SHRIMP-RG U-Pb isotopic systematics of zircon from the Angel Lake orthogneiss, East Humboldt Range, Nevada: Is this really Archean crust?: COMMENT

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Premo et al. (2008) present new SHRIMP-RG U-Pb zircon data from the orthogneiss of Angel Lake in the East Humboldt Range, Nevada, reinterpreting the age and origin of a rock body that previously had been interpreted as delimiting the southwestern extent of the Archean Wyoming province based on integrated field study and U-Pb ID-TIMS zircon analysis (Lush et al., 1988). Using zircons from the same sample originally collected by A.W. Snoke and J.E. Wright (RM-9), Premo et al. (2008) document Late Cretaceous ages of 91–72 Ma for the clear, oscillatory-zoned rims of many zircons from this sample, conclusively demonstrating the presence of Late Cretaceous melt in this migmatitic gneiss. Furthermore, they reinterpret the core grains as detrital zircons inherited from Meso- to Neoproterozoic metasedimentary source rocks. The potential detrital grains chiefly yield Late Archean apparent ages but also include a variety of Proterozoic apparent ages.

The work of Premo et al. (2008) clearly represents an important advance and offers a plausible interpretation of this regionally important rock unit. However, we note the lack of any significant discussion of the field relationships of this rock unit, and as the individuals who have been primarily involved in the field mapping of this area and the design of the sampling strategy, we seek to correct that shortcoming here, as well as to develop an alternative interpretation of the Premo et al. (2008) data that we believe better fits available constraints and preserves the earlier Archean interpretation (Lush et al., 1988). We propose that the orthogneiss of Angel Lake originated in Late Archean time, but was subsequently affected by intense Late Cretaceous metamorphism and migmatization that produced the observed Late Cretaceous zircon rims as well as resulting in profound disturbance of the abundant older zircon fractions. We note that either interpretation is consistent with earlier reports of Late Cretaceous metamorphism, deformation and migmatization in this deeply exhumed terrain (Snoke et al., 1997; McGrew et al., 2000). Finally, regardless of whether our interpretation or that of Premo et al. (2008) is preferred, we offer some comments on the importance of widespread mid-crustal melt for the interpretation of Late Cretaceous deep-crustal tectonics in the hinterland of the Sevier orogenic belt.

First, we focus on the field relationships necessarily neglected by Premo et al. (2008), who have not conducted field studies in the area. Previous mapping of the area documents a complex tectonic assemblage dominated by a large, southward-closing recumbent fold-nappe (the Winchell Lake nappe) ≥7 km in amplitude (Lush, 1982; Lush et al., 1988; McGrew, 1992; McGrew et al., 2000). The orthogneiss of Angel Lake cores this structure and is enfolded by a complex sequence of paragneiss units, the innermost of which is termed the paragneiss of Angel Lake, consisting mostly of migmatized quartzofeldspathic schist, but also including pure and impure quartzite and fuchsitic quartzite (see Snoke et al., 1997, their fig. 8). In turn, enfolding the gneiss complex of Angel Lake is a sequence of quartzite, schist, calcareous paragneiss, and calcite and dolomite marble that we correlate with the miogeoclinal sequence of the eastern Great Basin on the basis of similarity in lithostratigraphic sequence. Aside from the contrast in lithology, the main reason for inferring an older age for the gneiss complex of Angel Lake is that both the orthogneiss and paragneiss contain widespread bodies of amphibolite that are absent from the surrounding, inferred miogeoclinal metasedimentary sequence. We interpreted these amphibolite bodies to be metamorphosed mafic intrusions of probable Proterozoic age, and we note that Proterozoic metadiabase is widely reported from the Archean and Paleoproterozoic basement complexes of the western U.S.

Taken together, the above field relationships challenge the interpretation of Premo et al. (2008) of a Late Cretaceous age for the gneissic host rock of the Angel Lake sequence. If this rock is a Late Cretaceous granitic rock unit, then why is it not observed to intrude the surrounding metasedimentary sequences? More importantly, how would Premo et al. (2008) interpret the widespread orthoamphibolite boudins? Presumably, the monzogranitic orthogneiss did originate from melting and interaction with an older metasedimentary source, and there are metasedimentary enclaves within the orthogneiss that we originally interpreted as xenoliths of Archean paragneiss (McGrew, 1992). Possibly, these might be reinterpreted as Proterozoic xenoliths in a much-younger Cretaceous granite, but why then are there not also xenoliths of the surrounding inferred Paleozoic metasedimentary rocks (such as the marble, which is quite distinctive from anything observed in the paragneiss of Angel Lake)? While not absolutely definitive, these field relationships clearly favor the Archean interpretation.

We turn now to the character of the orthogneiss and the immediate relationships of the sample locality. When originally collecting the sample, A.W. Snoke and J.E. Wright were well aware of the migmatitic character of the rock, and because they were seeking to test an Archean age hypothesis, they sought to avoid obviously younger leucogranitic dikes, veins, and seams by picking through the rock fragments to sample those domains they judged to be most representative of the host gneiss. The host rock is a rather distinctive coarse-grained, biotite monzogranitic

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orthogneiss with a distinctive striped appearance due to alternation of biotite-rich seams with more feldspathic domains (Fig. 1). Locally, it contains distinctive large augen porphyroclasts, and in general appearance, it strikingly resembles Archean augen orthogneissic rocks observed throughout the Archean Wyoming province. Despite the best efforts of Snoke and Wright to avoid younger rock, the ubiquitous character of leucogranite penetration throughout this terrain makes it unsurprising that there would be a zircon fraction grown in equilibrium with younger melt that Premo et al. (2008) have now documented to be Late Cretaceous in age. As they rightly point out, this episode of melting correlates with an important magmatic event previously recognized in the East Humboldt Range and adjoining Ruby Mountains (Batum and Barnes, 1999; McGrew et al., 2000). However, this observation itself poses a question for the Premo hypothesis: if the younger leucogranitic rock is Late Cretaceous in age, is the distinctive gneissic host rock also the same age? Why then is there not a single example of a Late Cretaceous overgrowth on a slightly older Cretaceous igneous core?

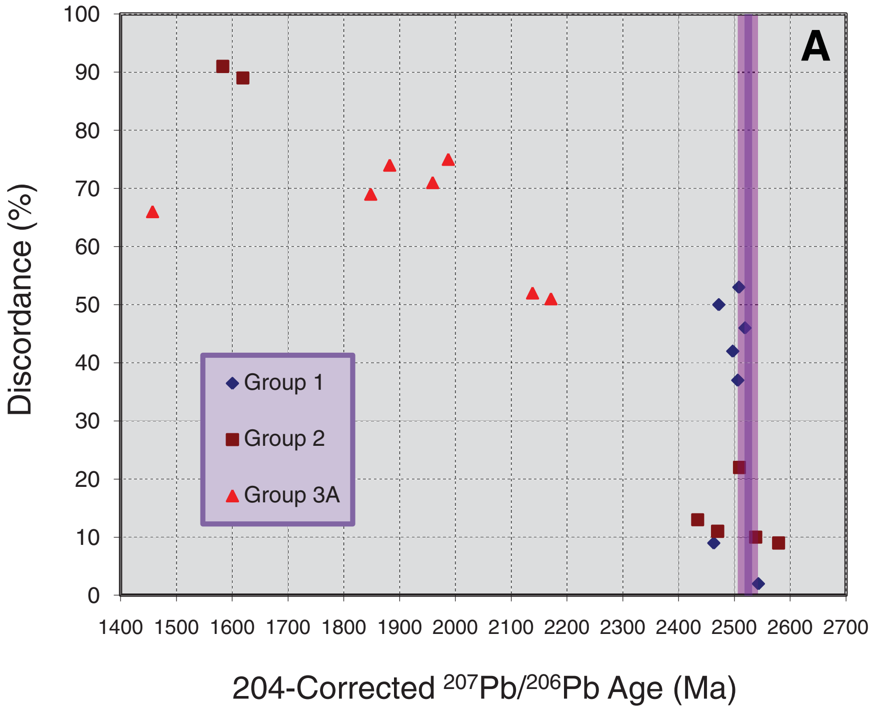
We also have some questions that pertain to the interpretation of the newly published SHRIMP results. In particular, one of the most challenging pieces of information for the Archean interpretation is the presence of Proterozoic zircons, but we note some characteristics of the age data for these zircons that call their significance into question. First, as shown in Figure 2A there is a strong correlation between the discordance of the zircons and their age, with all the Proterozoic zircons being >50% discordant, and, in general, the greater the discordance the younger the age. Why should only the most disturbed zircons yield Proterozoic ages? Additionally, as shown in Figure 2B, these same zircons yield exceedingly low Th/U ratios in contrast with the early Paleoproterozoic and Archean zircons, suggesting the possibility of metamorphic resetting, especially in the absence of clear oscillatory zoning. Moreover, Premo et al. (2008) demonstrate that these zircons fractions fall along a discordia with an upper intercept at 2526 ± 22 Ma and a lower intercept at 108 ± 91 Ma (Premo et al., 2008, Fig. 5). If these are indeed Proterozoic detrital zircons, then why should these unrelated Proterozoic zircon fractions happen to define a chord with an Archean upper intercept? Taken together, does the principle of parsimony not favor the alternative hypothesis that these relationships record differential Pb loss from an original Archean protolith?

Even if, for the sake of argument, we accept at face value the profoundly discordant $^{207}Pb/^{206}Pb$ ages reported by Premo et al. (2008), the correlation between these ages and previously reported zircon age peaks from the Great Basin is less than compelling. In particular, four of the nine Proterozoic zircon ages reported come from a time window in the mid- to early Paleoproterozoic (~1.95–2.5 Ga) that appears to be largely barren of zircon ages in the western U.S. Cordillera (e.g., Stewart et al., 2001). Furthermore, the complete absence of a Grenville-aged peak seems especially problematic for any likely NeoProterozoic source rock, such as the McCoy Creek Group.

One of the chief lines of evidence cited by Premo et al. (2008) is the apparently detrital character of some of the Archean zircon grains. In this we have little expertise, but we query whether the rounded morphologies of some of the metamict cores of grains could not be produced by solution in contact with the undoubted Late Cretaceous melt? Secondly, we note that although a few of the Late Archean zircons show striking detrital morphologies (most persuasively, grain 9 cited by Premo et al., 2008), most are not nearly so persuasive, and in any case, this observation does not preclude the Archean magmatic interpretation. Given the monzogranitic composition of the pluton and the presence of inferred metasedimentary xenoliths, it could very easily have a source terrain consisting, at least in part, of Archean metasediment, and so there is every prospect that there could be some older Archean detrital zircons incorporated along with juvenile Archean magmatic zircons. In particular, we note that the most persuasive detrital zircon cited by Premo et al. (2008) (grain 9 cited above) also yields one of the oldest $^{207}Pb/^{206}Pb$ ages (2543 Ma as contrasted with 2526 Ma for the upper intercept with concordia), making it an ideal candidate to be an older, Archean detrital zircon. The incorporation of slightly older Archean inherited zircons could also help to explain the spread in Archean $^{207}Pb/^{206}Pb$ ages cited by Premo et al. (2008).

Premo et al. (2008) also cite the tighter clustering of the Cretaceous REE (rare earth elements) patterns as contrasted with REE patterns from the Late Archean zircons as evidence for a detrital origin of the Archean grains. However, given the evidence discussed above that the Precambrian U/Pb ages are disturbed, is it surprising that the REE systematics of the Archean

Figure 1. Typical exposure of the migmatitic, banded biotite quartzofeldspathic orthogneiss of Angel Lake, northern East Humboldt Range, Nevada. We interpret this orthogneiss as an original Late Archean monzogranite that has experienced penetrative deformation and migmatization during the Late Cretaceous. This orthogneiss is pervasively injected with leucosome layers consisting of very coarse-grained leucogranite of presumed Late Cretaceous age, such as the pegmatite layer at the top of this photograph. Note the subconcordant amphibolite sheet (lower part of photograph), interpreted here as a partially dismembered original mafic dike. Locally, enclaves of paragneiss also occur within the orthogneiss body, and could be wall-rock xenoliths or dismembered infolds of the surrounding heterogeneous paragneiss unit.



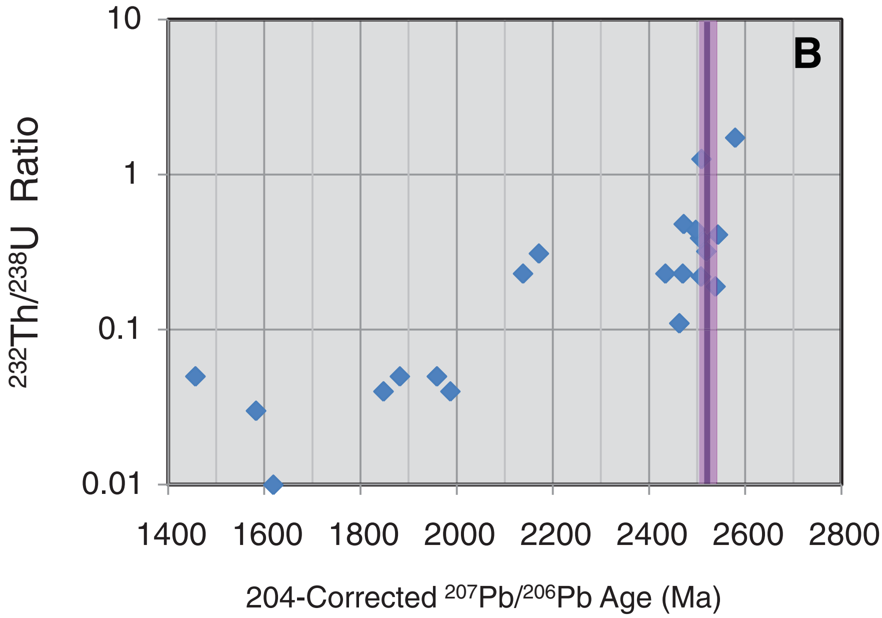


Figure 2. A) Plot of $^{207}Pb/^{206}Pb$ age versus % discordance for SHRIMP U-Pb zircon data of Premo et al. (2008). Proterozoic zircon data are >50% discordant, and in general, the younger the age, the greater the discordance. In contrast, all Archean zircon data are <55% discordant. Data points are color-coded according to which group they belong in the three groups identified by Premo et al. (2008). The violet band represents the upper intercept of concordia for this sample, with uncertainty. B) Plot of $^{207}Pb/^{206}Pb$ age versus $^{232}Th/^{238}U$ ratio for SHRIMP U-Pb zircon data of Premo et al. (2008). Note that the Proterozoic zircon data show low $^{232}Th/^{238}U$ ratios (mostly <0.1), suggesting metamorphic resetting, especially in the absence of clear oscillatory zoning. The violet band represents the upper intercept with concordia for this sample, with uncertainty.

grains would also be disturbed? After all, not only could the Archean rock include Archean detrital zircon grains as noted above, but it also has experienced polyphase deformation and high-grade metamorphism to which the Late Cretaceous zircon rims were not exposed. In this light, it is worth noting that the nature of the disturbance resembles other documented cases of metamorphic recrystallization that show enhanced LREE's and a decrease in Dy/Sm ratio (e.g., Hoskin and Black, 2000, fig. 6d). Finally, we note that the grain with the most disjunctive REE pattern, grain 2B (fig. 8b of Premo et al., 2008) also yields the very oldest zircon age reported (2579 Ma). We agree with the Premo et al. (2008) interpretation that this is likely an inherited Archean detrital grain, but that in no way precludes a slightly younger Archean magmatic age interpretation for the body as a whole.

We conclude that none of the lines of evidence advanced by Premo et al. (2008) definitively indicates a Late Cretaceous age for the orthogneissic host rock of Angel Lake. On the contrary, when interpreted within the context of the field relationships, the geochronological data favor the original Archean interpretation for the age of the orthogneiss of Angel Lake. Nonetheless, because the orthogneiss is observed only from the core of the Winchell Lake fold-nappe, it is at least somewhat allochthonous, and this interpretation does not necessarily require the directly underlying crust to be Archean in age, although it certainly does not preclude that possibility. In fact, a better delimitation of the extent of the Archean crust in the subsurface could help constrain the vergence direction of the fold-nappe.

Although we continue to prefer the original Archean interpretation of Lush et al. (1988), we acknowledge that the work of Premo et al. (2008) conclusively demonstrates the presence of Late Cretaceous melt in these migmatites and points toward a need for additional work to resolve between competing hypotheses for the age of the host gneiss. We suggest a variety of tests that could be applied with the collection of additional data to resolve this important problem. For example:

(1) Any zircons that could be extracted from the amphibolitic bodies common throughout the orthogneiss sequence of Angel Lake should not preserve detrital zircons, and (if interpreted as intrusions rather than xenoliths) should give a minimum age for the surrounding country rock. In the absence of zircon, an Nd model age might be just as persuasive.

(2) It would be interesting to compare the zircon systematics of the orthogneiss of Angel Lake with zircons from the inferred Neoproterozoic paragneiss complex of Lizzie's Basin in the central East Humboldt Range (tentatively

correlated with the McCoy Creek Group by McGrew, 1992) since, under the hypothesis of Premo et al., 2008, the McCoy Creek Group would be a likely potential source rock for the Angel Lake orthogneiss. Some of the paragneiss of Lizzie's Basin is extensively migmatized, whereas some is not, and individual units can be traced across the migmatitic front. Therefore, there is an opportunity to appraise not just the detrital zircon provenance of the metasedimentary host rock but also how the zircon systematics are affected by the process of partial melting and infiltration by exogenous fluids.

(3) A similar migmatitic boundary is described by McGrew et al. (2000) in the northern part of the East Humboldt Range, such that units on the upper limb of the fold-nappe are far less migmatized than the same units on the lower limb. The mapping of McGrew (1992) postdated the collection of sample RM-9, and with the benefit of hindsight it could be beneficial to resample the orthogneiss of Angel Lake at a structurally higher and hopefully less migmatized level. In the Clover Hill area, Snoke (1992) also recognized a less migmatized variant of the orthogneiss of Angel Lake that could be sampled and dated.

In sum, both hypotheses are falsifiable with existing technological capabilities, and we are optimistic that future work can conclusively distinguish between them.

Finally, we conclude by underscoring the tectonic significance of the discovery by Premo et al. (2008) of extensive Late Cretaceous melt within the core and lower limb of the Winchell Lake fold-nappe, regardless of whether or not the gneissic host rock of Angel Lake eventually turns out to be Late Archean in age. The presence of extensive syntectonic melt associated with fold-nappe emplacement compellingly suggests that the migmatitic isobath (i.e., the depth level at which large components of the crust reached partial melting conditions) strongly influenced the localization of strain at a crustal scale. We suggest that this profound rheological boundary zone concentrated tectonic dislocation in the deep crust beneath the hinterland of the Sevier orogenic belt such that minor perturbations in the flow-field at this boundary could amplify into major structures such as the Winchell Lake fold-nappe in this area or the Soldier Peak or Lamoille Canyon fold-nappes further south. In summary, the deep crust of the hinterland of the Sevier fold-and-thrust belt was dramatically weakened by the presence of abundant, syntectonic, anatectic granitic melt, and large-scale deep-crustal flow exerted a crucial control on the structural style in this part of the orogen during the Late Cretaceous.

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