

Depositional history, tectonics, and provenance of the Cambrian-Ordovician boundary interval in the western margin of the North China block: Reply

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INTRODUCTION

We thank Lee and Lee for their thoughtful comment on Myrow et al. (2015), a study of the Cambrian–Ordovician sections in Inner Mongolia, northwest China. We discuss the points that they raise below.

CAMBRIAN-ORDOVICIAN UNCONFORMITIES WITHIN THE NORTH CHINA BLOCK

The first point that these authors raise is concerned with the Cambrian–Ordovician unconformity we described at the Subaiyingou section in Inner Mongolia. In our paper, we mention three places in the North China block (i.e., Sino-Korean block), as well as other locations around the world, where Cambrian–Ordovician unconformities are present. The North China block localities we referred to include the eastern Taebaeksan Basin (South Korea); the northern Daqingshan Mountain region, west of Hohhot, North China; and the northeast Dayangcha region, Jilin Province, northeast China. Whether these sections have uniformities or not is not central to our paper, given that our paper concerns the western margin of the North China block, and that these other areas were discussed simply to provide coverage of the nature of the Cambrian–Ordovician interval in other parts of the North China block. We do not purport to be experts on these sections, so we use published

information to address the points brought up by the authors concerning the first and third of these localities.

Lee and Lee point out that there is a shift from carbonate-shale deposits to sandstone-rich strata across the Cambrian–Ordovician boundary in the Taebaeksan Basin region and suggest that the section is conformable, not unconformable, based on biostratigraphic data. In Table 1 of Myrow et al. (2015, p. 1190), we listed the section as containing a “brief unconformity between the uppermost Cambrian and lowermost Ordovician” based on detailed sedimentological and sequence-stratigraphic work of Kwon et al. (2006). Lee and Lee state that “Late Furongian to earliest Tremadocian trilobite biozones successively occur across the Hwajeol and Dongjeom formations, which are well correlated to those of North China and other parts of the world (Choi and Chough, 2005; Choi et al., 2016).” Lee and Choi (2007) presented the most detailed biostratigraphic data for the Dongjeom Formation, which has a fossiliferous lower member and sandstone-dominated unfossiliferous middle and upper members. The lower member has three uppermost Cambrian trilobite biozones (*Eosaukia/Mictosaukia*, *Pseudokoldinioidea*, and *Richardsonella*). The upper ~7 m of strata, just below the shift to sandstone-rich facies, contain fauna of the *Richardsonella* zone, which is mostly uppermost Cambrian but spans into the lower Tremadocian. Lee and Choi (2007) considered the fauna in the Dongjeom Formation to be Upper Cambrian (i.e., lower part of the *Richardsonella* zone), and from our review of

the literature, there are no diagnostic lowermost Tremadocian faunas in the formation. The recent publication by Choi et al. (2016, their figs. 3 and 8) also appears to show the lower part of the Dongjeom Formation as Furongian. The overlying Dumugal Formation contains Upper Tremadocian trilobites of the *Asaphellus* zone. Thus, the available data reveal a biostratigraphic gap between lower *Richardsonella* zone and *Asaphellus* zone faunas, which represents the entire lower Tremadocian. This gap is illustrated in Choi et al. (2016, their fig. 8). The fact that the intervening interval is made up largely of sandstone is consistent with a break in the section. In addition, Kwon et al. (2006) placed a megasequence boundary at the base of the Dongjeom Formation and described the overlying megasequence as consisting of “lowstand coarse-grained siliciclastics.” From a sedimentological perspective, the boundary is almost certainly at the base of the sandstone that rests on the fine-grained, carbonate-rich, uppermost Furongian strata at the top of the lower member of the Dongjeom Formation. Thus, based on previously published sequence stratigraphic interpretations and a lack of verifiable lower Tremadocian fauna, the most parsimonious interpretation is that there is a megasequence boundary, lowstand sandstone, and a hiatus in the section, as we originally described.

With regard to the northeast Dayangcha region of northeast China, Lee and Lee make reference to the paper by Ripperdan et al. (1993), which shows two significant breaks associated with the Cambrian–Ordovician interval, and Lee and Lee do not contest that conclu-

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sion. Lee and Lee thus appear to be making the point that these breaks were not produced by subaerial erosion. Myrow et al. (2015) did not state that the breaks were created by subaerial erosion (i.e., a subaerial unconformity or type 1 sequence boundary) in the text. In Table 1 of Myrow et al. (2015), we noted the presence of sedimentary structures suggestive of episodic subaerial exposure, such as desiccation cracks, based on the work of Zhang et al. (1999), and we noted that Zhang et al. (1999) mentioned subaerial erosional surfaces and drowning surface. It is unclear whether Zhang et al. (1999) considered the latter features to be related to short-term episodic events or to a major episode of erosion and production of an unconformity (i.e., type 1 sequence boundary). We have not worked on these sections and thus have no opinion on this conclusion. In either case, Ripperdan et al. (1993) reported breaks in the section, and we reported that in our paper. Lee and Lee appear to suggest that the facies of the section are inconsistent with subaerial exposure (e.g., lime mudstone and shale, and glauconitic strata). We would agree that the facies described by Chen et al. (1988) are not likely associated with subaerial exposure, but a subsequent study of the sedimentology and sequence stratigraphy included descriptions of desiccation cracks in an uppermost highstand systems tract strata (Zhang et al., 1999).

PROVENANCE

Lee and Lee suggest that a piece of evidence to support changes in provenance, a shift in detrital zircon spectra among Precambrian, Cambrian, and Ordovician samples described by Darby and Gehrels (2006), may not be valid based on the low numbers of analyzed grains in their study in the Ordovician sample ($n = 32$). Our sample, which was also taken from the lower part of the Sandaokan Formation, has more grains ($n = 53$). Our data set has strong peaks at ca. 1820 Ma and ca. 2520 Ma, which are close to the large peaks (i.e., ca. 1900 and 2600 Ma) that Darby and Gehrels (2006) described in their Ordovician sample. Taken together, data from Darby and Gehrels (2006) and our data, from approximately the same stratigraphic level, provide a statistically robust ($n = 85$) data set that supports a similar range of ages relative to the underlying Precambrian and Cambrian strata, but with much more pronounced Neoproterozoic to Paleoproterozoic peaks. We agree with Lee and Lee that the shift to larger peaks of these ages does not require a major shift in provenance, but it does likely reflect a change that resulted from uplift and

erosion, in this case, denudation to levels that were composed of greater percentages of older Precambrian source rocks.

UPLIFT/TECTONICS

Lee and Lee agree that there is evidence for a “major shift in sedimentary succession” in the North China block during the late Cambrian Series 3, noting that Meng et al. (1997) also interpreted a tectonic collision of the North China block at this time. We are confused as to what the authors are suggesting, since these points appear to support our own hypothesis that uplift took place during the Cambrian-Ordovician boundary interval. Lee and Lee make the case that there is evidence from across the North China block for widespread tilting, shoaling, and the development of unconformities. They wrote that “the tilting event could be responsible for the formation of the long-lasting unconformity, and discussion on this idea would be necessary” (Myrow et al., 2015, p. 1190). We do not understand what additional conclusions are needed. We do not suggest that evidence for changes across the boundary all across the North China block are necessarily directly related to tectonic activity along the western margin, but the effects could be quite widespread, and evidence of uplift in other parts of the North China block does not invalidate our hypothesis.

SEA LEVEL

Lee and Lee also raise the question of whether the Cambrian-Ordovician unconformity we describe for sections in Inner Mongolia might have been produced by eustatic falls instead of tectonic uplift. They mention three eustatic falls that might have caused the unconformity at the Subaiyingou section: (1) a third-order Cambrian Series 3–Furongian boundary event (Sauk II–III sequence boundary in Laurentia; Saltzman et al., 2004; Chen et al., 2011), (2) a Cambrian-Ordovician boundary event recorded in Laurentia (Sauk IIIA–IIIB sequence boundary; fig. 4 in Morgan, 2012), and (3) a second-order earliest Middle Ordovician event (Sauk-Tippicanoe sequence boundary; Meng et al., 1997; Kwon et al., 2006; Morgan, 2012). Both of the first two sea-level falls could have affected the Inner Mongolian region of the western North China block, but these could not be a factor for the majority of the hiatus represented by the unconformity in this area, because these events predate the majority of the missing time: specifically, all of the Lower Ordovician and most of the Middle Ordovician. In terms of the third event, the timing of the Sauk-Tippicanoe megasequence boundary corresponds with the transition between the *Histiodella*

holodentata and overlying zones (*Phramagodus harrisi* zone or equivalent *Histiodella kristinae* and *Eoplacognathus suecicus* zones; Ethington et al., 2012; Edwards and Saltzman, 2014, their fig. 4). Since the base of the Sandaokan Formation is part of the *H. holodentata* zone, the Sauk-Tippicanoe boundary must lie above the Cambrian-Ordovician unconformity and thus cannot be responsible in any way for the unconformity. Thus, although eustasy could have played a role in removal of some of the record in our succession (uppermost Cambrian in particular), it was not likely the major factor.

SUMMARY

We thank Lee and Lee for their thoughtful comment, and we appreciate their interest in rocks of this age exposed within the North China block. We do not see any evidence based on the literature show that breaks are absent from the sections they mention in the other parts of the North China block. We agree that the detrital zircon data do not suggest a radical change in provenance between Ordovician and older strata, but the shift in relative heights of peaks is consistent with a change in the various proportions of different age rocks being eroded at the time. The specific duration of the unconformity in Inner Mongolia is not consistent with eustasy being the major driver of erosion, although it may have had some influence in the erosion of latest Cambrian strata.

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