Cenozoic slab windows beneath the western United States

ABSTRACT

The weak lithosphere and high gravitational PE responsible for the current broadly distributed western U.S. deformation are consequences of flat-slab subduction during the Laramide orogeny and the subsequent removal of this slab. Flat-slab subduction cooled and hydrated the base of western U.S. lithosphere and slab removal brought asthenosphere in contact with this conditioned lithosphere, causing a phase of intense magmatism that propagated in two sweeps across the western U.S. Each sweep represents the opening of a slab-free window.

The southern window is associated with the northern propagation of the Mendocino fracture zone during development of the transform margin. This is the well-known window of Dickinson and Snyder (1979), although magmatism also occurred east of this window, in area occupied by very young Farallon slab.

The northern window initiated north of the area underlain by flat slab when the Siletzia terrain accreted to the margin of the Pacific Northwest ~48 Ma. Subsequent termination of Challis arc magmatism in Idaho and initiation of Cascade arc magmatism evidences a westward jump in subduction to Cascadia and establishment of a more typically dipping slab there. A tear is required between the normal-dip and flat segments of subducted slab that extends east from the southern point of accretion in southern Oregon. The northern window opened to the east as subducted Farallon slab beneath Idaho and Montana continued moving eastward, and it opened to the south across the

Great Basin as the torn northern margin of the flat portion of the Farallon slab propagated southward.

INTRODUCTION

In this paper I develop the idea that two slab-free windows opened and coalesced beneath the western U.S. (Fig. 1). I assume that the Farallon slab flattened against the base of western U.S. during the course of the Laramide orogeny. This idea was introduced by Cony and Reynolds (1977) based in the eastward sweep of magmatism during the early Laramide, and from ~45-75 Ma magmatism was essentially absent from the western U.S. south of the Challis-Absaroka volcanic trend (Fig. 2). This is convincing evidence for flat subduction during the Laramide to many researchers. Additional strong support for flat-slab subduction comes from the vigorous re-ignition of magmatism across the Cordilleria attributed to slab removal and heating of the metasomatized lithosphere (Humphreys, 1995), especially in the Basin and Range province, where lower lithosphere is thought to be relatively fertile (Humphreys et al., 2003). If this magmatic history represents slab ascent and contact with the base of North America and its subsequent removal, then the south-to-north propagation of initial ignimbritic magmatism across the southern Basin and Range and the north-to-south propagation across the northern Basin and Range represents the progression of slab removal (Humphreys, 1995).

The current physical state of the western U.S., including the high gravitational PE of the Cordillera and low strength of the western Cordillera, is largely a consequence of slab removal. The direct effect of removal was uplift caused by unloading; more indirect was magmatic heating and its consequent effects on contributing to lithospheric buoyancy and weakness. Seismic images of western U.S. upper mantle suggest that a pervasive small-scale convection affects the North American lithosphere that was in contact with the flat slab during the Laramide orogeny. This includes asthenospheric invasion of the lithosphere and lithospheric downwelling. Late Cenozoic evolution involves a gravitational collapse of the western Cordillera and growth of a distributed transform margin, both of which responded to the lithospheric strengths and weaknesses inherited from the prior tectonic assembly and magmatic modifications.

THE SOUTHERN SLAB-FREE WINDOW

The southern window is that first discussed by Dickinson and Snyder (1979) and associated with the termination of subduction and growth of the transform margin that now is dominated by the San Andreas fault (Atwater, 1970). As discussed by Glazner and Supplee (1982), the north-propagating sweep of intense magmatism across the southern Basin and Range coincides well with the projected location of the Mendocino transform and fracture zone beneath North America, and involves not only the area where geometric reconstruction implies an absence of slab beneath North America, but also the area to the east of this slab-free window, involving what was very young subducted Farallon slab south of the Mendocino transform beneath Sonora and New Mexico (what Severinghous and Atwater (1990) termed the region of slab gap). Figure 3a represents a concept where this warm, thin lithosphere drips off of basal North America. This tends to occur when the subducted slab looses its ability to transmit stress over length scales of a few hundred kilometers and slab dynamics becomes dominated by small-scale Rayleigh-Taylor convective instabilities (e.g., Molnar and Houseman, 2004). I envision this process dominating slab removal across most of the southern Basin and Range, especially in Mexico (i.e., south of the latitude of the initial Mendocino triple junction), where a clear magmatic sweep is not obvious (Ferrari, 1999).

THE NORTHERN SLAB-FREE WINDOW

At 50 Ma (Fig. 2a), just prior to the accretion of Siletzia, subducting Farallon slab appears to have been in contact with western U.S. lithosphere as far north as NE Wyoming, based on the near absence of magmatism to the south. To the north, I infer the NW-trending Absoraka-Challis-Kamloops volcanic trend represents a volcanic arc above slab (Christiansen and Yeats, 1992) that progressively steepened to the north, attaining a trench-arc separation (and inferred dip) that was normal beneath Canada. With Siletzia accretion (Duncan, 1982) at 45-50 Ma (in Fig. 2, I choose 48 Ma to represent the time of accretion), subduction jumped outboard of Siletzia, initiating the subduction-related magmatism that eventually created the Cascade arc (first magmatism, at ~43 Ma, was west of the current Cascade arc) and terminating Challis-Absoraka-Kamloops magmatism (waning by ~45 Ma) (Christiansen and Yeats (1992), Madsen et al. (2006) and references therein).

Two points about this suggested tectonic history warrant mention. First, the Siletzia terrain represented in Figures 2-5 extends farther east that that often shown; I include the inferred entire fragment of accreted ocean lithosphere, as envisioned by Riddihough

(1986), and not only the portion west of the comprises the Coast Ranges Washington and Oregon. Second, the Clarno volcanism in eastern Oregon, which occurred during the time of transition between Challis and Cascade activity, often is seen as part of a process such as slab rollback that propagated from the Challis to the Cascades (e.g., Christiansen and Yeats, 1992). I do not see how to do this in the context of Siletzia accretion. Rather, I envision the Clarno activity to represent melting of a hydrated pre-accretion forearc (Bostock et al., 2002), perhaps tectonically enhanced by a state of extension that would be expected during early Cascadia subduction (Gurnis, 1992).

A continuing occurrence of Laramide tectonism and absence of magmatism south of Siletzia suggests that the subducting plate remained in contact with North America lithosphere south of Siletzia, whereas initiation of the Cascades indicates normal-dip subduction beneath Siletzia. To accommodate the geometrical constraints, the Farallon slab apparently tore near the southern margin of Siletzia, creating a small window (light gray area in Fig. 2c) between the young slab subducting beneath the Cascade arc and the old subduction zone in central Oregon. That is, the accretion of Siletzia transfered a piece of ocean lithosphere to North America, creating a hole in the subducting lithosphere. Forward motion of subducted Farallon slab opened this window further by moving its trailing margin to the ENE (Fig. 2c-d). Simultaneously, the window opened to the south as the torn edge retreated southward (Fig. 2d). This south-propagating opening was the result of flat slab removal from the base of the lithosphere, exposing the (presumably cooled and metasomatized) lithosphere to infilling asthenosphere. The major consequence of the flat-slab retreat is southward propagation of the ignimbrite flareup across the Great Basin. The geometric form of the retreating of slab is not obvious, and could have involved a sideways slab rollback or a slab buckling, as illustrated in Figure 3b.

TECTONIC EVOLUTION: 40 Ma – RECENT

With continued slab removal the two propagating magmatic fronts swept across the southern and northern Basin and Range provinces towards each other (Fig. 4a). The thermally weakened lithosphere allowed core-complex extension to occur (Armstrong and Ward, 1991; Gans et al., 1989), which moved the Sierra Nevada and Klamath blocks to the west and rotated the Siletzia and the Blue Mountain terrains clockwise (as illustrated at 20 Ma in Fig. 4b). The Pacific plate, once it was placed against North America ~28 Ma (Atwater, 1970; Atwater and Stock, 1998), played an increasingly important role as a barrier to Basin and Range extension as it widened with the divergence of the Mendocino and Rivera triple junctions. At 7-8 Ma Pacific-North America relative motion grew less divergent (Atwater and Stock, 1998) and the motion of the Sierra Nevada and Klamath blocks responded by changing their velocity so as to move northwesterly relative to North America (Wernicke et al., 1998, Fig. 2b), thereby blocking most Basin and Range extension and effectively accomplishing a partial transfer of the Sierra Nevada block (Wernicke et al., 1998) and a total transfer of Baja (at ~6 Ma; Fletcher et al., 2007) to the Pacific plate.

As the Mendocino triple junction migrated north so to did the southern slab-free window, which opened beneath the California Coast Ranges (Furlong et al., 1989). However, a broad opening of a window beneath the western U.S. interior was not possible because the subducted slab there had already been removed during prior opening of the northern window, and so slab-window effects were confined to the near coast region. Slab that subducted beneath central and northern California at times after Siletzia accretion but prior to arrival of the Mendocino triple junction appears to have subducted in a relatively normal fashion, creating arc volcanism as far south as Lake Tahoe (Henry et al., 2004; Christiansen and Yeats, 1992).

CURRENT ACTIVITY

The current tectonic situation is represented in Figs. 5 and 6. The western U.S. is remarkable for the broad area that is tectonically and magmatically active and the broad Cordillera that is elevated. The area that is tectonically most active occupies roughly the western half of the western U.S. Cordillera, whereas in Canada and Mexico tectonic activity is limited nearly entirely to a narrow plate boundary transform fault (Figs. 5 and 6b). Within the broadly active western U.S., the westernmost portion is dominated by shear deformation (Fig. 5), and deformation to the east occurs at relatively low rates in nearly pure extension. In a general sense, shear deformation requires forces created in the far field to be transmitted through strong plates to areas of weakness, whereas dilational deformation is driven by a local concentration of gravitational potential energy (GPE).

The western deformation zone of shear deformation is 300-600 km wide and accommodates Pacific-North America transform interaction and oblique (dextral) subduction of the Gorda-Juan de Fuca plate (Fig. 5). Roughly three fourths of Pacific-North America relative motion occurs on the San Andreas system and about one fourth occurs east of the Sierra Nevada block on the Eastern California shear zone–Walker Lane Belt (e.g., Dixon et al., 1999) in the western Great Basin. As this interior shear zone crosses the Pacific Northwest, it is accommodated largely by rotation of the nearly non-deforming Siletzia block (McCaffrey, 2005; Svarc et al., 2002). The zone of shear deformation broadens as many of the accommodating faults change trend to become more northerly (releasing, or normal; red area in Fig. 5) in orientation as it approaches Siletzia, where deformation occupies the southern Oregon and NW Nevada Basin and Range (Hammond and Thatcher, 2005). North of Siletzia, a wide region of N-S contraction (blue area in Fig. 5) occurs along the northern margin of the block (the Yakima fold and thrust belt and the Seattle area faults). Kinematically, deformation adjacent to Siletzia serves to distribute what is elsewhere a relatively narrow shear system across the width of Siletzia, thereby accommodating the rigid Siletzia lithoshere within the shear zone.

The zone of extensional deformation, primarily the northern Basin and Range, is thought to be both weak (Lowry and Smith, 1995; Fig 6) and of large GPE (Fig. 6c). The weakness results from recent, large volume volcanic activity (i.e., the ignimbrite flareup), and it allows the existing stress to drive strain at geologically significant rates; the high GPE provides the necessary tensional stress (Humphreys and Coblentz, 2007). The high elevations indicate buoyancy at depth, and the high GPE (Fig. 6c) indicates that this buoyancy is relatively deep (in particular, deeper that the Moho). The fact that GPE is greatest near Yellowstone suggests that buoyant Yellowstone mantle is important there. However, high GPE extends across the entire elevated western U.S. (including the thick-lithosphere Rocky Mountains), which suggests to me that it is a heterogeneous combination of hydration and heating that contributes to the deep buoyancy (Humphreys et al., 2003).

Currently the base of western North America lithosphere under which flat-slab subduction occurred is actively involved in small-scale convection nearly everywhere (Fig. 6a). This includes areas that are seismically fast, which involves downwelling of lithosphere, and areas that are seismically slow (and which tend to be magmatically active), requiring the advective ascent of heat.

The form of downwelling could be whole-lithosphere removal (such as delamination, Bird, 1979), as proposed for the southern Sierra Nevada (Saleeby et al., 2003), Transverse Ranges (Bird and Rosenstock, 1984; Humphreys and Hager, 1990), east of the Rio Grande Rift (Gao et al., 2004; Song and Helmberger, 2007), below the source of the Columbia River flood basalts (Hales et al., 2005), or Rayleigh-Taylor "drips" off of the lower lithosphere (Molnar and Houseman, 2004), as proposed for the southern Sierra Nevada (Zandt and Carrigan, 1993), Transverse Ranges (Billen and Houseman, 2004), and the Penninsular Ranges (Yang and Forsyth, 2006).

The form of asthenospheric penetration is more curious. Simple replacement of delaminated lithosphere is possible. However, the Colorado Mineral Belt and Yellowstone low-velocity anomalies exist within what appears to be thick lithosphere that has not been removed (Dueker et al., 2001). Apparently heating from below has generated melt that has invaded the lithosphere. For Yellowstone, this appears to be related to anomalously hot mantle ascending as a plume (Fee and Dueker, 2004; Yuan and Dueker, 2005). However, for the Colorado anomalies, which extend to depths of ~200 km (Dueker et al., 2001; Humphreys et al., 2003), it is less clear if anomalously hot asthenosphere is involved. This deep melting may be enhanced by Laramide-age hydration of lower lithosphere (Humphreys et al., 2003).

Presumably the vigorous small-scale convection active beneath the western U.S. (imaged in Figure 6a) is unusual, although basal lithosphere is not comparably resolved anywhere else in the world. If unusual, I suspect that the weakening effects of hydration and the heating it caused (by inducing melting) are primarily responsible for the mobility of the lower lithosphere.

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To be completed later.

REFERENCES

Armstrong, R.L., and Ward, P., 1991, Evolving geographic patterns of Cenozoic magmatism in the North American Cordillera: The temporal and spatial association of magmatism and metamorphic core complexes: Journal of Geophysical Research, v. 96, p. 13,201–13,224.

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin, v. 81, p. 3513–3535.

Atwater, T., and Stock, J.M., 1998, Pacific-North America plate tectonics of the Neogene Southwestern United States: An Update, International Geology Review, v. 40, p.

375–402.

Billen, M.I., and Houseman, G.A., 2004, Lithospheric instability in obliquely convergent margins: San Gabriel Mountains, southern California: Journal of Geophysical Research, v. 109, B01404, doi:10.1029/2003JB002605.

Bird, P., 1979, Continental delamination and the Colorado Plateau: Journal of Geophysical Research, v. 84, p. 7561-7571.

Bird, P., and Rosenstock, R.W., 1984, Kinematics of present crust and mantle flow in southern California: Geological Society of America Bulletin, v. 95, p. 946–957.

Bostock, M.G., Hyndman, R.D., Rondenay, S., and Peacock, S.M., 2002, An inverted continental Moho and serpentinization of the forearc mantle: Nature, v. 417, p. 536–538.

Coney, P. J., 1980, Cordillerian metamorphic core complexes: An overview, in Crittendon, M. D., Coney, P. J., and Davis, G. H., eds., Cordillerian metamorphic core complexes: Geological Society of America Memoir 153, p. 7–31.

Coney, P., and Harms, T., 1984, Cordilleran metamorphic core complexes: Cenozoic extensional relics of Mesozoic compression: Geology, v. 12, p. 550–554.

Christiansen, R.L., and Yeats, R.L., 1992, Post-Laramide geology of the U.S. Cordillerian region: in Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordillerian Orogen: Conterminous U.S.: Boulder, CO, Geological Society of America, Geology of North America: v. G-3, p. 261–406.

Coney, P. J., and Reynolds, S. J., 1977, Flattening of the Farallon slab: Nature, v. 270, p. 403–406.

Dickenson, W. R., and Snyder, W. S., 1979, Geometry of subducted slabs related to the

San Andreas transform: Journal of Geology, v. 87, p. 609–627.

Dickinson, W.R., 2002, The Basin and Range province as a composite extensional domain, International Geology Review, v. 44, p. 1–38.

Dixon, T.H., Miller, M., Farina, F., Wang, H, Johnson, D., 1999, Present-day motion of the Sierra Nevada block and some tectonic implications for the Basin and Range province, North American Cordillera: Tectonics, v. 19, p. 1–24, 10.1029/1998TC001088.

Ducea, M.N., and Saleeby, J.B., 1996, Buoyancy sources for a large, unrooted mountain range, the Sierra Nevada, California; evidence from xenolith thermobarometry: Journal of Geophysical Research, v. 101, p. 8229–8244.

Dueker, K.G., Yuan, H. and Zurek, B., 2001, Thick-structured Proterozoic lithosphere of the Rocky Mountains, GSA Today, v. 11, no. 12, p. 4–9.

Duncan, R., A., 1982, A captured island chain in the Coast Range of Oregon and Washington: Journal of Geophysical Research, v. 87, p. 10827–10837.

Fee, D., and Dueker, K., 2004, Mantle transition zone topography and structure beneath the Yellowstone hotspot: Geophysical Research Letters, v. 31, L18603, doi:10.1029/2004GL020636.

Ferrari, L., Martinez, M.L., Diaz, G.A., Nunez, G.C., 1999, Space-time patterns of Cenozoic arc volcanism in central Mexico; from the Sierra Madre Occidental to the Mexican volcanic belt: Geology, v. 27, p. 303–306.

Fletcher, J.M., Marty Grove, M., Kimbrouh, D., Lovera, O., and George E. Gehrels, G.E., 2007, Ridge-trench interactions and the Neogene tectonic evolution of the Magdalena shelf and southern Gulf of California: Insights from detrital zircon U-Pb ages from the Magdalena fan and adjacent areas: Geological Society of America Bulletin v. 119; p. 1313–1336; DOI: 10.1130/B26067.1

Furlong, K.P., Hugo, W., Zandt, G., 1989, Geometry and evolution of the San Andreas fault zone in Northern California: Journal of Geophysical Research, V. 94, p. 3100–3110.

Gans, P.B., G. A. Mahood, E. Schermer, 1989, synextensional Magmatism in the Basin and Range Province: A Case Study from the Eastern Great Basin: Geolical Society of Amweica, Special Paper 233.

Gao, W., Grand, S., Baldridge, W.S., Wilson, D., West, M. Ni, J., and Aster, R., 2004, Upper mantle convection beneath the central Rio Grande rift imaged by P and S wave tomography: Journal of Geophysical Research, v. 109, B03305, doi:10.1029/2003JB002743.

Glazner, A.F., and Supplee, J.A., 1982, Migration of Tertiary volcanism in the southwestern United States and subduction of the Mendocino fracture zone: Earth and Planetary Science Letters, V. 60, p. 429–436.

Gurnis, M., 1992, Rapid Continental Subsidence Following the Initiation and Evolution of Subduction: Nature, v. 255, p. 1556–1558, doi:10.1126/science.255.5051.1556.

Hales, T.C., D. Abt, E. Humphreys, and J. Roering, 2005, A lithospheric instability origin for Columbia River flood basalts and Willowa Mountains uplift in northeast Oregon: Nature: v. 438, p. 842–845.

Hammond, W.C., and Thatcher, W., 2005, Northwest Basin and Range tectonic deformation observed with the Global Positioning System, 1999–2003: Journal of Geophysical Research, v. 110, B10405, doi:10.1029/2005JB003678.

Henry, C.D., Cousns, B.L., Castor, S.B., Faulds, J.E., Garside, L.J., and Timmermans, A., 2004, The Ancestral Cascades Arc, northern California/western Nevada: Spatial and Temporal Variations in Volcanism and Geochemistry, Eos Trans. AGU, v. 85(47), Fall Meet. Suppl., Abstract V13B-1478.

Humphreys, E., and D. Coblentz, D., 2007, North America dynamics and western U.S. tectonics: Reviews of Geophysics, v. 45, RG3001, doi:10.1029/2005RG000181.

Humphreys, E., and Hager, B.H., 1990, A kinematic model for the late Cenozoic development of southern California crust and upper mantle: Journal of Geophysical Research, v. 95, p. 19,747-19,762.

Humphreys, E., 1995, Post-Laramide removal of the Farallon slab, western United States: Geology: v. 23, p. 987–990.

Humphreys, E., Hessler, E., Dueker, K., Erslev, E., Farmer, G.L., and Atwater, T., 2003, How Laramide-age hydration of North America by the Farallon slab controlled subsequent activity in the western U.S.: International Geology Review, v. 45, p. 575–595.

Humphreys, E. and Dueker, K.G., 1994, Physical state of the western U.S. upper mantle: Journal of Geophysical Research, v. 99, p. 9635-9650.

Lowry, A.R., and Smith, R.B., 1995, Flexural rigidity of the Basin and Range-Colorado Plateau-Rocky Mountain transition from coherence analysis of gravity and topography : Journal of Geophysical Research, v. 99, p. 20,123–20,140.

Madsen, J.K., Thorkelson, D.J., Friedman, R.M., and Marshall, D.D., 2006, Cenozoic to Recent plate configurations in the Pacific Basin: Ridge subduction and slab window magmatism in western North America: Geosphere, v. 2, p. 11–34, 10.1130/GES00020.1.

McCaffrey, R., 2005, Block kinematics of the Pacific–North America plate boundary in the southwestern United States from inversion of GPS, seismological, and geologic data: Journal of Geophysical Research, v. 110, B07401, doi:10.1029/2004JB003307.

Molnar, P., and Houseman, G.A., 2004, The effects of buoyant crust on the gravitational instability of thickened mantle lithosphere at zones of intracontinental convergence: Geophysical Journal International, v. 158, p. 1134–1150.

Priest, G.R., 1990, Volcanic and tectonic evolution of the Cascade volcanic arc, central Oregon, Journal of Geophysical Research, v. 95, p. 19,583–19,599.

Riddihough, R.P., Finn, C., Couch, R., 1986, Klamath-Blue Mountain Lineament, Oregon: Geology, v. 14, p. 528–531.

Saleeby, J, Clemens-Knott, D., and Ducea, M., 2003, Production and loss of high-density batholithic root - southern Sierra Nevada, California: Tectonics, v. 22, doi:10.1029/2002TC001374.

Severinghaus, J., and Atwater, T., 1990, Cenozoic geometry and thermal state of the subducting slabs beneath North America: in Wernicke, B.P., ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada, Geological Society of America Memoir 176, p. 1–22.

Song, T-R.A, Helmberger, D.V., 2007, P and S waveform modeling of continental sub-lithospheric detachment at the eastern edge of the Rio Grande Rift: Journal of Geophysical Research, v. 112, B10405, doi:10.1029/2007JB004942.

Svarc, J.L., Savage, J.C., Prescott, W.H., and Murray, M.H., 2002, Strain accumulation and rotation in western Oregon and southwestern Washington: Journal of

Geophysical Research, v. 107, 2087, 10.1029/2001JB000625.

Wernicke, B.P., Axen, G.J., and Snow, J.K.,1998, Basin and Range extensional tectonics at the latitude of Las Vegas, Nevada: Geological Society of America Bulletin, v. 100, p. 1738–1757.

Yang, Y., and Forsyth, D.W., 2006, Rayleigh wave phase velocities, small-scale convection, ans azimuthal anisotropy beneath southern California: Journal of Geophysical Research, v. 111, B07306, doi:10.1029/2005JB004180.

Yuan, H., and Dueker, K., 2005, Teleseismic P-wave tomogram of the Yellowstone plume: Geophysical Research Letters, v. 32, L07304, doi:10.1029/2004GL022056.

Zandt, G., and Carrigan, C.R., 1993, Small-scale convective instability and upper mantle viscosity under California: Science v. 261, p. 460–463.

FIGURES

Figure 1. Western US. Relief, with the two slab-free windows highlighted. Arrows show direction of window opening.

Figure 2. Mid-Eocene tectonic and magmatic evolution of western U.S. Subduction zone (purple line) and Mesozoic accreted and plutonic terrains of the Sierra Nevada, Klamath and Blue Mountains (pink) are after Dickinson (2002). Accreted oceanic Siletzia terrain (green) and major subduction-related volcanism (yellow) are also indicated, as is the area of flat-slab subduction (south of brown line). (a) Prior to Siletzia accretion at 50 Ma. Challis-Absaroka volcanic belt shown, which I take to represent a volcanic arc connecting a normal subduction zone beneath Canada and the flat slab. (b)

Immediately after accretion of Siletzia at ~48 Ma. Also shown is the current position of the accreted terrains and the paths taken by these terrains (after Dickinson, 2002). The kink occurs at 7-8 Ma (Wernicke et al, 1998). (c) Magmatic adjustment at 45 Ma, after Siletzia accretion. Challis-Absaroka magmatism is waning while Cascade magmatism is starting; its location indicates normal-dip subduction beneath Siletzia. The subducted Farallon slab must be torn between the flat- and normal-dip segments of subducted slab. The light gray area is the young northern slab-free window created by the accretion of Siletzia, shown here after 3 m.y. of Farallon slab motion following Siletzia accretion. (d) The opening northern window, which opens because of the forward motion of the Farallon slab (here at 6 m.y. after Siletzia accretion) and the southern retreat of the northern edge of the flat slab (indicated with red line). Southward slab retread is marked by the initiation of intense ignimbritic volcanism.

Figure 3. Conceptual rendering of the subducted Farallon slab at ~40 Ma. (a) Subduction occurs normally beneath Siletzia (dark gray lithosphere) and Canada to the north. The flat slab is shown as buckled (see (b) for alternative), with the northern tear propagating south, thereby exposing hydrated basal lithosphere to asthenospheric heating. Similarly, the Mendocino fracture zone (mfz) propagates north, leaving hot thin slab beneath Mexico and the SW U.S. This thin slab is shown dripping off, which exposes hydrated basal lithosphere to asthenospheic heating. (b) Two possible ways in which the flat slab may have been removed from North America lithosphere. In both cases the subducting Farallon slab moves toward the viewer (i.e., out of the page) and the Mendocino fracture zone propagates north with the Farallon plate motion. The “tacoing” case is represented in (a), where the two sides propagate toward the center and descend.

In the “sideways rollback” case, the northern edge of the flat Farallon slab peels away from the lithosphere in a north-to-south direction.

Figure 4. Magmatic and tectonic state at ~20 Ma. (a) shows the two slab-free windows (light gray areas) opening by propagating towards one another (see Fig. 3). Background figure shows the occurrence of volcanic activity at ~21 Ma (from the NAVDAT web site), showing clearly the concentration of volcanic activity neat the opening edge of the slab window. The red line shows the Mendocino transform fault, and the purple line shows the edge of North America at 21 Ma (solid where margin is transform, dashed where it is subduction). (b) The main tectonic elements (see Fig. 2 for symbol explanation), showing the extending continental interior moving the margin of North America to the west and rotating Siletzia. The Klamath and Blue Mountains terrains are being separated in a manner that is not understood.

Figure 5. Current tectonic situation, emphasizing the shear margin. At the southern and northern ends, Pacific-North America (P-NA) relative motion is accommodated on narrow transform systems (black and yellow line for strike-slip fault; see also Fig. 6b). At the latitude of California, the San Andreas fault (SAF) and eastern California shear zone (ecsz) accommodate P-NA relative motion, with the Sierra Nevada (sn) and Klamath (k) blocks occupying a transitional setting (motion shown with respect to North America). Northern motion of the Klamath block is accommodated by rotation of the Siletzia block (green), shown as broken and separating at the Cascade graben (Priest, 1990). The shear zone broadens across the width of the rotating Siletzia block, necessitating extension of the NW Basin and Range (B&R) and contraction across the Yakima fold and thrust belt (f&th). Siletzia rotation is consistent with the oblique

convergence of the Juan de Fuca plate (JdF) south of Canada; no shear deformation occurs where JdF subduction is normal.

Figure 6. (a) Seismic velocity anomaly at 100 km, showing the common occurrence of small-scale convection. Blue-colored mantle to the north and east is North America craton. Beneath westernmost U.S., where velocities average slow and lithosphere is thin, blue indicates sinking lithosphere (subducting Juan de Fuca slab or downwelling North America lithosphere). Beneath the Rocky Mountains, Snake River Plain and Yellowstone, where lithosphere is thick, slow mantle represents hot (probably partially molten) mantle (Humphreys and Dueker, 1994). Figure from Humphreys et al., 2003. (b) Velocity relative to North America, showing the "cavity" of deformation that affects much of western U.S. Note that most of the northern Basin and Range moves at low speeds toward the Pacific plate, whereas the western margin of North America becomes partly entrained with the Pacific plate. (c) Gravitational potential energy (GPE) and the stresses it creates. the large magnitude of GPE indicates that the buoyancy which elevates the western U.S. is at ~100 km, implying that the mantle lithosphere or asthenosohere is of unusually low density. Note that high GPE and the consequent extensional stresses expend over the entire Cordillera, whereas it is primarily the western Cordillera is deforming at significant rates. This suggests that the western Cordillera is unusually weak.