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ABSTRACT

The early Tertiary Orocopia-Chocolate fault in southern California was originally interpreted as a southwest-directed thrust assisting tectonic underplating of the Orocopia Schist beneath North America during subduction. However, the predicted thrusting direction is opposite to that observed for the fault. Although this problem appeared to be resolved by interpreting the Orocopia-Chocolate fault as a normal fault, this alternative is inconsistent with the fact that neither an early Tertiary breakaway nor early Tertiary upper plate extension has been observed. I suggest that the fault was a northeast-directed passive-roof thrust that linked with a southwest-directed basal décollement (the Vincent thrust) during early Tertiary flat subduction of the Farallon plate beneath North America. This model may also explain a similar structural relationship between the Main Central thrust and the South Tibet detachment fault in the Himalaya.

Keywords: passive roof thrust, fault-bend fold, Pelona, Orocopia, exhumation, erosion.

INTRODUCTION

The origin of the Vincent and Orocopia-Chocolate faults in southern California has been long debated. These faults juxtapose the Pelona-Orocopia Schist below and the North American cratonal rocks above (Fig. 1). The Pelona-Orocopia Schist is thought to have derived either from a mélange complex or part of a forearc basin (Barth and Schneiderman, 1996; Jacobson et al., 1996). Although the Vincent fault is clearly a ductile thrust (Ehlig, 1981; Jacobson, 1997), the origin of the Orocopia-Chocolate fault remains unclear. Kinematic studies on this fault show a top-to-the-northeast sense of shear (Simpson, 1990; Jacobson and Dawson, 1995), opposite to that predicted by the northeastward subduction model of Burchfiel and Davis (1981). This led to the suggestions that the Orocopia-Chocolate fault was either a suture (Haxel and Dillon, 1978) or a northeast-directed thrust (Crowell, 1981), but both possibilities were ruled out by later studies (Tosdal, 1990; Jacobson and Dawson, 1995). The apparent discrepancy between the northeastward-subduction model and the observed fault kinematics may be resolved if the Orocopia-Chocolate fault is considered to be an east-directed detachment fault (Jacobson et al., 1996). However, as shown herein, this alternative model is also inconsistent with the regional geology.

The $^{40}Ar/^{39}Ar$ thermochronology indicates that the Vincent thrust was active at 60–55 Ma and its motion stopped after 50 Ma (Grove and Lovera, 1996; Jacobson, 1990). The Orocopia-Chocolate fault in the Orocopia Mountains was probably active between 41 and 52 Ma, as indicated by cooling ages of muscovites from the footwall (Jacobson, 1990). In the Gavilan Hills, $^{40}Ar/^{39}Ar$ muscovite and biotite ages show that the hanging wall and footwall of the early Tertiary Orocopia-Chocolate fault ceased its motion ca. 48 Ma (Jacobson et al., 2001). Rapid cooling from ~350 °C to 150 °C at 30–24 Ma in the hanging wall of the Orocopia-Chocolate fault in the Gavilan Hills was attributed to later normal faulting (Jacobson et al., 2001), but could also be caused by middle Tertiary igneous activities in the region (Sherrod and Tosdal, 1991).

Jacobson et al.'s (1996) detachment-fault model can be tested by examining the original geometry of the Vincent and Orocopia-Chocolate faults, because it predicts the existence of an early Tertiary breakaway and significant hanging-wall extension in the early Tertiary (Fig. 2A). Palinspastic reconstruction and observations made in the region show no evidence for either the presence of an early Tertiary breakaway or early Tertiary upper plate

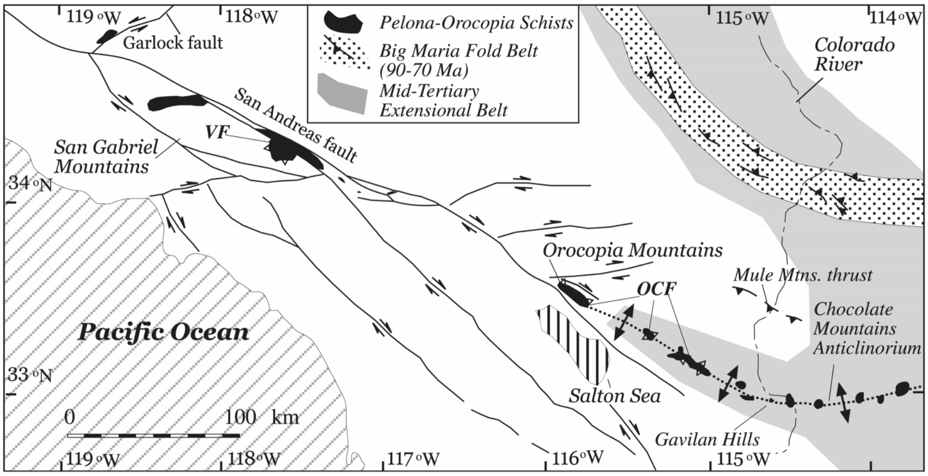

Figure 1. Tectonic map of southern California, after Law et al. (2001), Tosdal (1990), and Spencer and Reynolds (1990). VF—Vincent fault, OCF—Orocopia-Chocolate fault.

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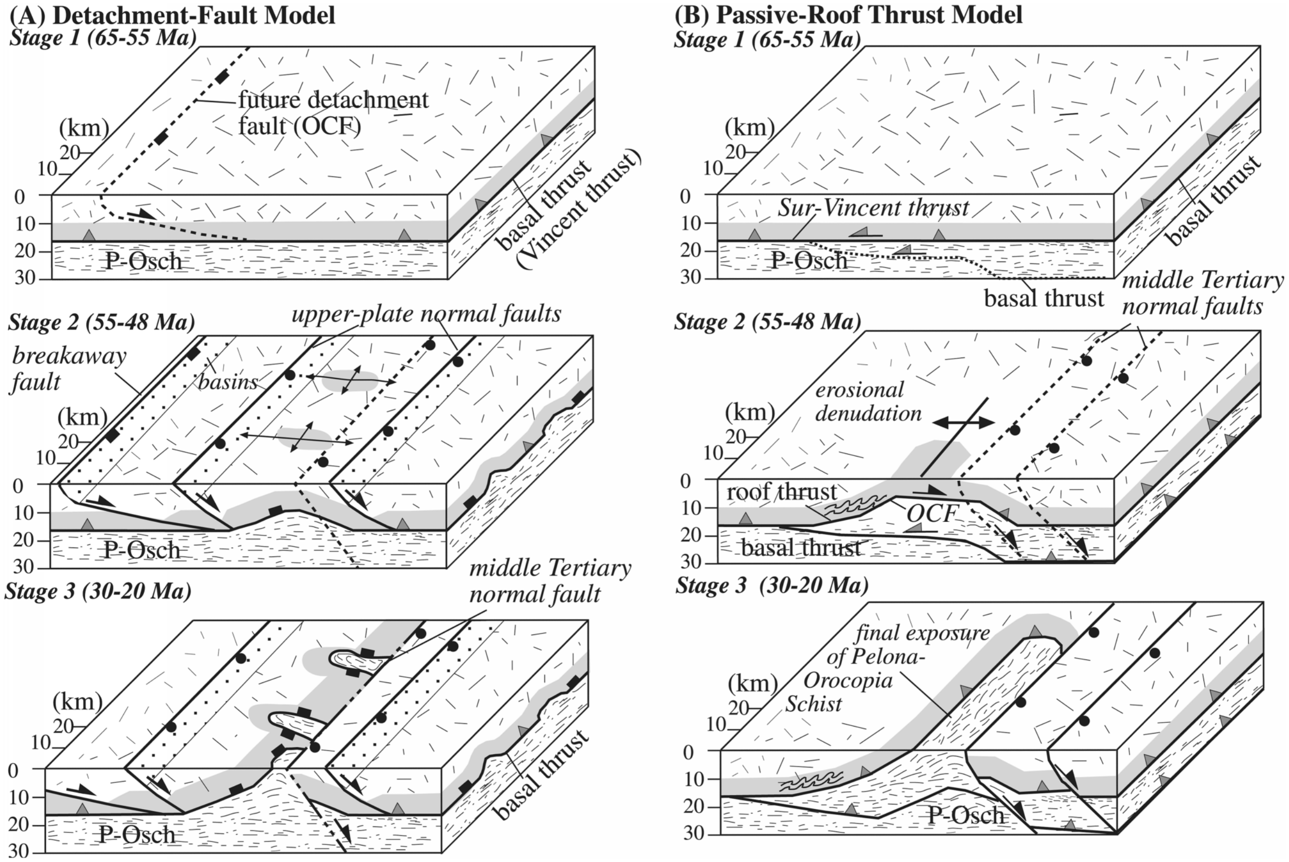

Figure 2. Models for origin of Vincent and Orocopia-Chocolate faults. A: Detachment-fault model. B: Passive-roof thrust model. P-Osch—Pelona-Orocopia Schist, VF—Vincent fault, OCF—Orocopia-Chocolate fault.

extension in the region (Ehlig, 1981; Richard, 1993) (Fig. 3).

PASSIVE-ROOF THRUST MODEL

The Pelona-Orocopia Schist is exposed along the axial zone of the >30-km-wide and 200-km-long Chocolate Mountains anticlinorium (Figs. 1 and 3) (Richard, 1993). It trends east and is defined by the Pelona-Orocopia Schist in the core and Precambrian gneiss, Jurassic metasedimentary rocks, and Jurassic to Late Cretaceous plutonic rocks along its two limbs (Haxel et al., 1985). The involvement of Late Cretaceous plutons suggests that the anticlinorium formed in the Cenozoic. The pre-Cenozoic crystalline and metasedimentary rocks in the hanging wall of the Orocopia-Chocolate fault along the crest of the anticlinorium are depositionally overlain by Oligocene-Miocene volcanic and clastic sedimentary rocks (Haxel et al., 1985; Richard, 1993). The lack of early Tertiary sedimentation on top of the anticlinorium implies, but does not require, that the region was a structural high, possibly resulted from the formation of the anticlinorium in the early Tertiary. The anticlinorium was cut by mid-Tertiary normal faults in the Chocolate Mountains (Sherrod and Tosdal, 1991), suggesting that it formed in the early Tertiary. The broad Chocolate Mountains antiform was clearly superposed by late Tertiary folding, as indicated by short wavelength folds involving Miocene strata in the eastern Orocopia Mountains (Crowell, 1975; Law et al., 2001).

The development of the anticlinorium may have been associated with marine sedimentation of the Paleocene (ca. 66–57 Ma) San Francisquito Formation in the San Gabriel Mountains (Ehlig, 1981; Grove, 1993) and the

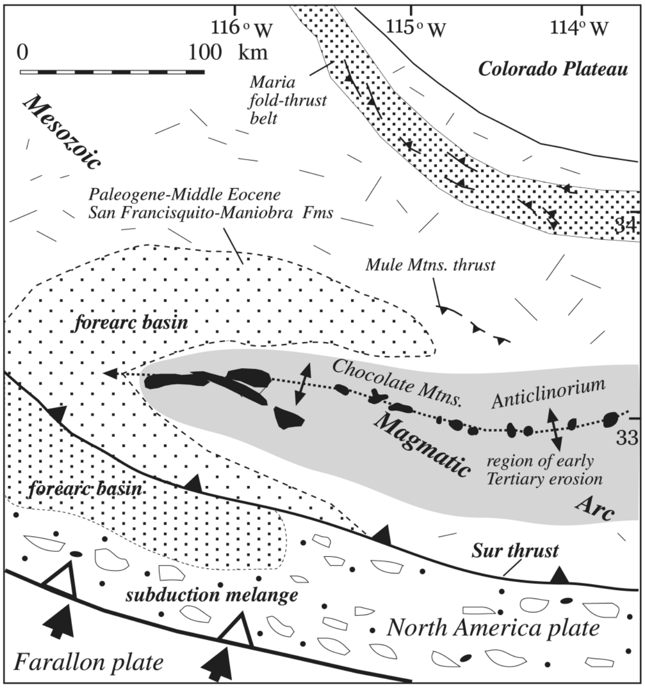

Figure 3. Early Tertiary paleogeologic map of southern California and western Arizona after removing middle and late Tertiary extension and strike-slip faulting (Richard, 1993). Map combines reconstructions of Ehlig (1981) and Hall (1991) with consideration of Powell's (1993) estimates of rotation for San Gabriel and Orocopia-Chocolate. Note that Pelona-Orocopia Schist was not exposed at this time (Ehlig, 1981).

lower to middle Eocene (ca. 57–43 Ma) Maniobra Formation in the eastern Orocopia Mountains (Fig. 2; Crowell, 1975). The two formations could have been originally part of a forearc basin along the western edge of North America that was locally partitioned by the anticlinorium into the western and eastern subbasins (Fig. 3). The eastern subbasin was eventually filled up above sea level between late Eocene and early Oligocene time, as represented by the sedimentation of the Oligocene-Miocene Diligencia Formation above the Maniobra Formation (Crowell, 1975).

If development of the anticlinorium was related to early Tertiary deep-seated faulting, the associated fault must have the same age, length, and trend. The only structure with a comparable size and age is the Vincent-Orocopia-Chocolate fault system. Its spatial relationship to the antiform (Fig. 3) suggests that the two could have been kinematically related in a fault-bend fold system (Fig. 2B). That is, the Orocopia-Chocolate fault is a passive roof thrust, which began as a southwest-directed thrust and was reactivated later as a northeast-directed roof thrust. The Vincent thrust could be both a part of the basal thrust and the northeast-directed passive-roof thrust on the forelimb of the fault-bend fold. In this case, the passive roof thrust (Orocopia-Chocolate fault) was connected with a southwest-directed décollement (Vincent thrust) along which the forearc mélange complex and possibly part of the forearc basin were subducted (Fig. 4).

The structural model proposed here requires exhumation of the Pelona-Orocopia Schist by erosion during contraction (Fig. 2B). Apatite fission-track and (U-Th)/He analyses of rocks in the hanging wall of the Vincent thrust show that the most dominant long-wavelength (>40 km) signature is a cooling event that occurred between 60 and 40 Ma (Blythe et al., 2000). The similarity of apatite fission-track and (U-Th)/He ages to muscovite and K-feldspar ages in the hanging wall of the Vincent thrust (Jacobson, 1990; Grove and Lovera, 1996; Blythe et al., 2000) suggests that cooling from ~350 °C to ~100–60 °C was relatively rapid between ca. 60 and 50 Ma. This result implies that a >10-km-thick crustal section was removed during early Tertiary thrusting along the Vincent thrust. Erosional denudation has been shown to be an efficient way of exhuming rocks in contractional orogenic belts (Schneider et al., 1999; Yin and Nie, 1993).

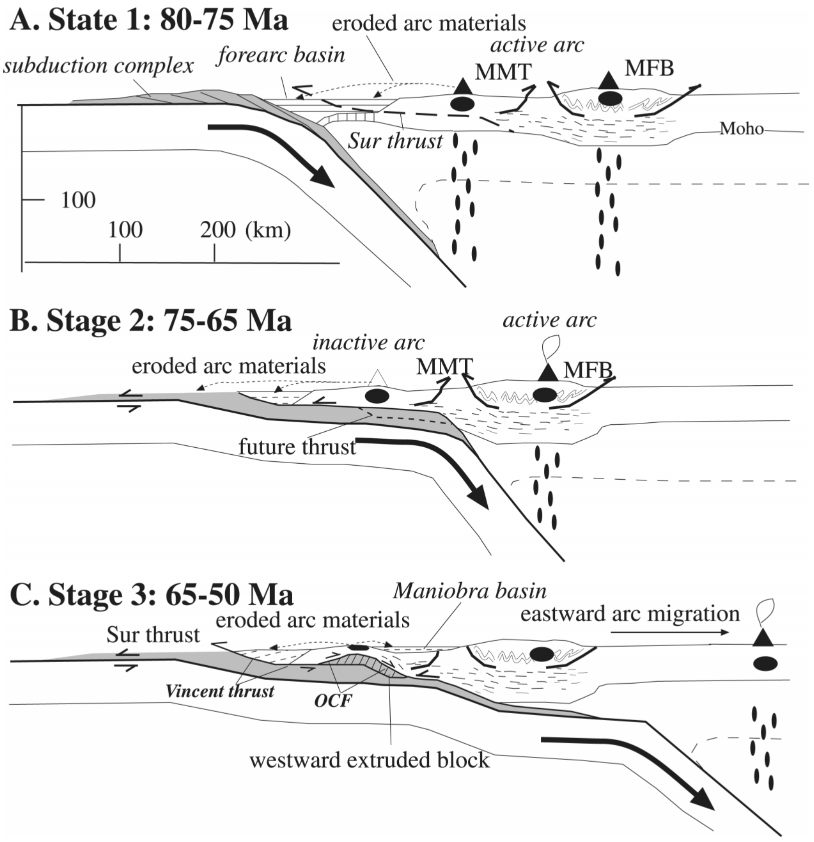

Figure 4. Emplacement history of Pelona-Orocopia Schist. A: Between 85 and 70 Ma, Big Maria fold belt (MFB) and Mule Mountains thrust (MMT) developed, causing sediments to be shed westward from arc. B: Between 70 and 65 Ma, forearc-basin sediments and mélange complex were underthrust beneath North America during flat subduction of Farallon plate. C: Between 65 and 50 Ma, fault-bend fold was generated above new east-dipping thrust ramp and was extruded westward. Extruded thrust sheet is bounded at top by Orocopia-Chocolate fault (OCF) acting as a passive roof thrust.

DISCUSSION

Passive roof thrusts are common in foreland thrust duplexes (Banks and Warburton, 1986) or fault-bend folds (e.g., Yin and Oertel, 1993). Clearly, a rigorous application of the flexural-slip folding mechanism to quantify the geometry of the inferred fault-bend fold may not be appropriate, because crystal-plastic deformation was involved when the Vincent and Orocopia-Chocolate faults developed (Simpson, 1990). Nevertheless, the model shown in Figures 3B and 4 requires only that deformation occurred along discrete shear zones with a flat-ramp geometry. Both the variation of schist composition from graywacke to mafic-schist layers (e.g., Ehlig, 1981; Jacobson and Dawson, 1995) and the presence of foliation surfaces could have provided the mechanical anisotropy needed for the development of the inferred fault-bend fold system. Thrusts in plastically deformed crystalline terranes, such as the Main Central thrust system in the Himalaya, have been shown to follow the geometry of a fault-bend fold (e.g., Johnson et al., 2001).

Westward extrusion of the thrust sheet below the Orocopia-Chocolate fault (Figs. 3B and 4) could have been caused by westward spreading of the ductile lower crust from an already thickened region beneath the Big Maria fold belt (~60 km; Spencer and Reynolds, 1990) (Fig. 4). It is also possible that the water-rich schist was significantly lighter and rose along the subduction zone to initiate motion on the proposed roof thrust (e.g., Chemenda et al., 2000).

Retrograde metamorphism in the lower plate schist has been cited as major evidence for the interpretation that the Orocopia-Chocolate fault is a detachment fault (Jacobson and Dawson, 1995). However, retrograde metamorphism could have occurred during westward extrusion of the fault-bend fold if erosion rates kept pace with rock uplift. The fluids derived from prograde metamorphism of the schist could have been transported upward along the roof fault, causing retrograde metamorphism. This explanation requires retrograde metamorphism to be synkinematic with respect to motion on the Orocopia-Chocolate fault. In this regard, there is no difference in terms of the timing of retrograde metamorphism between the passive-roof–fault model and the detachment-fault model. Alternatively, the retrograde metamorphism in the upper and lower plates of the Orocopia-Chocolate fault could have been induced by younger normal faults (Fig. 2B). This scenario predicts that retrograde metamorphism postdates motion on the Orocopia-Chocolate fault.

Although the roof thrust in my proposed model appears to be locally normal slip (i.e., on the back limb of the fault-bend fold) (Fig. 4C), its role is to accommodate horizontal shortening and vertical thickening rather than crustal thinning as predicted by the detachment-fault model. The South Tibet detachment fault of Burchfiel et al. (1992) may have played a similar role to the Orocopia-Chocolate fault, assisting crustal thickening of the Himalaya. That is, the High Himalayan crystalline terrane was once a fault-bend-fold thrust sheet moving along a gentle basal thrust (Main Central thrust). The thrust sheet originated in the lower crust due to southward push by spreading of the thickened lower Tibetan crust, causing the initiation of its roof fault, the South Tibet detachment system. This possibility may be tested in the future near the Himalayan syntaxes where the connection between the Main Central thrust and the South Tibet detachment may still be preserved. It is interesting to note that the tectonic settings for the Himalayan collisional belt and the Pelona-Orocopia Schist are remarkably similar, both involving flat subduction.

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