mountains. The Peach Spring Tuff is a high-volume Miocene extrusion well-dated to 18.6 Ma with a source caldera lying roughly at the junction of the California, Arizona,
and Nevada state lines (Pamukcu et al. 2013), distinguished in the field by the presence of sanidine. Note the chaotic vertical-axis rotations of the Peach Spring within the Colorado River core complex belt, ranging from roughly 51° counterclockwise to 37° clockwise. These rotations have been attributed to doming around metamorphic core complex uplifts by (McCarthy et al. 1991) and to rotation along oblique-slip detachment faults by Calderone et al. (1990). In the northern MFTB, rotations are milder, peaking at 19° counterclockwise in the northwestern Piute Mountains. West of here, in the area between the MFTB and the CMEC (Central Mojave Extensional Corridor, to the west of the map extents) represented by the relatively undeformed and unmetamorphosed Ship, Clipper, and Marble Mountains, rotations are 0° within error. Unfortunately, the Peach Spring Tuff has not been found in the southern limb of the MFTB (see Glazner et al. 1986, Pamukcu et al. 2013) and so there is no information on post-Peach Spring rotations in that area. To the west in the CMEC, mild post-Peach Spring rotations of 13° clockwise to 10° counterclockwise are reported by Well and Hillhouse (1989), although Garfunkel (1974) proposes 30-40° counterclockwise rotations in the CMEC and Dokka and Travis (1990) and McFadden et al. (1990) propose up to 26° clockwise rotations accommodated along Late Neogene strike-slip faulting trending perpendicular to the Garlock Fault in the north.

**Discussion**

Here an attempt will be made to interpret the above data in a way consistent with existing model histories of the Maria Fold and Thrust Belt and the Colorado River Extensional Corridor.

*Relation of Mesozoic metamorphism, deformation, and plutonism/magmatism*

In Figure 2, the presence of at least greenschist-grade metamorphism even in areas with no Mesozoic plutonism or preserved ductile deformation structures suggests a regional metamorphic event. Late Cretaceous magmatism, expressed on the surface
as plutonism, is clearly related to higher metamorphic grade; Jurassic magmatism appears to have had little effect on peak temperatures. A reasonable explanation for this magmatism-metamorphism relation, assuming broadly similar crustal densities and magmatic densities and temperatures for the two periods of magmatism, is that the Late Cretaceous plutons were emplaced in overthickened crust relative to the Jurassic plutons, so that while the plutons intruded through similar thicknesses of lower crust, the Late Cretaceous plutons crystallized at greater depths and thus were able to conductively heat the surrounding rock. The folds existing at the surface of the MFTB today represent a mid-crustal depth, where temperatures were high enough to allow purely ductile deformation in Paleozoic strata. Thus there was certainly coeval brittle compressional deformation in the shallow crust, taking the form of overthrusting. It is proposed that the crustal overburden greatly thickened between the times of emplacement of the Jurassic and Late Cretaceous plutons (as in Hoisch 1987); several authors infer that significant deformation and metamorphism in the MFTB began in this time period (for example, DeCelles 2004, Reynolds et al 1989, Foster et al 1990, 1991, 1992, Hoisch et al 1988, Salem 2009).

A potential problem with this interpretation is found in the Stepladder, Turtle, and Arica Mountains, which constitute an abnormally low greenschist-grade belt of metamorphism trending north-south, despite the presence of Late Cretaceous plutons. This weak metamorphic grade is in contrast to the amphibolite-grade metamorphism observed just to the west in the Old Woman Mountains and to the south in the Big Maria Mountains. However, the absence of ductile compressional structures in the Turtle and Stepladder Mountains suggests that these ranges represent a shallower structural level than the ranges of the MFTB. This hypothesis is further supported by pre-latest Cretaceous ages on K-feldspar closure in the Stepladder Mountains, about 13 million years earlier than in the highly deformed and metamorphosed Old Woman and Piute Mountains (see Figure 4). It is possible that crustal overthickening was of a lesser extent in the Turtle and Stepladder ranges, but the likely driving force is that the magnitude of post-plutonic uplift and unroofing was small relative to the MFTB and the CRCCB.
Several authors note that the Late Cretaceous metamorphic event was immediately followed by a period of syn to post-compressional extension (for example, Hodges and Walker 1991, Foster et al 1992, McCaffrey et al 1999, Saleeby 2003), which is reflected in the cooling of the Old Woman and Piute Mountains through K-feldspar closure at approximately 60 Ma (see Figure 4, also Figure 6 below). A sample from the Stepladder Mountains showed dates of cooling through biotite and K-feldspar temperatures to be concordant at 73 Ma (Foster et al 1992), indicating extremely rapid cooling and unroofing of the Stepladder Mountains at this time. Since the Late Cretaceous plutons in the Turtle and Stepladder Mountains apparently did not significantly raise peak metamorphic temperatures, it is proposed that these plutons were emplaced after this local extension in the Turtle and Stepladder Mountains, allowing them to crystallize at shallow crustal levels relative to the MFTB. In this interpretation, the coexistence of ductile deformation, Late Cretaceous magmatism, and low metamorphic grade in the Arica Mountains remains unexplained, but the perpendicularity of ductile structures here to those in surrounding regions allows the possibility that the folds described by Blatz (in print) are actually misidentified extensional drag folds or earlier Jurassic folds. The lack of thermochronology studies in the Arica Mountains means this issue will remain unexplained for now.

Relation of Mesozoic compression and Cenozoic extension

Recall in Figure 3 the similarity between the shapes and locations of the MFTB and the Colorado River core complex belt. To help explain this similarity, an appeal is made to the model of Armstrong and Ward (1991) for Late Tertiary core complex formation in a belt to the west of the Laramide Orogeny mountains. Armstrong and Ward definitively linked the presence of metamorphic core complex emplacements to the presence of high-volume Tertiary magmatic fields (1991). Their model proposes that once compressional tectonics had ceased with the total subduction of the Farallon Plate and the shift in the Pacific coastal margin to a transform boundary, the belt of maximally thickened crust to the west of the Laramide retained large amounts of gravitational
potential energy, which exerted an extensional stress on the middle and lower crust underneath. However, the unusually shallow subduction of the Farallon Plate also left a large magmatic gap from the Arizona/Mexico border to the middle latitudes of Nevada starting at approximately 55 Ma (see Figure 1, magenta lines, Armstrong and Ward 1991, 1993). The thickened belt of crust cooled in response to the cessation of magmatism, raising middle and deep crustal viscosities sufficiently to prevent gravitational collapse. The southern magmatic field then slowly propagated northwards to finally close the magmatic gap at approximately 22 Ma. The increased temperature at the middle and lower crust from this magmatic field lowered viscosities sufficiently to allow extreme extension driven by gravitational collapse, eventually replacing what was previously the maximally overthickened crust with detachment systems and metamorphic core complexes.

Applying the above general model of Armstrong and Ward to the CRCCB, the hypothesis is proposed that the CRCCB was previously the area of most overthickened crust; extreme extension was driven by gravitational collapse of this overthickened crust but triggered by the closure of the Laramide Magmatic Gap. The applicability of Armstrong and Ward's model in the Colorado River core complex belt is directly supported by seismic reflection data of the Whipple Mountains core complex, where the maximally extended area is revealed to lie over crust that is still 3 kilometers thicker than its surroundings, with an unusually thick mid-crustal layer of roughly 15 kilometers (McCarthy et al 1991). Furthermore, ages of the onset of extension based on Ar-Ar and apatite fission dating weakly decrease from south to north across the area (see Figure 4, also Table A below), consistent with extensional triggering by the northward sweep of magmatism. These dates are compatible with the reintroduction of magmatism at ~22 Ma, as several million years likely elapsed between the reintroduction of magmatism and sufficient exhumation to cause cooling below K-feldspar closure and apatite fission. Corroborating views of the development of the Cordilleran metamorphic core complexes are expressed by Yin and Dunn (1992), Behr and Platt (2010), Spencer and Reynolds (1991), John (1987), Wernicke et al (1987), Coney and Harms (1984), Hodges and Walker (1992), Wells et al (2005), and John and Foster (1999).
It is proposed above that the Colorado River Core Complex Belt represents the belt of maximal overthickening at the cessation of compressional tectonics. Therefore it is not surprising that the Maria Fold and Thrust Belt mimics its shape and lies behind it with respect to the compression direction. From Ar-Ar and apatite fission dates (see Figure 4) it appears that at least the northern areas of the MFTB underwent Latest Cretaceous-Early Tertiary extension and unroofing prior to the closure of the Laramide magmatic gap (Foster et al 1992, Hoisch et al 1988). Syncompressional extension in this time is also reported in the Big and Little Maria Mountains, although not corroborated by Ar/Ar dating (Hodges and Walker 1992, Wells et al 2012). Cooling curves show that cooling rates were rapid in the Old Woman and Piute Mountains in the Latest Cretaceous (as in Foster et al 1992), while cooling curves for the Sacramento and Chemehuevi Mountains to the east show relatively slow cooling and temperatures roughly 100° C above the Old Woman area from the Cretaceous to the Miocene (see Figure 6 below). Thus it is likely that Latest Cretaceous extension west of the CRCCB was relatively weak or nonexistent in the CRCCB itself, and it is possible that this MFTB extension actually drove further compression in the CRCCB, causing the CRCCB to be the maximally overthickened belt by the time of closure of the Laramide magmatic gap at 22 Ma (Armstrong and Ward 1991). Therefore the proposed controlling factor on Tertiary extension was earlier Mesozoic compression.
Figure 6: Cooling Curves. Selected cooling curves based on Ar/Ar closure dates of hornblende, biotite, and K-feldspar, and apatite fission dates. All curves are reported on the same scale. Magenta curves represent extreme possibilities based on given data from individual samples, and cyan curves are interpretive averages. The vertical orange lines bound the onset of extension, while the vertical green lines roughly bound the formation of the Laramide magmatic gap. Key observations are the rapid cooling rate in the northern MFTB ranges (Piute and Old Woman) between 75 and 70 Ma, the rapid cooling rate in all four ranges around 20 Ma, and the ~100°C difference in the northern MFTB ranges (top) and the Sacramento and Chemehuevi Mountains (bottom) between 60 and 20 Ma. Data for the Piute and Old Woman Mountains is from Hoisch et al (1988) and Foster et al (1991), and data from the Sacramento and Chemehuevi Mountains is from Foster and John (1999) and Foster et al (1990, 1991).
Figure 7: Geologic map of the northwestern Piute Mountains. Data was partially produced by this author during MIT undergraduate field camp in January 2014. Stratigraphy is as shown in key in the top right. Strike/dip symbols only report dips in the Peach Spring Tuff. The fold referenced in the text is shown as a blue dashed line towards the left of the map, while older folds are in lighter colors shown in the key. Extension direction is shown as a large black arrow. The key observation is the dashed blue fold in the 18.6 Ma Peach Spring Tuff. See Appendix for citations.

The Peach Spring Tuff was the focus of fieldwork performed for this study and is useful in recognizing post-18.6 Ma deformation. When I was a part of the Massachusetts Institute of Technology undergraduate geology field camp in January 2014, I was responsible along with Paul Southard for mapping of the northwestern portion of the Piute Mountains. A generalized geologic map of this work is presented
above in Figure 7 in order to illustrate an apparent fold in the Peach Spring Tuff. This fold, shown with a dashed blue line in the northwest corner, is clearly of post-Peach Spring age as the Peach Spring dips towards the fold axis on either side of it, which likely implies a synclinal structure for this fold. Interestingly, the data of Well and Hillhouse (1989) show this opposite dip sense to either side of the fold (see Figure 5), but they do not make any reference to a post-Peach Spring fold in the area. Note that reported post-18.6 Ma rotations are not sufficient to explain these attitudes without further folding. Even more interesting is an anomalously low K-feldspar closure date of 18 Ma in the northern Piute Mountains and an apatite fission date of 18 Ma in the northwestern Old Woman Mountains by Foster et al (1990), which opens the possibility of a local patch of slower cooling and slight post-Peach Spring uplift. Minor uplift in the Piute and Old Woman Mountains has been proposed to have lasted until 16 Ma by Foster et al (1991), and they further mention that the currently exposed level in the Piute Mountains records a temperature gradient of ~130° C at 18 Ma. Potentially, the Peach Spring was buried by heavy later Cenozoic volcanism and drag from later extensional unroofing created this synclinal fold. Such extension-related folds are documented to the west in the Central Mojave by Fletcher et al (1995) and mentioned to the east in the Whipples by Davis et al (1980) and Yin and Dunn (1992). The north-south trending axis of the inferred Piute fold is perpendicular to and thus consistent with the east-west extension here during this time (Foster et al, 1991, also see black arrow on Figure 7). This presence of a fold in the Peach Spring Tuff would bracket the end of extension in the Piute Mountains to after 18.6 Ma, agreeing with the interpretation of Foster et al (1991, 1992) from thermochronology data.

Figure 8 below incorporates peak metamorphic temperatures from Figure 2, K-feldspar closure dates from Figure 4, and Peach Spring Tuff attitudes and stereonets from Figure 5. The fold shown in Figure 7 is evident from the two upper-rightmost stereonets, taken from opposite sides of the fold axis. It is clear that the Peach Spring in the Clipper, Ship, and Marble Mountains lies quite flat relative to its attitudes in the northern MFTB (see equal-area contoured stereonets below map). Furthermore, the eastern Piute Mountains is tilted roughly 30° to the west/northwest, while the western
Piute Mountains and the entire Old Woman block is tilted to the east roughly 30°. This differential tilting is suggestive of an accommodating fault between the Piute and Old Woman Mountains. No evidence of a fault is observed along the supposed fold axis in the northwestern Piute Mountains, while the Piute/Old Woman fault is independently proposed by Foster et al (1991).

With regards to metamorphic grade, Figure 8 suggests that in areas that underwent no Miocene extension there is low-grade metamorphism. This relation is likely because this extension and related uplift was localized to areas which previously experienced intense compression and overthickening. It seems likely that if mid-crustal layers of the Clipper Mountains were exposed, high-grade metamorphism and ductile deformation would be observed. However, since this area was not overthickened, there were no forces to drive rapid extension or uplift and so the area has been more or less tectonically inactive since approximately 60 Ma, an idea supported by Foster et al (1991, 1992). Note how the overall tilt and spread of the Peach Spring data increases from west to east in the three regions shown at the bottom of Figure 8. In the unextended Ship Mountains region (Howard et al 1995, Fox and Miller 1990), the Peach Spring lies very flat on average. In the mildly extended Old Woman Mountains region, the Peach Spring is chaotically oriented but not flat on average. In the extremely extended Colorado River region, the average tilt is greater and the spread is similarly chaotic. Recall from Figure 5 how these three regions also differed in degrees of vertical-axis rotations: rotations in the Ship Mountains region were 0° within error, in the northern MFTB were up to -19°, and in the CRCCB were as high as -51°. Figure 5 also shows higher rotations to be related to a higher spread in bedding attitudes. Thus it is proposed that tilt, spread of attitudes, and degree of rotation of the Peach Spring Tuff can all be used as reliable indicators of the degree of post-Miocene extension.
Figure 8: Peach Spring Tuff Attitudes in Relation to Metamorphic Grade. Attitudes and stereonets of the Peach Spring Tuff compared with K-feldspar closure dates and metamorphic grade. Peak metamorphic temperatures are reported as in Figure 2. Some strikes and dips are data of Hillhouse and Well, but stereonet data was purely generated by this author. Numbers by strike/dip symbols indicate dip – paleomagnetic data is not reported. Equal-area stereonets below the map consist of all data in the map area west of the MFTB (bottom left), all data in the map area within the MFTB (bottom center), and all data from east of the MFTB (bottom right). The key observation is the increase in the dip and spread of data from west to east, correlating with an increase in extensional magnitude from west to east.
The relation of magmatism and deformation: A model for Mesozoic-Cenozoic evolution

It has been proposed above that the crustal overburden began thickening between Jurassic and Late Cretaceous times; thus it is reasonable to propose that compressional stress increased from the Jurassic to the late Cretaceous. The alignment of evidence from Figure 2 with this concept depends on the debated ages of major compression in the southern portion of the MFTB (see Data section underneath Figure 2). If it is assumed that all reported ages are Cretaceous, then it can be inferred that the pre-Sevier continental truncation proposed by Burchfiel and Davis (1975) left an arcuate shape in the cratonal boundary which caused the compressional stress to swing around 90° to remain perpendicular to the cratonal boundary. If, however, the northeast-southwest compression is assumed to be Jurassic, then it is more likely that Cretaceous compression was uniformly northwest-southeast. As this assumption does not fit well with the model being developed, I will side with the majority of literature reviewed and assume that all major deformation was Cretaceous in age.

A model for the history of the MFTB and CRCCB will now be developed and presented.

First, consider the curvature of the northeastward extents of the Jurassic plutonic arc and note its similarity to the curvature of the MFTB zone in Figures 2 and 3. Burchfiel and Davis (1975) suggest that the continent-ward extent of Mesozoic magmatic arcs was in the ancient cratonal-miogeoclinal boundary transition zone. Magmatism was likely most intense here due to the relative impermeability of the craton to magma intrusions. Furthermore, Burchfiel and Davis also suggest that deformation was most intense in the boundary zone due to heightened ductility caused by the localization of magmatism (1975). Hollister and Crawford (1986) propose a similar view, with the slight difference being that the high ductility was the result of melt-enhanced deformation, which was also localized along the miogeoclinal/cratonal transition zone. It has been noted in the Geological Setting section that the MFTB and CRCCB areas are likely in a transitional zone between cratonal assemblages to the east and miogeoclinal assemblages to the west, and so these models are considered plausible here.
Therefore, it is proposed that the arcuate shape of the Jurassic arc is mimicking the shape of the Jurassic cratonal boundary.

Next, note how the Late Cretaceous plutonic arc is more widely scattered and shifted to the northeast relative to the Jurassic arc, and recall that this arc emplaced largely S-type igneous rocks as opposed to earlier I-type igneous rocks (Miller and Bradfish 1980, Miller and Wooden 1994). The same authors suggest that the Late Cretaceous S-type arc incorporated a higher degree of re-melted cratonal rock. Therefore it is further proposed that the cratonal boundary was migrating towards the northeast at this time, largely through re-melting of the craton.

Several authors have proposed increased convergence rates of the Farallon plate in Cretaceous times (for example, DeCelles 2004, Hildebrand 2009). This increased regional compressional stress state - convergence rates increased from 8 mm/yr in the Late Jurassic to 125 mm/yr in the Late Cretaceous (DeCelles 2004) - could explain why no metamorphism or deformation occurred until after the emplacement of the Jurassic plutons. The Jurassic plutons are widely considered to have been synextensionally emplaced (DeCelles 2004, Saleeby 1992, Dickinson and Lawton 2001, Reynolds et al 1989), as evidenced by the presence of Jurassic limestones in the McCoy Mountains formation in the southernmost parts of the MFTB; in contrast, it is proposed that the Cretaceous magmatic arc was largely syncompressional and preferentially placed plutons on the miogeoclinal side of the boundary, lowering its viscosity and localizing ductile deformation structures along with high-grade metamorphism to the present-day MFTB area. This hypothesis is further supported by the observation that most Late Cretaceous plutons are peraluminous S-type granitic rocks, which in the classification of Chappell and White (1974) are generally associated with heightened metamorphic grade and deformation relative to the I-type plutons emplaced in the Jurassic. Sometime while the Late Cretaceous plutons were crystallizing, gravitational collapse likely drove localized extension and significant unroofing in the MFTB but not in the CRCCB (see Figures 6 and 7, Boettcher et al 2002, Wells et al 2005, Wells et al 2011), even though I have proposed the CRCCB to be the area of maximal overthickening. The delay in collapse of the CRCCB is
explained by appealing to the northeastward migration of the cratonic boundary
proposed earlier in this section. In Latest Cretaceous times, just after the end of MFTB
compression, the CRCCB likely lay towards the cratonal side of the boundary, which
prevented substantial shallow magmatism and gravitational collapse while collapse and
extension was occurring in the MFTB to the west and south, which lay more towards the
miogeoclinal side of the boundary. The MFTB extension was likely caused by the sweep
of the Cretaceous magmatic arc underneath it, analogous to the Tertiary extension in
the CRCCB. As the S-type magmatic arc shifted the boundary northeastward
underneath the CRCCB, the magmatism was gradually choked off by the Farallon plate,
allowing CRCCB crustal viscosities to remain high enough to prevent collapse. It is also
possible that the extension in the MFTB caused compression in the lower-temperature,
higher-viscosity CRCCB, which likely shifted overburden to the west and east and
helped to prevent CRCCB gravitational collapse. To quickly summarize, the MFTB
escaped significant Tertiary extension because it shed gravitational potential energy
during magmatically facilitated Latest Cretaceous extension; the CRCCB escaped this
Latest Cretaceous extension because the position of the cratonal boundary caused less
magmatic heating there than in the MFTB.

Since the favored model of Tertiary extension is driven by gravitational collapse
of magmatically weakened overthickened crust (as in Armstrong and Ward 1991), it is
presumed that the extremely extended Colorado River core complex belt was, like the
MFTB, also the site of high-grade metamorphism and ductile compressional
deformation. The Tertiary extension has apparently destroyed or obscured all evidence
of this earlier compression in the CRCCB, as well as leaving no Paleozoic strata in
which to observe definitively Cretaceous metamorphic temperatures. The only possible
remnant evidence unearthed in the data compilation is a biotite-facies retrograde
metamorphic event of unknown age reported in the Mohave Mountains east of the
Colorado River (Pike and Hansen, in print).

It has been proposed above that the arcuate shape of the MFTB is due to the
shape of the Jurassic and Cretaceous plutonic arcs, whose shapes in turn were due to
the shape of the cratonal boundary. In support of this, an appeal is made to Burchfiel et
al (1992), where it is proposed that in pre-Sevier orogeny time a large NW-SE trending transform fault truncated the continental margin near the Mojave Desert area (see Figure 9 below). This truncation created a 90° bend in the margin and subduction zone, and lines up extremely well with the observation of largely NE-oriented compression in the southern MFTB and SE-oriented compression in the northern MFTB. The truncation likely left an arcuate shape in the cratonic boundary as well. Further supporting evidence is presented by Hildebrand (2009), where it is noted that, in the Western Canadian Cordillera, the current edge of the North American cratonic crust is just east of the Cordilleran belt of core complexes, and appears to roughly mimic its shape. Finally, note in Figure 1 how the southwest corner of the Colorado Plateau appears to have an arcuate shape much like the MFTB and CRCCB. Therefore it is considered quite reasonable to attribute the location and shape of both the MFTB and the CRCCB to the location and shape of the cratonic boundary.

In summary, the proposed model for the evolution of the MFTB and CRCCB incorporates the shape of the miogeoclinal-cratonic boundary zone as the primary control on the localization of maximal deformation and metamorphism. The main facilitating factor of both deformation and metamorphism was the high-volume peraluminous Late Cretaceous magmatic arc, whose northeastward extent was controlled by the cratonic boundary. The Late Cretaceous arc induced Latest Cretaceous syn- to post-compressional extension in the MFTB perpendicular to the cratonic boundary, but not in the CMEC to the west (where the crust was not thick enough) or in the CRCCB to the east (where the magmatism was not intense enough). Long before the time of closure of the Laramide Magmatic Gap (~22 Ma), the MFTB had shed most of its overburden, leaving the CRCCB as the relatively thickest crustal area. By this time the cratonic boundary had migrated far enough northeastward to allow magmatically triggered gravitational collapse in the CRCCB, causing maximal Late Tertiary extension to be localized there. Minor extension persisted in the Old Woman and Piute Mountains at least until after 19 Ma as evidenced by differential tilting of the Peach Spring Tuff. See Figure 10 below for a crude sketch of this model.
Figure 9: Late Paleozoic Continental Margin Truncation. Figure 7 from Burchfiel et al (1992) showing proposed continental margin truncation, with MFTB location overlaid on top. The key point is how well the bend in the continental margin lines up with the bend in the MFTB, and how the subduction directions match the observed compression directions.
Figure 10: Illustration of Proposed Model for the Evolution of the MFTB and CRCCB. Shown are four cross-sectional sketches for different time periods, from top to bottom: mid-Cretaceous, Late Cretaceous, Early-Mid Tertiary, and Early Miocene. Left of the page is southwest. Red lines bound the MFTB, blue lines bound the CRCCB, and the dashed black line is the cratonal boundary. Red arrows indicate stress state, orange blobs are magma and plutons, and the gray blob is the Farallon Plate. Shifts in the cratonal boundary take place over time, not over depth.
Conclusions

1. Metamorphic temperatures and mid-crustal ductile deformation are both spatially related to the high-volume peraluminous Late Cretaceous magmatic arc. No such relation is observed with the metaluminous Jurassic magmatic arc, which was likely emplaced synextensionally.

2. The Stepladder and Turtle Mountains, separating the MFTB from the CRCCB, cooled at relatively old ages and thus represent a relatively shallow structural level, as do the Ship, Clipper, and Marble Mountains separating the MFTB from the CMEC. These areas likely accommodated differential extensional stresses between the MFTB and the CRCCB and the MFTB and the CMEC respectively in both the Latest Cretaceous and Late Tertiary episodes.

3. The MFTB underwent rapid exhumation due to extension through gravitational collapse in the Latest Cretaceous (approximately from 75 to 70 Ma), shedding most of its overburden and allowing it to escape substantial Late Tertiary extension.

4. The extreme extension of the CRCCB in the Late Tertiary was due to the gravitational collapse of magmatically weakened overthickened crust, and onset was coeval with the closure of the Laramide magmatic gap at 22 Ma and the reintroduction of widespread magmatism to the region.

5. The primary control on the localization of compressional deformation, metamorphism, and later extension was the cratonal-miogeoclinal boundary zone, largely through its influence on emplacement of Late Cretaceous plutons. The boundary in turn was likely controlled by the Late Paleozoic continental margin truncation. A northeastward migration of this boundary from Cretaceous to Tertiary time is inferred.

6. While the northern MFTB was relatively unaffected by Late Tertiary extension compared to the CMEC and the CRCCB, attitudes of the Peach Spring Tuff show that minor extension and uplift continued past 18.6 Ma in that area. In general,
more chaotic rotations and attitudes of the Peach Springs Tuff are shown to correlate with higher degrees of post-18.6 Ma extension.

7. While Neogene strike-slip faulting caused vertical-axis rotations in the Peach Spring Tuff in the Western and Central Mojave, its rotations in the Eastern Mojave and Colorado River region are due to rotation along detachment faults and uplift doming of metamorphic core complexes. Such rotations are not sufficient to explain the \( \sim 90^\circ \) bends in the MFTB and CRCCB, which are instead likely due to the shapes of the cratonic boundary and the Colorado Plateau uplift. However the possibility of unreported higher-magnitude pre-Peach Spring rotations cannot be ruled out.

**Future Study**

In order to support or refute the model proposed for the Mesozoic-Cenozoic evolution of the MFTB and CRCCB, the following areas of study would be illuminating:

1. Seismic refraction studies in the Colorado River area confining the present location of the cratonic boundary;
2. Paleomagnetic studies of post-Cretaceous, pre-Miocene vertical-axis rotations;
3. Definitive age constraints on compressional deformation in the southern MFTB;
4. Further study on the debated transform-fault truncation of the cratonic boundary of Burchfiel and Davis (1975).

**Appendix**

Here all data sources used in the above figures are cited.

**Figure 1**

Figure 1 is adapted in part from Armstrong and Ward (1991, 1993), Fletcher and Karlstrom (1990), Spencer and Reynolds (1990), and Karlstrom et al (1993). Mapping software used for this and all subsequent maps was done with ArcGIS 10.2.2 on a
Figure 2


Figure 3


Figure 4


**Table A: Compiled Pb-U, Ar-Ar, and Zircon and Apatite Fission Dates.** U-Pb, Ar-Ar, and zircon/apatite fission dates used for figures 4 and 6. $T_C$ refers to approximate closure temperature, and numbers in brackets [X] indicate the data source, given in the data cited for Figure 4 above.
The paleomagnetic data and some attitude measurements come from Well and Hillhouse (1989). Most other data is this author’s own work, partially completed under the guidance of Benjamin Klein of the Massachusetts Institute of Technology. Some data in the Piute Mountains comes from data of the Massachusetts Institute of Technology 2014 Field Geology course, contributors to which are noted in the citations for Figure 7 below. Stereonet software used was Stereonet 8 by Rick Allmendinger.

Figure 6

Figure 7
The data in Figure 7 is entirely the result of the Massachusetts Institute of Technology 2014 Field Geology II course. Student contributors were Kelly Kochanski, Allie Anderson, Kaylee Brent, Emily TenCate, and James Pershken of the Massachusetts Institute of Technology, and Paul Southard of the University of Massachusetts at Amherst. Instructors for the course were Oliver Jagoutz, Daniel Sheehan, John Southard (retired), and Claire Bucholz of the Massachusetts Institute of Technology.

Figure 8
Figure 8 is merely a juxtaposition of Figures 3 and 5 and introduces no additional data.

Figure 9
Figure 9 is from Burchfiel et al (1992).

Figure 10
Figure 10 is this author’s own (very rough) interpretation and uses no data.
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