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HEAT AND DETACHMENT IN CORE-COMPLEX EXTENSION; Ivo Lucchitta, U.S. Geological Survey, 2255 N. Gemini Drive, Flagstaff, Arizona 86001

The Basin and Range extensional province of western North America is characterized by normal faulting ranging in age from Miocene to Holocene. Two phases are generally present. The earlier Phase I is characterized by closely spaced faults that have strongly rotated intervening blocks through either curvature of the fault plane (listric faults) or progressive tilting of both faults and blocks like a row of dominos. Nearly horizontal faults are a common feature. Together, these characteristics define the "thin-skin" tectonic style of Anderson (1971). The later Phase II is characterized instead by high-angle normal faults that typically have different trends and wider spacing than those of Phase I. Rotation of intervening blocks is modest to absent. These are the faults that have produced the basins and ranges visible today. Similar faults, entirely devoid of rotation, extend onto the uplifted but little-deformed Colorado Plateau adjoining the extensional province. In the northern Basin and Range Province, faulting of Phase II is still going on today. In the Sonoran and Mojave desert regions of Arizona and southeastern California, by contrast, faulting has ceased entirely (Phase III). Bimodal volcanism, most abundant during Phase I and least abundant during Phase III, is the ubiquitous accompaniment to the extension. Each tectonic phase is accompanied and characterized by a distinctive sequence of co-eval deposits (respectively, Sequence I, II, and III). The contemporaneity and coupling of volcanism and tectonism suggest a genetic link between the two; a similar argument can be advanced for the close succession and partial contemporaneity of the three tectonic phases. In this paper I present the view that the volcanism and the three tectonic phases are the result of a single process acting and evolving through time.

Metamorphic core complexes are currently one of the most hotly debated features of the Basin and Range Province, where they are exposed in a belt parallel to and somewhat west of the western margin of the craton. Many core complexes have three chief components: 1. an upper plate composed of unmetamorphosed to weakly metamorphosed rocks that have failed in brittle fashion and Phase I style. 2. a lower plate composed typically of penetratively lineated cataclastic gneiss that has yielded in ductile fashion and is cut by no Phase I faults and only a few Phase II faults. Lineation becomes weaker upward, and chlorite microbreccia and a silicified zone appear as one approaches 3. the basal detachment fault, a gently undulating and nearly horizontal feature that separates the lower and upper plates and marks a sharp discontinuity in the style of deformation. The fault also marks a sharp and major break in metamorphic grade, except for those complexes whose lower plate exposes sedimentary rocks rather than mylonitic gneiss. Characteristic of many core complexes are small to large gravity-glide sheets embedded in sedimentary and volcanic rocks of the upper plate.

Current knowledge of core complexes leads to conflicting interpretations, the crux of which has to do with age of mylonitization, and the relation between mylonitization, detachment faulting, and brittle extension of the upper plate. One school holds that all these phenomena are contemporaneous, and typically of mid-Tertiary age. According to some, the detachment marks the transition from ductile to brittle behavior, the former occuring variously at middle- or upper-crustal levels. Others feel instead that the detachment has a gentle but constant dip, and now juxtaposes rocks originally formed at different crustal levels. The second main school holds instead that the mylonites and the detachment with associated extension are entirely different in age (latest Cretaceous to early Tertiary versus Miocene), and thus not related genetically.

I propose that the volcanism, the three tectonic phases, and at least part of the lower-plate mylonitization are the result of a single mid-Tertiary thermotectonic process acting and evolving through time. I further propose that these phenomena may be superposed on earlier (Cretaceous) thermotectonic features, and localized by residual heat from the earlier event. These suggestions are based on detailed field work in west-central Arizona, where exposures are good, all three tectonic phases are well-represented, and all three elements of core complexes well-displayed. This area further benefits from the close proximity of the craton (Colorado Plateau) to a core complex, a boundary condition that helps refine and restrict possible interpretations.

A few years ago, it was widely held that the upper plate consisted of a sort of large gravity-glide sheet (for example, Shackelford, 1976). In the Bill Williams area of west-central Arizona, however, it is possible to start in the upper plate directly above the detachment fault, and travel northeastward toward the Colorado Plateau on essentially continuous bedrock exposure. This led Neil Suneson and me to conclude that the upper plate is continuous with basement rocks of the Colorado Plateau, and thus cannot be a gravity-glide sheet (Lucchitta and Suneson, 1981a; Lucchitta and Suneson, 1981b). Penetrative lineation in the lower plate indicates movement either to the northeast or the southwest. The argument given above suggests that the lower plate, a relatively small tectonic element, has moved relatively southwestward from under the craton, and is the active element. Brittle deformation of the upper plate is a passive response to lower-plate movement, as probably is the case with thin-skin tectonics in general. These concepts have been echoed by Wernicke and incorporated in his well-known hypothesis (Wernicke, 1981).

Movement along the detachment fault occurred throughout deposition of the Miocene syntectonic sedimentary and volcanic Sequence I, as shown by dips within the sequence that change gradually from nearly vertical in the lower beds to gently tilted in the upper ones. These dips were produced by rotation of blocks along faults that merge with or are truncated by the detachment, but do not continue beneath it. The sequence of K/Ar radiometric dates helps to document the history of the detachment (Suneson and Lucchitta, 1979; Suneson and Lucchitta, 1983). Basalt near the base of the sequence and 17-18 m.y. old dips steeply, and thus predates most of the movement. Conglomerate interbedded with 12-14 m.y. rhyolites dips only gently, and thus post-dates most faulting. This conglomerate nevertheless is cut by the detachment and listric faults, indicating that the late movements of Phase I were still going on. Concurrently with the faulting, the central area of the core complex was domed up, as indicated by ponding, reversal of drainage, and the emplacement within the Sequence I package of breccias and gravity-glide sheets derived from the uplifted area. Characteristic of this phase are mineralized veins emplaced along the listric faults, and deposits of carbonate, hematite, and copper sulfates, locally with respectable silver and gold concentrations, along the detachment fault. These features suggest hydrothermal activity, which also would explain the breccias (hydrofracturing) and gravity-glide sheets (pore overpressure).

Phase I gradually gave way to the classic basin-range faulting of Phase II, which was accompanied by minor tilting and emplacement of basalts typically 9 to 12 m.y. old. Rhyolites are absent. Both the faults and the basalts occur over much wider areas than the corresponding features of Phase I. Phase II graded into the tectonic quiescence of Phase III, whose early part was marked by the emplacement of small volumes of basalts 5.5-8.5 m.y. old, whereas no volcanic activity occurred later on.

The basalts and rhyolite of Phase I are the volcanic rocks most significant volumetrically, even though they are restricted to a relatively small area. This is especially true of the rhyolites which, however, were emplaced in small centers. Basalts of Phase II are widely distributed, but much smaller in volume than earlier volcanic rocks. Basalts of Phase III are negligible volumetrically.

The picture that emerges is this: (1) intense tectonism, doming, and volcanic activity in a relatively restricted area beginning about 17 m.y. ago, and peaking 12-14 m.y. ago, with emplacement of much rhyolite and accompanied by hydrothermal activity. (2) cessation of rhyolite activity, decrease in volcanism and change in tectonic style, but involvement of a much larger area between about 12 and 9 m.y. ago. Finally, (3) rapid decrease of volcanism and tectonism 8.5-5.1 m.y. ago, and complete quiescence after that.

The coexistence of tectonism and volcanism, and their systematic change with time, suggest that both are the result of thermotectonic processes whose evolution produced the various volcanic and tectonic styles that one sees. This idea is further reinforced by the probable hydrothermal activity, and especially by the fact that the various rhyolite masses, which are small individually and of lower-crust derivation (Suneson and Lucchitta, 1983), could not reach the surface without congealing unless the entire crust was hot. These and other observations are woven into the following model, which is derived from west-central Arizona but probably can be applied to other areas of core-complex or thin-skin tectonics as well.

In mid-Miocene time, probably starting about 17 m.y. ago, parts of west-central Arizona were affected by a thermal pulse associated with northeast-southwest extension. The pulse, which presumably reflects injection of basalts and perhaps of plutonic masses in the lower and middle crust as well, resulted in a steep thermal front migrating upward. Heating was not uniform, so that the surface defined by any isotherm within the front was mildly irregular and showed blister-like domes or welts in the hotter spots. Within the front was a critical surface marking the transition from ductile behavior below to brittle behavior above. This surface was defined primarily by temperature, but also by factors such as pressure and the presence of water. The surface coincided with the detachment fault, given the prevailing extensional regime. When the rhyolites were emplaced 12-14 m.y. ago, at the height of heating, the critical surface was at most a few km beneath the topographic surface in the hottest areas, which were marked by intense deformation along closely spaced Phase I listric faults that had a small radius of curvature and merged with the detachment. The position of the thermal front at this time may well have been controlled and stabilized by interaction with groundwater producing a convective hydrothermal system carrying heat to the topographic surface as fast as it was supplied from below, in the manner of Yellowstone. This mechanism permits elevated temperatures and very steep thermal gradients to exist in a constant position at very shallow depths beneath the surface. The detachment fault, coincident with the critical surface, was the base of the zone of circulation because ductile flow sealed the rocks beneath it. Consequently, materials such as silica and calcite precipitated above or at the detachment, but at no significant depth beneath it.

With waning of the thermal pulse, rhyolite effusion was shut off, the isotherms sank, and the configuration of the critical surface became smoother through equilibration between areas previously relatively hot and those relatively cold. Even though the critical surface was now deeper than it had been previously in the hot spots, it was still shallow enough to be "seen" by faults at the topographic surface, and this over a wide area. The result was the widely distributed, widely spaced basin-range faults, with large radius of curvature (Phase II). In its descent, the critical surface would have generated and left behind many planes of detachment, none, however, as prominent as the upper one owing to much shorter residence times. This is what one sees in the field and in seismic profiles.

Finally, further cooling caused the critical surface to sink to a level unreachable by faults at the topographic surface, so that tectonism ceased and volcanism shut off as well. This is the quiescence of Phase III.

The model as presented accounts quite well for many of the structural and volcanic features of west-central Arizona as they changed through time. It does not account directly for two things: (1) the Cretaceous dates that have been obtained in places, and the relatively high-pressure phases that have been observed locally in rocks of the lower plate; and (2) the presence in other core complexes of major detachments at stratigraphic breaks within sedimentary sequence rather than at the interface between metamorphic and sedimentary rocks. I propose that these questions can be resolved in part by the characteristics of the K/Ar clock, in part by reactivation of older structural and tectonic features.

Several independent criteria suggest that the temperature in lower-plate rocks, below but near the detachment fault was in the range of 320-360° C. According to E.H. McKee (personal communication, 1983), this is the temperature at which the K/Ar clock begins to be reset at geologically significant rates through argon loss. One would therefore expect that varying amounts of "old" argon would be preserved, depending on the Tertiary thermal history of the particular rocks sampled. Considering that Precambrian igneous and metamorphic rocks probably were the protolith for much of the lower-plate mylonite gneiss, one would expect a wide range of K/Ar dates, as a result of contamination by "old" argon. According to this argument, only the youngest K/Ar ages would be significant with regard to the mylonitization event.

Mixing of older (late Cretaceous-early Tertiary) and mid-Tertiary ages can also result from mid-Tertiary resoftening of areas previously affected by late Cretaceous-early Tertiary thermal softening and deformation. Residual heat from the early event would cause such areas to fail preferentially during the Miocene thermal event, resulting in widespread juxtaposition of older and younger ages and deformation features.

Finally, given strong extension, mechanical inhomogeneities such as old near-horizontal faults and contacts between rocks of widely different strengths are likely to produce detachment and discontinuities in structural style above or even far away from a critical surface of the kind discussed above. Even in this case, however, a detachment related to the critical surface should be present at some depth. In fact, the logic of the critical surface dictates that such a detachment should be present everywhere, the only variable being depth and thus the kind and amount of effects visible at the topographic surface. The ultimate and perhaps outrageous consequence is that such a detachment should be present beneath an entire extensional terrane like the Basin and Range Province.

In summary, it is proposed here that the Miocene to Recent structural and volcanic features of the Basin and Range Province can be explained by a single thermotectonic process acting through time. This process consists of a thermal pulse resulting in a high-temperature regime that includes a steep thermal front moving first up toward the topographic surface, then down owing to cooling induced by a combination of convection and conduction. Within the front is a PT condition defining a critical surface that separates brittle from ductile behavior, and is marked by a nearly horizontal detachment fault. The most prominent and structurally highest position of the detachment results from interaction between the critical surface and a hydrothermal system near the topographic surface. These various features can be superposed on older ones through thermal remobilization or structural reactivation.

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