Reply to comment by E. L. Miller et al. on "Geodynamics of synconvergent extension and tectonic mode switching: Constraints from the Sevier-Laramide orogen"

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1. Introduction

[1] We welcome the comment from *Miller et al.* [2012] and the opportunity to address their concerns and to expand on several aspects of the proposed geodynamic model in *Wells et al.* [2012]. Many of the points raised in the comment concern Late Cretaceous crustal anatexis and extension, aspects of the proposed geodynamic model that were developed in more detail in *Wells and Hoisch* [2008]. We address each of their three main points below.

2. Sub-Tertiary Unconformity

[2] *Miller et al.* [2012] contend that the geodynamic model presented in *Wells et al.* [2012] contradicts the structural relief and exhumation implied by the diachronous unconformity of Latest Cretaceous to early Miocene age between the fold-thrust belt and the magmatic arc (referred to here as the sub-Tertiary unconformity) [e.g., *Armstrong*, 1968, 1972; *Rodgers and Janecke*, 1992; *Gans and Miller*, 1983; *Colgan and Henry*, 2009; *Van Buer et al.*, 2009; *Long*, 2011]. While we note that the subcrop maps referenced by *Miller et al.* [2012] do not include the region surrounding the Raft River-Albion-Grouse Creek (RAG) metamorphic core complex, we nonetheless address their applicability to other parts of the Sevier hinterland for evaluating Late Cretaceous extension. The subcrop map compilations for the region east of the Roberts Mountains thrust identify domains of higher exhumation (4–8 km) that define the frontal ramp to the major quartzite-dominated thrust sheets of the Sevier fold-thrust belt (e.g., Paris-Willard-Sheep Rock-Canyon Range-Wah Wah) [*Armstrong*, 1968; *Rodgers and Janecke*, 1992; *Long*, 2011] at the shelf-platform transition to the Late Precambrian-Devonian passive margin. The subcrop map compilations also define a western thrust system [*Camilleri et al.*, 1997] comprising the central Nevada thrust belt (Eureka belt of *Speed et al.* [1988], *Taylor et al.* [2000], and *Long* [2011]) and Windermere thrust to the north at the shelf-slope margin [*Camilleri and Chamberlain*, 1997; *Camilleri et al.*, 1997] that is broadly associated with conodont CAI values of 3–6 [*Crafford*, 2007]. Between these thrust ramps lies the region for which, harkening back to *Armstrong* [1968, 1972], subcrop maps to the sub-Tertiary unconformity and low conodont CAI values (2–3.5) in Upper Paleozoic strata have been interpreted, as stated by *Miller et al.* [2012], to "show that broad folding and minor thrust faults characterized the surface geology of the hinterland region." This region, which at the latitude of the study area lies between the Raft River Mountains and the Malad ramp to the east [*Rodgers and Janecke*, 1992], is probably underlain by a thrust flat in the Sevier orogenic wedge. This represents one domain within a broad hinterland that spans the region between the Sevier fold-thrust belt to the magmatic arc which has been interpreted to be a high elevation plateau in Cretaceous time [e.g., *Vandervoort and Schmitt*, 1990; *Allmendinger*, 1992; *Camilleri et al.*, 1997; *DeCelles*, 2004].

[3] Several workers have challenged the characterization of low-structural relief for the Sevier hinterland [*Barley and Gleason*, 1990; *Vandervoort and Schmitt*, 1990; *Camilleri*, 1996; *Druschke et al.*, 2009a, 2009b, 2011]. *Druschke et al.* [2009a, 2009b, 2011] addressed the validity of the characterization of low-structural relief, and reported a number of regions where the angularity across the unconformity is 45°, locally reaching 90°. Clasts derived from Ordovician and Devonian strata within the Maastrichtian member A of the Sheep Pass Formation document exhumation of Lower Paleozoic rocks at that time [*Druschke*, 2008]. Additionally, the local high-energy character of the sedimentary deposits immediately overlying the unconformity, including megabreccias in the Maastrichtian part of the Sheep Pass Formation interpreted as landslides and scarp-front alluvial conglomerates, requires significant relief in Late Cretaceous time [*Vandervoort and Schmitt*, 1990; *Druschke et al.*, 2009a, 2009b]. *Armstrong* [1968] also recognized exceptions to the generalization of low relief, "The near-parallelism of units, however, is only a generalization. In many areas, sharp angular unconformities occur, and the paleogeologic reconstruction must maintain consistency with these relationships. The paleogeology becomes increasingly complex westward into

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central Nevada." In the area of "increasingly complex" paleogeology representing the western thrust system, *Camilleri* [1996, 2010] documented Eocene volcanic rocks resting on metamorphosed upper Paleozoic rocks in the Pequop Mountains, requiring 11 km of pre-volcanic exhumation along the Pequop fault, a normal fault whose initial formation is bracketed between 84 and 75 Ma [*Camilleri and Chamberlain*, 1997]. Kilometers of structural relief under the unconformity and bedding discordances >10° are common enough that to interpret the pre-Tertiary rocks as weakly deformed is unjustified [e.g., *Druschke et al.*, 2009b].

[4] *Miller et al.* [2012] state that "the rarity of deposits such as the Late Cretaceous Sheep Pass Formation [e.g., *Druschke et al.*, 2011] across the vast region of the hinterland between the Snake River Plain and the Snake Range, Nevada, indicates that extensional faulting and the formation of syn-extensional basins was not significant during the late Mesozoic." However, it is also possible to interpret the Sheep Pass Formation to represent exceptional preservation rather than exceptional deposition. The Maastrichtian to Paleocene interval of the Sheep Pass Formation currently is found in a wide geographic area including the Egan Range, Grant Range, Pancake Range, and Fish Creek Range, and in drill core and cuttings from White River and Railroad Valleys [see *Fouch*, 1979; *Vandervoort and Schmitt*, 1990; *Druschke et al.*, 2009a, 2009b]. A low preservation potential may be predicted based on the constraints of erosion magnitudes inferred from the sub-Tertiary unconformity subcrop maps and conodont CAI values, shallow burial of Late Cretaceous deposits, and the <1 km thickness of the Late Cretaceous to Paleocene part of the Sheep Pass Formation. The original distribution of similar deposits in Late Cretaceous to Paleocene time appears to have been significantly more extensive; the presence of clasts of the Maastrichtian Sheep Pass member A in Eocene conglomerate in the Egan Range indicates that portions of the Sheep Pass type section were exhumed and denuded as early as the Eocene [*Druschke et al.*, 2009b].

[5] With respect to Cretaceous normal faults, *Miller et al.* [2012] ask, "Why is there so little evidence for such structures geologically and in the Cenozoic unconformity data"? This question points out the sparse supporting field relationships and thus, either the hypothesis is wrong or there are reasons that the evidence is sparse. We believe the latter to be the case. It is our view that subsequent deformation, erosion, and burial have partially obscured the geologic record of Cretaceous extension—and similarly partially obscured the geologic record of Cretaceous and Jurassic shortening. In the eastern Mojave Desert of California where Mesozoic plutons are more abundant, Phanerozoic sedimentary cover on Precambrian basement is thin, and the younger structural overprint is less pervasive and of shorter duration, Late Cretaceous cooling can be linked to specific extensional structures (e.g., Iron Mountains shear zone, western Old Woman Mountains shear zone, Pinto shear zone, etc.) [*Wells and Hoisch*, 2008, and references within]. In the Great Basin, stratigraphic and structural conditions help both to facilitate, and to obscure, the earlier deformation. Extension sufficient to significantly exhume metamorphic rocks (though not necessarily to the surface) appears to be restricted to the regions near large-scale crustal ramps where footwall strata were underthrust during prior shortening [e.g., *Miller and Hoisch*, 1995; *Camilleri and Chamberlain*, 1997; *Lewis et al.*, 1999], resulting in tectonically buried inclined panels of metasedimentary rock [cf. *Miller et al.*, 2012, Figures 1b and 1c]; this underthrusting of strata may have been enhanced by downwelling mantle lithosphere. Geometric and kinematic reactivation [e.g., *Holdsworth et al.*, 1997], including bedding-parallel slip down barometric gradients [e.g., *Camilleri and Chamberlain*, 1997; *Lewis et al.*, 1999; *Wells*, 2001], creates discontinuities in metamorphism but not in stratigraphic age, thus obscuring early contraction and later extension (i.e., RAG, Snake Range, Wood Hills-East Humboldt Range, Funeral Mountains). An additional stratigraphic control on deformation localization has played a role in obscuring Mesozoic tectonism at higher crustal levels within Mississippian strata of the Great Basin. A décollement zone within shale of the Mississippian Chainman Shale-Diamond Peak Formation and its eastward equivalent, the Manning Canyon Shale, separates the overlying, thickly bedded Pennsylvanian and Permian carbonate (Ely Limestone, Oquirrh Group and equivalents) from underlying Mississippian sandstone and carbonate. Long thrust and normal fault flats in this stratigraphic horizon separate broadly spaced ramps, thus greatly separating domains of contraction or extension at different crustal levels. This weak Mississippian shale has been used, and reused, as a décollement horizon during contraction and extension [cf., *Allmendinger and Jordan*, 1981; *Wernicke*, 1982; *Jordan and Allmendinger*, 1982], obscuring older deformations by younger reactivations.

[6] Reconstructions of paleogeology from the subcrop to the sub-Tertiary unconformity requires much extrapolation as the ancient erosion surface is only exposed as traces in tilted fault blocks, and a significant portion of the pre-Tertiary erosion surface is buried beneath Eocene and younger deposits. N-trending half grabens filled with Quaternary deposits constitute ∼50% of the modern planimetric area, and exposures of pre-Miocene strata constitute only ∼24% (calculations made using GIS database in *Crafford* [2007]). Notwithstanding the lessening of this area due to post-unconformity extension, it is fair to say that the majority of the paleo-erosion surface is currently obscured beneath Cenozoic volcanic rocks and modern basin fill in N-trending half-grabens. This imparts an inherent bias toward recognition of structures that have a significant E or W component to their strike, a fact that must be considered when using these data to eliminate, rather than support, the existence of structures. Additionally, estimation of the magnitude of Cretaceous to Eocene exhumation of upper crustal rocks across the eastern hinterland remains difficult for several reasons: (1) the thickness of Upper Paleozoic rocks is highly variable across the region, from ∼3.5 to ∼9 km in thickness; (2) the thickness of Mesozoic strata which may have blanketed part of the region is incompletely understood; Triassic sedimentary deposits are mostly preserved in the cores of synclines, and Lower Jurassic sedimentary deposits shown to have stratigraphic and provenance correlations to the Lower Jurassic strata of the Colorado Plateau are restricted to the single western occurrence near Currie, NV [e.g., *Lucas and Orchard*, 2007]; (3) Conodont CAI values represent the most regionally extensive data but due to the semiquantitative nature of this empirical geothermometer, and the sensitivity to temperature duration in addition to temperature magnitude [e.g., *Rejebian et al.*, 1987], the utility of the

measure is limited; (4) with few exceptions [i.e., *Cline et al.*, 2005] regional low-temperature thermochronometry studies of the Phanerozoic sedimentary rocks necessary to assess the magnitude of exhumation are lacking.

3. Generation of Late Cretaceous Peraluminous Granites and Their Abundance

[7] *Miller et al.* [2012] question how the record of Late Cretaceous magmatism in the hinterland of the Cordilleran fold-thrust belt is consistent with a model of lithospheric delamination and anatexis, citing age, composition, and inferences of melting mechanisms for granites. We address the following specific points: does delamination produce metaluminous or peraluminous granites?; where are the 83–69 Ma magmatic rocks in light of the recent compilation of *du Bray* [2007] and the NAVDAT database?; and what is the melting mechanism for Late Cretaceous granites?

[8] The proposed geodynamic model [*Wells and Hoisch*, 2008; *Wells et al.*, 2012] incorporated the production of the long recognized Late Cretaceous *peraluminous* granites in the hinterland of the Cordilleran fold-thrust belt, not of *metaluminous* granites. These include the strongly peraluminous monzogranites and granodiorites of the Cordillleran Interior of *Barton* [1990] and *Miller and Barton* [1990], the Late Cretaceous (83–75 Ma) plutonic suite of *Wright and Wooden* [1991], and the Late Cretaceous Cordilleran-type peraluminous granites of *Patiño Douce* [1999]. Genesis of peraluminous granites is proposed to be by heating of an ancient and thickened melt-fertile lower crust through underplating of basaltic asthenosphere-derived decompression partial melts. It is inferred that the intrusion of basalt into the lower crust provided the necessary heat to drive anatexis [e.g., *Annen and Sparks*, 2002], and chemical input from basalt may have been insignificant, thus producing peraluminous, not metaluminous, granites. Peraluminous granites rose into and crystallized within the middle crust, with few exceptions, and were not accompanied by volcanism [*Barton*, 1990; *Miller and Barton*, 1990] (NAVDAT). Thus, the proposed Late Cretaceous delamination cycle does not require the production of *metaluminous* granites, and the absence of abundant metaluminous granites of this age is consistent with the proposed model [cf. *Miller et al.*, 2012, point 2]. We note that a mass contribution from basalt to crustal partial melts can lead to metaluminous compositions, but this is not the process that is envisioned.

[9] *Miller et al.* [2012] state that peraluminous granites younger than 85 Ma are sparse in the hinterland, and that there are few metaluminous plutons or their volcanic equivalents of 75–50 Ma. As the proposed model accounts for peraluminous and not metaluminous granites, we only address the abundance of the former. Plutons in the 83–69 Ma age range have been widely noted in the hinterland of the Cordilleran fold-thrust belt, a significant fraction of which are strongly peraluminous [e.g., *Barton*, 1990; *Miller and Barton*, 1990; *Patiño Douce et al.*, 1990; *Wright and Wooden*, 1991]. Existing regional compilations of the age of magmatism for the hinterland include the compilations published in *Barton et al.* [1988], *Barton* [1990], and *Miller and Barton* [1990] based on the CONTACT88 database and a recent compilation of *du Bray* [2007] for northern Nevada. The CONTACT88 database calculates intrusive flux based on the area of presently exposed plutonic rocks per million years. CONTACT88 shows peaks in intrusive flux at ∼75 Ma for eastern Washington-Idaho-western Montana, and for Utah-eastern Nevada-southeastern California [*Miller and Barton*, 1990, Figure 3]. Recent studies have substantiated the significant ∼75 Ma intrusive flux in the eastern Mojave Desert [e.g., *Foster et al.*, 1989; *Barth et al.*, 2004; *Wells and Hoisch*, 2008] and in the Idaho Batholith [*Gaschnig et al.*, 2010, 2011]. *Miller et al.* [2012] state that "monazite ages from pegmatites in the Ruby Mountains form two clusters: One ∼80–90 Ma and the other ∼42–35 Ma [*Howard et al.*, 2011]." We are puzzled by this statement because *Howard et al.* [2011] conclude that " Zircon and monazite dated by U-Pb (sensitive high-resolution ion microprobe, SHRIMP) for this rock type cluster diffusely at ages near 92, 82(?), 69, 38, and 29 Ma, and indicate successive or rejuvenated igneous crystallization multiple times over long periods of the Late Cretaceous and the Paleogene." We note that the relative probability diagram for the age of magmatism (Figure 2 of *Miller et al.* [2012]) derived from the compilation of *du Bray* [2007] also includes plutons from northwestern Nevada which represent a northward continuation of the Sierra Nevadan arc [e.g., *Van Buer and Miller*, 2010]; this is thus not a good representation of Cordilleran Interior granites.

[10] We disagree with the contention expressed by *Miller et al.* [2012] that "crustal shortening, thermal equilibration and partial melting" necessarily produced the Late Cretaceous peraluminous granites of the Cordilleran Interior. It is our understanding that there is no consensus on the mechanisms for melting of the crust other than that the granites represent melts of ancient continental crust with only a minor mantle component. Proposed mechanisms come close to spanning the spectrum of possibilities for granite production, including an increased mantle heat flux from thermal or viscous thinning, magmatic underplating or delamination, decompression of crust, fluid infiltration, slab-related arc magmatism, and crustal thickening [see *Wells and Hoisch*, 2008, and references within]. Crustal thickening was undoubtedly important, as the melting site during anatexis was deep [e.g., *Miller and Barton*, 1990; *Kapp et al.*, 2002; *Patiño Douce*, 1999; *Gaschnig et al.*, 2011], and there is a strong correlation between the location of Cordilleran-type peraluminous granites and the occurrence of the belt of metamorphic rocks in the hinterland including the metamorphic core complexes. However, it remains unclear whether thrust burial was sufficiently deep to produce conditions favorable for biotite-dehydration partial melting. Lower temperature muscovite-dehydration partial melting, limited in melt percent by the abundance of muscovite, is thought to be insufficient to produce the volumes of melt required for migration and accumulation of melts [*Clemens and Vielzeuf*, 1987; *Patiño Douce et al.*, 1990; *Barton*, 1990]. Furthermore, the timing and magnitude of thrust burial relative to partial melting remains incompletely understood, hindering a rigorous assessment of how well the thermal incubation process explains anatexis in the Cordilleran hinterland [e.g., *England and Thompson*, 1984]. Following *Barton* [1990] and

Miller and Barton [1990], we view crustal thickening as a necessary precondition, but not sufficient by itself to produce the melts, and call upon an additional heat source from the mantle.

4. Specifics of the Raft River-Albion-Grouse Creek Mountains

[11] *Miller et al.* [2012] contend that the magmatic, metamorphic, and structural record of the RAG does not support the geodynamic model of *Wells et al.* [2012]. Specifically, it is stated that "not only are metaluminous magmas in the age range 75–50 Ma absent, but there are also no known felsic intrusions or leucocratic pegmatites in the age range ~75–50 Ma that would provide evidence for the crustal anatexis proposed by *Miller et al.* [2012] in their Figure 9c [*Wells et al.*, 2012, Figure 1c]. The delamination model we have published calls for the production of granites of peraluminous composition and in the age range of 83–69 Ma, not 75–50 Ma metaluminous plutons as stated by *Miller et al.* [2012]. We agree with *Miller et al.* [2012] that there are no recognized Mesozoic magmatic rocks in the RAG core complex, with the exception of Late Jurassic dioritic dikes cutting Mississippian rocks in the Black Pine Mountains [*Wells et al.*, 1990]. There are large areas of the Archean basement, however, which have not received geochronologic study, and there may be unrecognized Mesozoic plutons. This is a subject of ongoing investigations. However, the production of Late Cretaceous anatectic melts are not required to be ubiquitous in the delamination hypothesis—especially should delamination have been piecemeal—and in the case of the RAG, in the absence of recognized Cretaceous plutonism, mantle-derived heating helps to explain the recognized heating during decompression between 85 and 68 Ma in the PTt path. We do not consider the results of geochronologic studies of *Strickland et al.* [2011a, 2011b] to be at odds with our interpretation of the structural and metamorphic history [*Wells et al.*, 2012, Table 1] and the proposed geodynamic model—this is directly addressed in *Wells et al.* [2012, pp. 9 and 10] and we consider this a false dichotomy. Furthermore, we agree with the statement of *Miller et al.* [2012] that the history of "metaluminous magmatism, followed by crustal melting and peraluminous magmatism together with episodic extensional thinning of the crust took place from the Late Eocene to the Late Oligocene (between ~42–25 Ma)." This is not in conflict with our published interpretations. In our view, Cenozoic extension in this region was episodic and protracted, with initial Cenozoic extension pre-dating Oligocene plutonism in the Late Eocene, Oligocene extension associated with crustal melting and intrusion, and final extension synchronous with and postdating Miocene volcanism related to the Snake River plume track. With respect to the question "And what specific ductile extensional fabrics have ages that are clearly bracketed as ~75–50 Ma"?, the extension we advocate is bracketed between 86 and 65 Ma by the PTt path presented in *Wells et al.* [2012]. The Mahogany Peaks and Emigrant faults are two specific structures we correlate to this decompression event; the Mahogany Peaks fault has an independent age bracket between 90 and 60 Ma [*Wells et al.*, 1998]. Additionally, the pervasive top-to-NW shear fabric in the Grouse Creek and Albion Mountains that predates Oligocene plutonism, which we have interpreted to be Eocene based on continuity of 45–37 Ma $^{40}Ar/^{39}Ar$ cooling ages within the shear zone and in its footwall in a N-S belt, is permissively a Late Cretaceous extensional fabric.

5. Closing Remarks

[12] *Wells et al.* [2005] invoked delamination of mantle lithosphere to explain observations of coeval mid-crustal intrusion and extensional exhumation in the eastern Mojave Desert, and subsequently expanded this interpretation to include the Sevier hinterland in the Great Basin [*Wells and Hoisch*, 2008]. We recognize that Late Cretaceous peraluminous magmatism is more prevalent at the level of exposure in the eastern Mojave Desert than in the Great Basin, and that the record of Late Cretaceous extension is somewhat more cryptic in the Great Basin than in the eastern Mojave Desert, but we find the similarities in their Cretaceous geologic records sufficiently compelling to suggest that similar processes affected both regions. Contrary to the objections of *Miller et al.* [2012], we do not view the constraints on structural relief, exhumation, and magmatic record of the Sevier hinterland, nor the magmatic, metamorphic, and structural record of the RAG, contradictory with the geologic predictions of the proposed geodynamic model.

[13] In the Sevier hinterland, it remains unclear whether magnitudes of horizontal extension were comparable between the upper and middle crust, and thus it remains unclear whether extensional processes affecting the middle crust and the upper crust were coupled or decoupled from each other. Various scenarios have been proposed to explain decompression of the middle crust without commensurate extension of the upper crust, including blind extensional allochthons [*Hodges and Walker*, 1992; *Applegate and Hodges*, 1995], middle crustal flow [*Lewis et al.*, 1999; *McQuarrie and Chase*, 2000], or diapirism [e.g., *Fayon et al.*, 2004]. In consideration of the observations supporting surface-breaking faults [e.g., *Camilleri and Chamberlain*, 1997; *Druschke et al.*, 2009a], we cannot confidently discount the possibility that upper crustal extension was coupled with middle crustal deformation processes.

[14] The model of Cretaceous delamination of mantle lithosphere in the western United States at the onset of the Laramide orogeny presented in *Wells and Hoisch* [2008], and expanded on in *Wells et al.* [2012], relies on observations of the geologic consequences of delamination and the elimination of competing models. The interpretation can be further evaluated by additional research including: (1) further construction of PTt paths from exhumed deep levels of the orogen, in particular better defining the timing of peak pressure, peak temperature and initiation of exhumation, (2) comparison between PTt paths and numerical simulations of alternative mechanisms including delamination, (3) paleoelevation studies of Cretaceous to Early Tertiary sedimentary basins and paleohydrologic systems to determine the topographic evolution of the Sevier hinterland through the Late Cretaceous to Paleocene, (4) further study of potential Maastrichtian-Paleocene sedimentary deposits in the Sevier hinterland, and (5) further petrochemical and field studies of the Late Cretaceous granites to evaluate their petrogenesis.

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