Role of crustal thickening and extensional collapse in the tectonic evolution of the Sevier-Laramide orogeny, western United States

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ABSTRACT

The effects of crustal thickening and extensional collapse of continental crust, combined with variations in plate-convergence forces, provide a coherent explanation for evolution of the Cretaceous–early Tertiary Sevier-Laramide orogeny. Crustal thickening of the Sevier-Laramide hinterland region was triggered by the combination of compressive plate-convergence forces and subduction-induced conductive heating of the crust. Eastward progradation of the locus of Sevier-Laramide deformation through time reflects the progressive widening of the region of crustal thickening. The region of maximum crustal thickening migrated outward until about 80 to 75 Ma, when it encountered excessively strong lithosphere of the Colorado Plateau. The locus of deformation was then transmitted laterally across both a hinterland that had attained maximum crustal thickness and the rigid Colorado Plateau, into the Laramide Rocky Mountain foreland. An episode of vigorous extensional collapse of orogenically thickened crust affected the southern Cordillera between about 75 and 35 Ma. Early Tertiary waning of plate-convergence rates and continued subduction-induced conductive heating of thickened crust allowed extensional collapse along the southern Cordillera region to drive the Colorado Plateau block northward. The result was the late Laramide phase of Rocky Mountain foreland deformation. Because of this, compressive deformation in the central and southern Laramide Rocky Mountain region continued through Eocene time, rather than ceasing at 56 Ma, as it did in the northern Cordillera.

INTRODUCTION

The Sevier-Laramide orogeny of the western U.S. Cordillera persisted from Cretaceous to early Tertiary time (Fig. 1; Cross, 1986; Coney, 1987). Early stages of deformation (120–80 Ma) were characterized by development of a magmatic arc and foreland fold-thrust belts (mainly the Sevier fold-thrust belt). Beginning at about 80 to 75 Ma, the locus of deformation began to prograde eastward into the Laramide Rocky Mountain foreland. There, extensive deformation began in the latest Cretaceous and ended at about 56 Ma in the northern Cordillera and about 35 Ma in the southern and central Cordillera (Dickinson et al., 1988; Cather and Chapin, 1990). Laramide Rocky Mountain foreland deformation has been modeled as a multistage event (early and late Laramide) on the basis of space-time variations in structural patterns (Chapin and Cather, 1983; Cather and Chapin, 1990). Differences in early and late Laramide strain patterns are attributed to changes in the sense of rotation of the rigid Colorado Plateau block (Fig. 1).

Variations in modes, geometry, and rates of subduction between the North American plate and various underriding oceanic plates (Farallon, Vancouver, and Kula) have been considered the major tectonic controls for evolution of the Sevier-Laramide orogeny (Engebretson et al., 1985; Cross, 1986; Coney, 1987; Stock and Molnar, 1988). In this paper, I propose, on the basis of crustal thickening and gravitationally driven extensional collapse, an additional major tectonic control for the evolution of the Sevier-Laramide orogeny.

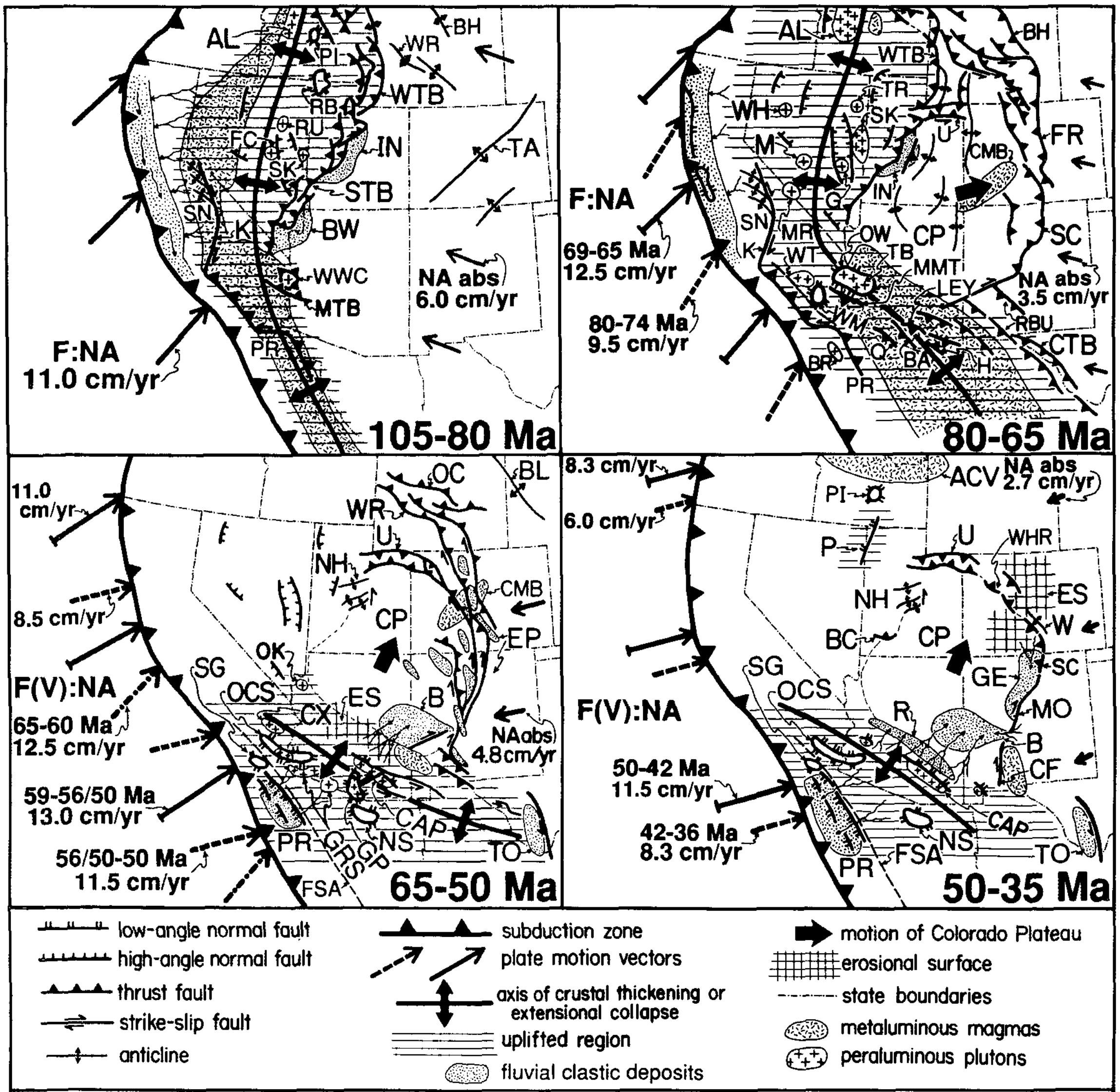
CRUSTAL THICKENING AND EXTENSIONAL COLLAPSE

In a Cordilleran tectonic setting, deep-seated conductive heating of orogenic crust induced by subduction progressively decreases crustal strength (Barton, 1990). Compressive plate-convergence forces may then drive crustal thickening and topographic uplift by telescoping the thermally weakened zone (Coney, 1987; Barton, 1990). Once maximum elevation (depending on crustal strength) is attained, the uplifted region may continue to grow laterally by overthrusting and thickening of crust of the adjacent lowlands (Dewey, 1988; Molnar and Lyon-Caen, 1988). Uplifted plateau regions may act as efficient stress guides by transmitting horizontally applied stresses from one flank to the other. Plateau regions that stand higher than about 3 km in topographic relief also have the gravitational potential to collapse and spread laterally (Dewey, 1988). A decrease in boundary forces (e.g., induced by a minor slowing in plate-convergence rate), coupled with a decrease in strength of thickened crust, may allow gravitationally induced extensional collapse of the elevated region to drive foreland fold-thrust deformation (Dewey, 1988; Molnar and Lyon-Caen, 1988). Extensional collapse of an orogen may assist in driving foreland thrusting as long as it remains topographically higher than the zone of thrusting. Kinematic slip directions of foreland structures are then controlled by varying combinations of gravitational body forces and plate-convergence forces (Dewey, 1988; Molnar and Lyon-Caen, 1988).

Thickening of continental crust along the current Basin and Range province during the Sevier-Laramide orogeny has been proposed to have led to Cenozoic extensional collapse (Coney, 1987; Wernicke et al., 1987). Analogy with the currently active Andean Cordillera of South America, however, indicates coeval development of hinterland crustal thickening, uplift and extensional collapse, and deformation along flanking foreland fold-thrust belts (Dewey, 1988; Molnar and Lyon-Caen, 1988). An increasing body of data indicates that continental crust thickened during the Sevier-Laramide orogeny was also uplifted and extensionally deformed coeval with foreland fold-thrust events. Hodges and Walker (1990) have inferred that along the current Basin and Range province, extensional collapse *during* the Sevier-Laramide orogeny locally equaled, or even exceeded, the amount of Cenozoic extensional deformation.

TECTONIC SCENARIO FOR EVOLUTION OF THE SEVIER-LARAMIDE OROGENY

Along the western U.S. Cordillera, arc magmatism and fold-thrust deformation began ca. 120 Ma (for references see Chen and Moore, 1982; Heller et al., 1986; Vandervoort and Schmitt, 1990). This pattern of deformation intensified by ca. 105 to 100 Ma, owing to a moderate increase in Farallon–North American plate-convergence rate (see Engebretson et al., 1985). The result was a slight eastward shift and enhanced vigor of arc magmatism (Chen and Moore, 1982) and an increase in subduction-induced conductive heating of hinterland crust (see Barton, 1990). These factors reduced lithospheric strength, allowing plate-convergence stresses to more effectively thicken hinterland crust. This led to the beginning of major deformation along the Sevier fold-thrust belt (Fig. 1, 105–80 Ma; see Heller et al., 1986). The culmination of crustal heating and thickening



ACV-Absaroka & Challis volcanics
AL -Atlanta lobe of Idaho batholith
B -Baca Formation
BA -Baboquivari thrust fault
BC -thrust fault in Bryce Canyon area
BH -Big Horn Mountains
BL -Black Hills
BR -Borrego pluton
BW -Baseline & Willow Tank Formations
CAP-Santa Catalina, Rincon, Tortolita, & Picacho Mountains
CF -Caballo & Fra Cristobal Mountains
CMB-Colorado Mineral Belt
CP -Colorado Plateau
CTB-Chihuahua fold-thrust belt
CX -Coxcomb pluton
EP -Echo Park-type basins
ES -Eocene erosional surface
FC -Fish Creek Range
FR -Front Range
G -Grant Range
GE -Galisteo & El Rito Formations
GP -Gu Chuapo, Pan Tak, & Presumidio Peak plutons
GRS-Gunnery Range & Senita plutons
H -Huachuca Mountains
IN -Indianola Formation
K -Kern Canyon fault
LEY-Little Rincon, Edgar, & Youtcy thrust faults
M -Manhattan pluton
MMT-Mule Mountain thrust fault
MO -Montosa fault
MR -Mineral Ridge pluton
MTB-Maria fold-thrust belt
NH -folded North Horn Formation
NS -northern Sonora, Mexico
OC -Owl Creek Mountains
OCS-Orocopia, Chocolate, & Sortan faults
OK -OK pluton
OW -Old Woman Mountains
P -Pilot Mountains
PI -Pioneer Mountains
PR -Peninsula Ranges
Q -Quitobaquito thrust fault
R -Mogollon Rim & Eager Formations, & Rose Well & Frazier Well gravels
RB -Raft River & Black Mountains
RBU-Rio Grande & Burro Uplifts
RU -Ruby Mountains
SC -Sangre de Cristo Range
SG -San Gabriel Mountains
SK -Snake Range & Kern Mountains
SN -Sierra Nevada
STB-Sevier fold-thrust belt
TA -Transcontinental Arch
TB -Tank Pass & Browns Canyon plutons
TO -Tornillo Basin
TR -Toana Range
U -Uinta Mountains
W -Wet Mountains
WH -plutons in West Humboldt Range
WHR-White River Mountains
WM -western Mojave region
WR -Wind River Mountains
WT -White Tank pluton
WTB -Wyoming fold-thrust belt
WWC-Whipple Wash & Chemehuevi plutons

Figure 1. Sequential time-slice diagrams of western U.S. Cordillera illustrating Cretaceous to Eocene tectonic evolution of Sevier-Laramide orogeny. Relative plate-convergence vectors 74 Ma and older and absolute plate motion vectors are from data of Engebretson et al. (1985). Relative plate-convergence vectors 69 Ma and younger are from data of Stock and Molnar (1988). References for most of data are given in text; those not given in text are found in Chapin and Cather (1983), Heller et al. (1986), Keith and Wilt (1986), Cross (1986), Dickinson et al. (1988), Lundin (1989, for thrust fault in Bryce Canyon area), Miller and Gans (1989), S. B. Keith (1989, personal commun., for Manhattan pluton and plutons in West Humboldt Range), May (1989), Barton (1990), Bykerk-Kauffman (1990), Foster et al. (1990), Hodges and Walker (1990, for western Mojave region), Harrison and Chapin (1990, for boundary fault of Caballo and Fra Cristobal mountains), Hayden (1991, for Montosa fault), and Gehrels and Smith (1991, for Little Rincon thrust fault). FSA refers to future site of San Andreas transform fault. West of dashed line, San Gabriel Mountains and Peninsular Ranges are palinspastically restored to accommodate late Tertiary movement on San Andreas transform fault (see May, 1989). F(V):NA and NA abs refer to relative motion between Farallon (Vancouver) and North American plates and absolute North American plate motion, respectively.

in the Great Basin hinterland and deformation along the Sevier fold-thrust belt is reflected by the peak of hinterland metamorphism that occurred between 90 and 70 Ma. In addition, strongly peraluminous plutons, indicative of a rising geothermal gradient, crustal thickening, and more thorough anatexis of continental crust, were intruded into the Great Basin region mainly between 90 and 70 Ma (Miller and Gans, 1989; Barton, 1990).

Local Late Cretaceous extensional collapse also took place in the Great Basin hinterland. Large-magnitude extensional strains occurred along low-angle faults in the Raft River and Black Pine mountains between 90 and 82 Ma (Wells et al., 1990). Additional normal faults of Late Cretaceous–early Tertiary age are present throughout the Great Basin (Hose and Danes, 1973; Loring, 1976; Allmendinger and Jordan, 1984; Vandervoort and Schmitt, 1990).

A similar but more diachronous pattern of metaluminous to peraluminous arc magmatism, crustal thickening, and fold-thrust deformation progressed eastward across the southern Cordillera between 90 and 65 Ma. This was followed by rapid isostatic uplift, cooling, widespread erosional denudation, and intrusion of strongly peraluminous plutons between 75 and 35 Ma (see Keith and Wilt, 1986; Todd et al., 1988; Jacobson, 1990; Spencer and Reynolds, 1990; Foster et al., 1990; Goodwin and Haxel, 1990). Extensional features related to this 75 to 35 Ma event include the following.

1. Low-angle normal faulting and uplift occurred along the Peninsular Ranges of southwestern California in the early Tertiary (Todd et al., 1988).

2. Top-to-the-southwest, normal-displacement shear deformation occurred in the Old Woman Mountains between 73 and 68 Ma (Foster et al., 1990).

3. Isotopic cooling dates from the Little Maria–Big Maria Mountains suggest that extensional collapse occurred here after 70 Ma (Ballard, 1990).

4. Dike trends in the southern Cordillera indicate that north-northwest–south-southeast crustal extension occurred throughout this region between 75 and 50 Ma (for references see Chapin and Cather, 1983; Keith and Wilt, 1986). Paleocene–early Eocene age dikes in the Baboquivari Mountains of south-central Arizona reveal a local pattern of northeast-southwest crustal extension (Goodwin and Haxel, 1990).

5. Late-stage deformation along parts of the Late Cretaceous Orocopia–Chocolate Mountain thrust fault system is thought to be top-to-the northeast extension formed during rapid uplift of the underlying Orocopia-Pelona schist (Jacobson, 1990). On the basis of cooling ages, this normal-slip deformation may be entirely or partly Eocene in age (Jacobson, 1990). Extensional deformation also occurred along the nearby top-to-the-northeast, normal-displacement Sortan fault during Paleocene and/or Eocene time (see Jacobson, 1990).

6. A complex phase of early Tertiary deformation occurred along the Santa Catalina–Rincon–Tortolita–Picacho metamorphic core complex zone (see Keith and Wilt, 1986; Rehrig, 1986; Guerin et al., 1990; Bykerk-Kauffman, 1990). Kinematic indicators in lineated mylonites related to this event reveal a multidirectional strain pattern with top-to-the west, southwest, northeast, and east deformation. Top-to-the-east Eocene fabrics found in the Santa Catalina Mountains are associated with younger over older faulting and tectonic thinning of strata (Bykerk-Kauffman, 1990). The origin of all these fabrics is unclear, but some may be related to extensional deformation (see Guerin et al., 1990; Bykerk-Kauffman, 1990).

7. Lineated mylonites found in northern Sonora, Mexico, record an early Tertiary extensional deformation event (Anderson et al., 1980).

The early Tertiary Mogollon Rim, Eagar, and Baca Formations of New Mexico and Arizona were deposited by an extensive braid-plain system shed northeastward off widespread topographic highlands of the southern Cordillera (Cather and Johnson, 1986; Potochnik, 1989).

DISCUSSION

The events outlined above indicate that a high-standing plateau developed along the Great Basin hinterland and southern Cordillera region during Late Cretaceous crustal thickening (Coney, 1987; Molnar and Lyon-Caen, 1988; Vandervoort and Schmitt, 1990; Wells et al., 1990). Episodes of extensional collapse of this elevated plateau occurred between 90 and 60 Ma along the Great Basin and 75 and 35 Ma in the southern Cordillera. Plateau collapse occurred after a critical elevation or geothermal gradient had been reached and/or after a decrease occurred in confining pressure exerted by plate-convergence forces. The seemingly confusing, multidirectional kinematic slip pattern of early Tertiary extensional structures in the southern Cordillera (see Bykerk-Kauffman, 1990; Guerin et al., 1990; Goodwin and Haxel, 1990) is characteristic of extensional collapse deformation (e.g., see Fig. 2 of Ratschbacher et al., 1989). Widespread preservation of Paleozoic-Mesozoic strata, combined with the lack of evidence for regional, large-magnitude extensional deformation in the Great Basin hinterland, as compared to the southern Cordillera, implies that plateau elevations in the Great Basin hinterland were much lower than those in the southern Cordillera.

The space-time pattern of crustal thickening and extensional collapse in the Great Basin and southern Cordillera region may relate directly to the structural evolution of the Laramide Rocky Mountain foreland. The sense of rotation of the Colorado Plateau block varied in accordance with space-time differences in the applied regional stress pattern. Eastward progradation of the locus of Sevier-Laramide deformation through time reflects the progressive widening of the region of maximum crustal thickening and uplift. The elevated Great Basin hinterland plateau continued to migrate outward until 80 to 75 Ma, when it encountered excessively strong lithosphere of the Colorado Plateau. The locus of deformation was then transmitted laterally, across both a hinterland plateau that had attained its maximum crustal thickness and rigid Colorado Plateau crust, into the Laramide Rocky Mountain foreland. Transmission of plate-convergence stresses across thickened hinterland crust caused the Colorado Plateau block to be driven east-northeastward, resulting in the early phase of Laramide Rocky Mountain foreland deformation (Fig. 1; 80–65 Ma). This tectonic scenario is similar to the deformation pattern in northwestern Tibet, where strong lithosphere of the Tarim basin (Colorado Plateau analogue) is transmitting plate-convergence stress from Tibet to the Tien Shan Mountains (Rocky Mountain analogue; Molnar and Lyon-Caen, 1988). This mechanism allowed plate-convergence stresses, generated by low-angle or flat subduction (e.g., Cross, 1986; Coney, 1987), to be transmitted into the Laramide Rocky Mountain foreland. Therefore, it is not necessary to invoke Cordilleran-wide flat subduction and generation of tractional forces along the base of Colorado Plateau and Rocky Mountain foreland lithosphere as an explanation for Laramide foreland deformation (e.g., Cross, 1986). Rather, flat subduction may have been more restricted in areal extent and perhaps occurred only beneath the Sevier-Laramide hinterland region (see Molnar and Lyon-Caen, 1988).

Twice during early Tertiary time, Farallon (Vancouver)–North American plate convergence slowed significantly. This occurred between 56 and 50 Ma and at 42 Ma (Stock and Molnar, 1988). The initial slowing in plate-convergence rate is linked to the 56 Ma cessation of Laramide Rocky Mountain foreland deformation in the northern Cordillera. Compressive deformation continued, however, in the central and southern Rocky Mountain foreland after these slowdowns. It is hypothesized that early Tertiary extensional collapse of the southern Cordillera drove the Colorado Plateau north-northeastward, resulting in the late phase of Laramide Rocky Mountain foreland deformation (Fig. 1; 65–50 Ma and 50–35 Ma). This type of deformation was allowed by (1) the release of confining pressure on the elevated plateau of the southern Cordillera as a result of slowdowns in relative plate convergence rates, and (2) the lowering of crustal strength owing to continued conductive heating of the crust induced by subduction. Heating of the southern Cordillera crust is indicated by the strongly peraluminous nature of early Tertiary plutons found in this area (see Keith and Wilt, 1986; analogue of Barton, 1990, model for the Great Basin). A gradual reduction in strain rates in the southern and central Rocky Mountain foreland during the late Eocene (Fig. 1, 50–35 Ma; see Cather and Chapin, 1990) reflects the continued waning of both plate-convergence and extensional collapse rates.

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