Messinian climate change and erosional destruction of the central European Alps: COMMENT AND REPLY

COMMENT:

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The contribution of Willett et al. (2006) is interesting because understanding the effects of climate change on erosion rates may help ascertain the causality of human activity. However, their evidence for climate influence on Alpine erosion rates is indirect and not robust. It is not erosion or exhumation rates that are dealt with by Willett et al. (2006), but merely accommodation, which is a function of rates of creation of sedimentation space, sediment supply, and deposition; these are quite different issues.

The amounts of sediment per time unit show similar patterns north and south of the Alps, in the Molasse and Po basins, respectively. The uppermost Messinian is aberrant only in the Po Basin (Willett et al., 2006). Because this would argue against climate influence on Alpine erosion, Willett et al. explain it by assuming desiccated Mediterranean basins and, consequently, a significantly lowered base level during the aftermath of the Messinian salinity crises. The only argument left for climate influence is a decrease in amounts of sediment in pre-Messinian time and an increase in post-Messinian time. This could reflect slow establishment of evaporative climate conditions before and during formation of evaporites, and the return to normal climate after the salinity crisis. However, Willett et al. use the 'desiccation model' (Hsü et al., 1973) that is commonly explained by tectonic closure of the Atlantic–Mediterranean connection, and climate implicitly does not play a role in this model. Even if this model is correct, Alpine erosion serves as a very insensitive climate proxy at best.

A second serious problem with Willett et al.'s argument is that the Po Basin is not only a Molasse basin for the Alps but also a synsedimentary foreland basin of the northern Apennines. The Po Basin and other Northern Apennine foreland basins received clastic sediment both from the Alps and from the Apennines themselves. Foreland basins successively developed from the Oligocene until the Pleistocene as a result of loading upon advancement of Apennine thrust sheets. During advancement of the deformation front, the foreland, as well as thrust-top basins, were successively uplifted and eroded, yielding clastic sediment. The Miocene, and in particular the Messinian, was a time of intense tectonic reorganization of the Mediterranean, which consisted of a number of basins in a complex array of differentially moving plates and microplates. Tectonic activity is well documented in the Apennines. Angular unconformities between Lago Mare deposits and underlying evaporites in the northern Apennines mark Messinian tectonic phases (Artoni et al., 2004). Similar Tortonian and Messinian syntectonic activity took place in the Eastern Betic basins (Krijgsman et al., 2006) and other parts of the Mediterranean (e.g., Aksu et al., 2005). Several phases of synsedimentary tectonic activity deforming individual Messinian evaporitic successions have been reported from the Levantine basin (Netzeband et al., 2006). This forms compelling evidence for a major change in the Messinian plate kinematic framework.

Although the clastic nature of part of the Messinian evaporite deposits was recognized early, e.g., in the Sicilian basins (Schreiber et al., 1976), it has long been ignored. Recent studies reveal that the Mediterranean never dried up (Roveri et al., 2001; Matano et al., 2005) and the evaporite deposits in the deep basins are cannibalized shallow-marine evaporites (Manzi et al., 2005; Roveri and Manzi, 2006). Deposition in deeper basins by mass-flow mechanisms such as turbidity current flows, submarine debris flow, and large-scale slides-slumps is in full agreement with the well-documented Messinian tectonic activity.

Accommodation of the Po Basin thus cannot be used to quantify Alpine erosion rates. Neither can a dramatic lowering in base level be evoked for explaining increased rates of net deposition. A desiccated Mediterranean, merely based upon wrongly interpreted core material with nodular calcium sulfates (Hardie and Lowenstein, 2004), seems unlikely.

The significant climate changes during the salinity crisis (e.g., Andersen et al., 2001) and afterwards in the Pliocene (e.g., Chandler, et al., 1994) are not reflected at all in the data presented by Willet et al. It thus seems that tectonic activity in the source and depositional areas was the main factor determining the amounts of sediment per stratigraphic time unit.

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In his Comment, Molenaar argues that foreland sedimentation is determined by accommodation space, not sediment yield and therefore our methodology of measuring sediment volume does not actually measure erosional fluxes from the Alps. Using sediment volumes to estimate erosion is always a risky proposition as few orogenic systems are closed to sediment loss and mass balance is only possible in a closed system. Following (Hay et al., 1992) and (Kuhlemann, 2000), we (Willett et al., 2006) argue that the Alpine depositional system is largely closed if we consider distal basins, including the Rhine and Rhone deltas and the Adriatic Sea. If this is correct, we are, in fact, measuring erosional yield from the Alps.

Molenaar's second point, that the Po Basin and the Adriatic Sea serve as the foreland of the Apennines as well as the Alps is true. However, we have accounted for the relative contribution of the Apennines. We were perhaps not clear in our original paper, as we simply cited Bartolini et al. (1996), but following their analysis, we assume that only 25% of the Pliocene and Quaternary sediment in the Adriatic and 33% of the sediment in the Po is from an Alpine source. This is a conservative estimate; Kuhlemann (2000) assumed that 50% of the sediment was Alpine derived. Unless more than 90% of the Pliocene sediment in the Adriatic derives from Apenninic sources, our conclusion that the Alpine yield increased from the Miocene to the Pliocene in the southern drainage basins is robust. Furthermore, the Apennines are not relevant to the northern drainage basins, which also exhibit an increase in sediment yield at the onset of the Pliocene.

Molenaar also takes issue with the prevailing theory for the Messinian salinity crisis (MSC). We find the chronology and sequence of events developed over the last decade (Krijgsman et al., 1999; Rouchy and Caruso, 2006; Roveri and Manzi, 2006)) quite compelling and the many meticulous studies of the late Messinian stratigraphy provide exceptional resolution of changes in depositional and climatic environment. No reasonable tectonic model can explain the rapid changes and short duration of the MSC (650 k.y.) or, particularly, the basin-wide synchronicity of the MSC depositional events, leaving us to investigate hydrologic and climatic forcing (Pierre et al., 2006). The final 180 k.y. of the MSC is characterized by the Lago Mare depositional conditions. The deposits of the Lago Mare are typically high-energy, fluvio-deltaic clastic sediments, brackish water lagoonal deposits and reworked evaporites, all of which suggest an increase of fresh water supplied to the basins and an increase in fluvial transport, and the simplest explanation for these two phenomenon is higher precipitation in proximal drainage basins. In addition, the extensive evidence of submarine erosion indicates a lowered base level for some fraction of the MSC. This would result in reworking of shelf sediments and thus provides an explanation for the extreme post-evaporitic Messinian sedimentation rates we find. For this reason, we do not interpret these sediments as being diagnostic of increased Alpine erosion, although the alternative interpretation lends more support to our thesis that the climate became more erosive during Lago Mare time.

Finally, we have not ignored independent data on climatic change at this time. The evidence for a global change in ice volume at precisely the onset of the Lago Mare conditions is one of the most compelling points that this is a climatically-driven event, and we cited two of the papers documenting this global change (Hodell et al., 2001; Vidal et al., 2002). Regional data are more contentious. There is not palynological support for extensive vegetation change at the onset or termination of the MSC. However, there is a clear increase in the relative frequency of *Pinus* pollen at the onset of Lago Mare conditions (Bertini, 2006; Fauquette et al., 2006). This is often interpreted as representative of a change in pollen transport conditions, but this could include increased fluvial transport in response to increased precipitation in source areas. This would also explain the apparent increase in continentality in the near shore marine record as observed by Warny et al. (2003).

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