Messinian climate change and erosional destruction of the central European Alps

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ABSTRACT

At the end of the Miocene, the European Alps ceased outward expansion, and tectonic uplift and exhumation shifted into the orogen interior. This shift is consistent with a change from orogenic construction to orogenic destruction, reflecting an increase in the ratio of erosional flux to accretionary flux. The coincidence of this change with an increase in sediment yield from the Alps suggests a climate-driven increase in erosional flux. The timing of deformation and sediment release from the southern Alps indicates that the tectonic change occurred synchronous with the last phase of the Messinian salinity crisis. We attribute the increase in erosional flux to a climatic shift to wetter conditions throughout Europe, likely augmented by the base-level fall that occurred during the Mediterranean dessication. This climate change is represented in the stratigraphic record by the Lago Mare deposits of the Mediterranean salinity crisis.

Keywords: Mediterranean salinity crisis, European Alps, Miocene, climate, erosional flux, accretionary flux.

INTRODUCTION

The close link between tectonics, surface erosion, and climate in the evolution of mountain belts has been hypothesized in a variety of theoretical and applied studies (Willett, 1999). The sensitivity of tectonics to erosion is particularly acute in active orogenic wedges that develop at convergent plate boundaries, where tectonic accretion of crustal material leads to self-similar growth of a critical wedge at a rate modulated by the accretionary flux and the erosional flux (Hilley and Strecker, 2004; Whipple and Meade, 2004). If accretionary flux outpaces erosional flux, an orogen enters a constructive state, expanding by propagation of deformation outward (Jamieson and Beaumont, 1988) (Fig. 1A). In the alternative case, an erosional flux larger than the accretionary flux will destroy the critical topography, leading to a smaller active wedge as deformation focuses in the core of the orogen to restore the critical taper, leading to a destructive state (Fig. 1B). The strong feedback mechanisms in this coupled system imply a tendency toward a steady state (Willett and Brandon, 2002). Changes in either the accretionary or erosional flux lead to changes in the steady width of the orogenic wedge, with transient deformation and sediment yield between these steady states (Stolar et al., 2006).

The late Tertiary history of the western and central European Alps is an example of such a coupled system; rates of growth of the orogen are dependent on the relative tectonic and erosional fluxes. The late Oligocene–early Miocene was characterized by focused exhumation of the Alpine core north of the Insubric Line with a stable foreland to the south, suggesting a near-steady size of the orogen (Schlunegger and Willett, 1999). In the middle Miocene, the Alps entered a constructional phase, expanding to the north and to the south (Schmid et al., 1996). Expansion came to an abrupt halt in the late Miocene or early Pliocene, with Lombardic thrusts at the southern Alpine front sealed by undeformed Pliocene sediments (Pieri and Groppi, 1981), the cessation of shortening in the Jura (Becker, 2000), and inversion and erosional unroofing of the Molasse Basin (Cederbom et al., 2004). In this paper we argue that the cessation of outward tectonic growth of the Alps is the direct response of intensified erosion that occurred in response to a wetter, more erosive climate that initiated in the Messinian and persisted into the Pliocene.

NEOGENE ALPS: EXPANSION AND CONTRACTION OF AN OROGENIC WEDGE

The western and central European Alps are a doubly-vergent orogen that formed in the Tertiary; they comprise highly metamorphosed crystalline rocks in their core (Lepontine core complex) and low-grade to unmetamorphosed thick-skinned and thin-skinned thrust belts on the external flanks (Schmid et al., 1996) (Fig. 2). Both sides of the Alps are bordered by peripheral foreland basins, the Molasse Basin in the north and the Po Basin in the south. The Jura Mountains, an external fold-and-thrust belt, is linked at depth to the Alps, making the Molasse Basin a piggyback basin in its late history. The Jura deformation initiated in its western end before 20 Ma (Bourquin et al., 1946), and became active toward the northeast in the late Miocene (Kälin, 1997). Deformation ceased prior to 3.4 Ma (Bolliger et al., 1993; Becker, 2000). In the latest Miocene or early Pliocene, the Molasse Basin was inverted; erosion continues to the present day. Cederbom et al. (2004) reported apatite fission-track data from the Molasse Basin that provided maximum ages of 4.8–5.6 Ma for the onset of cooling and provided an estimate of several kilometers of post-Miocene erosion (Fig. 2). Erosion of the Molasse Basin and the cessation of deformation in the Jura are consistent with stepping back of deformation into the orogen interior, most likely into the External Massifs, which exhibit young apatite fission-track ages (Michalski and Soom, 1990; Leloup et al., 2005) and evidence of recent deformation (Seward and Mancktelow, 1994; Persaud and Pfiffner, 2004).

In the south, the Lepontine core is separated from the south-vergent southern Alps by the Insubric Line, which partly accommodated crustal convergence between the European and Apulian plates by south-directed reverse faulting in the Oligocene and early Miocene (Schmid et al., 1996). Syntectonic stratigraphy suggests that Neogene deformation south of the Insubric Line started ca. 18 Ma. This deformation, referred to as the Lombardic phase, propagated southward, reaching its southernmost extent in the Messinian (Schumacher et al., 1996) (Fig. 2).

The timing of the end of Lombardic deformation is well defined by seismic reflection profiling of Alpine structures buried beneath the Po Basin sediments; age control is provided by exploration wells (Pieri and Groppi, 1981; Schumacher et al., 1996; Fantoni et al., 2001). Alpine structures involve Aquitanian–Tortonian units. Late Messinian postevaporitic deposits and early Pliocene units blanket the Alpine structures with little or no deformation, indicating deactivation of the thrusts in the Messinian, between 7.25 Ma and 5.3 Ma. The lack of preservation of early and middle Messinian deposits in the Po Basin makes more precise dating difficult, but evaporites associ-

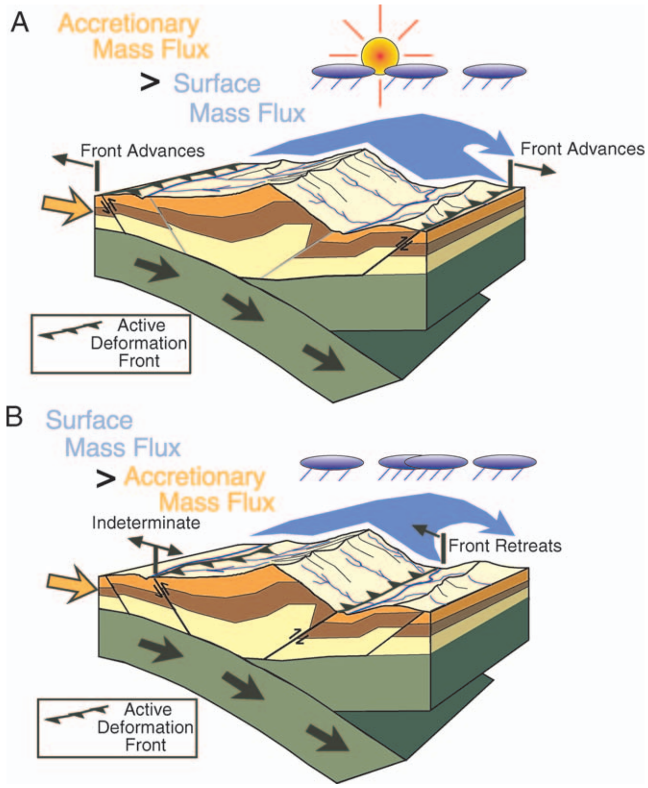

Figure 1. Constructive (A) and destructive (B) states of orogen, based on relative magnitude of accretionary flux, driven by convergence and erosional flux. Note difference in motion of deformation front relative to foreland.

ated with the late Messinian desiccation of the Mediterranean are ponded behind thrust structures that were active at the time of evaporite deposition (Fantoni et al., 2001). Postevaporitic deposits show little or no deformation, suggesting that deactivation of the thrusts occurred just prior to 5.33 Ma.

The Neogene history of the western and central Alps is thus characterized by orogen expansion to the north and south that reached its zenith in the latest Messinian, at which point the active wedge decreased in size, both thrust fronts became inactive, and deformation focused into the wedge interior. We interpret this change as indicating a shift from construction (Fig. 1A) to destruction (Fig. 1B).

MESSINIAN SALINITY CRISIS AND EROSION OF THE ALPS

The Messinian salinity crisis (MSC), in which the Mediterranean lost its connection with the world ocean system and became desiccated, is well identified throughout the Mediterranean Basin by both evaporitic deposits and erosional features associated with the catastrophic drop in base level (Hsü et al., 1977). The southern margin of the Alps underwent massive erosion as base level for alpine rivers dropped by hundreds or even thousands of meters. The Alpine rivers carved deep valleys across the modern Po Basin and incised far into the Alps, creating the deep valleys that today confine the Alpine lakes of northern Italy (Bini et al., 1978; Finckh, 1978) (Fig. 2A). The western and eastern Alps were less affected by the drop in base level because the wider continental shelf in these regions limited incision, but the widespread Messinian unconformity throughout northern Italy indicates extensive erosion in the central Alps and its foreland. The timing of the onset of the salinity crises has been well dated as 5.96 Ma (Krijgsman et al., 2002); the termination is taken to be the final marine incursion at end of the Miocene at 5.33 Ma. However, the stratigraphic record of the latest Messinian indicates a complex return to full marine conditions. Deep desiccation of the Mediterranean occurred over a short interval between 5.59 and 5.50 Ma, following deposition of the lower primary evaporates (Krijgsman et al., 1999). Subsequently, renewed deposition occurred under the so-called Lago Mare conditions, characterized by fluvial-deltaic and lagoonal environments and the presence of brackish-water fauna (Cita, 1979). These Lago Mare conditions indicate a change in the water budget of the Mediterranean Basin. This change has often been interpreted as establishment of a connection to Paratethys water bodies in eastern Europe or Asia (Hsü et al., 1977). However, the Lago Mare deposition is also characterized by proximal, coarse-grained, terrigenous fluvial-deltaic sediments with high-energy-transport and common flood deposits (Cita, 1979; Rouchy et al., 2001; Roveri et al., 1998; Fortuin and Krijgsman, 2003). This change in depositional environment indicates that the change in water budget reflects increased precipitation and runoff throughout the Mediterranean region, including the Alps (Rizzini and Dondi, 1978), and was not simply an expansion of the drainage area, although this may have occurred independently.

SEDIMENT YIELD

Although there is widespread evidence of incision in the Messinian, the depositional record of this erosion is difficult to assess given the deep basin deposition, wide dispersal, and short time span. For these reasons, sediment yield assessments have largely ignored the Messinian sediment budget or averaged it into the late Miocene (Kuhlemann, 2000; Kuhlemann et al., 2001). To obtain better resolution of sediment yield from the Alps, we calculated the sediment volume in the Po Basin from seismic reflection profiles using a stratigraphic classification that subdivides the Miocene (Fantoni et al., 2001) (for data and methodology, see GSA Data Repository[1]). This compilation indicates a large volume of sediment deposited in the late Messinian, corresponding to the postevaporitic Lago Mare sediments (Fig. 3B). Although this volume partially reflects recycling of shelf material in response to base-level fall, much of this sediment is coarse material from terrestrial, primarily alpine, sources. Furthermore, high yields continued through the Pliocene. Thus, there appears to be a systematic increase in sediment yield both north (Fig. 3A) and south (Fig. 3B) of the Alps, and this increased yield initiated during the late phase of the MSC.

INTERPRETATION: MESSINIAN CLIMATE CHANGE

The cessation of deformation in both the Lombardic thrust belt and the Jura as well as the inversion and erosion of the Molasse Basin occurred in the latest Miocene or early Pliocene. The coincidence of this decrease in the actively deforming width of the Alps with an increase in the sediment yield suggests that an increased erosional flux exceeded the accretionary flux and the orogen shifted from a constructive state (Fig. 1A) to a destructive state (Fig. 1B). On the southern Alpine front, for which the timing is known, the cessation of deformation occurred concomitant with the MSC, suggesting that Mediterranean dessication played a role in the increase of erosional flux. The deep incision of the southern Alps probably contributed to the abrupt halt of southward propagation of the Lombardic thrust belt, but the high sediment yield continued through the Pliocene and is also observed for drainages north of the Alps, so base-level fall cannot entirely explain the increase in ero-

[1]GSA Data Repository item 2006127, data and methodology, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

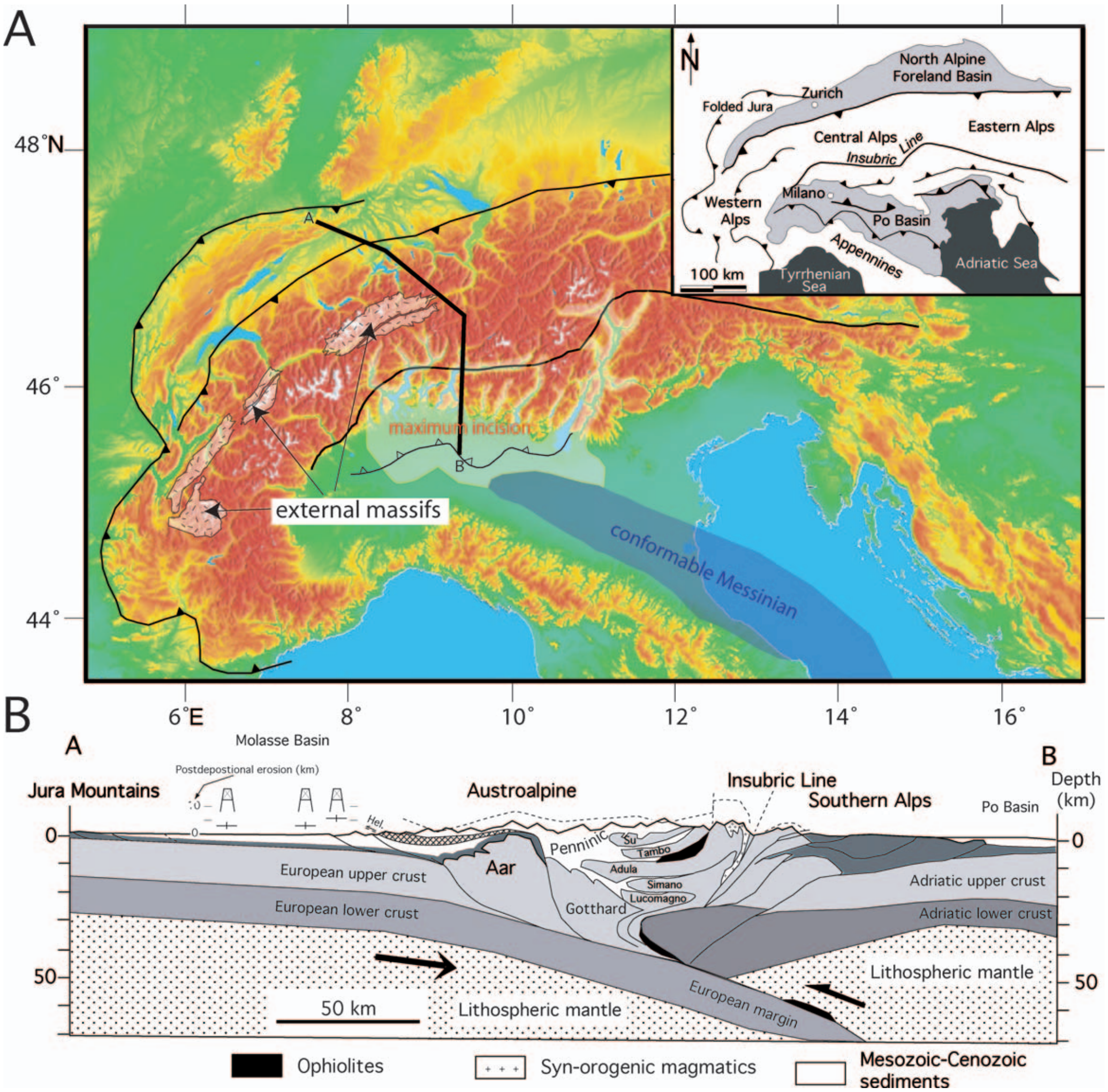

Figure 2. A: Topography and principle tectonic features of Alps. Documented region of Messinian erosion is indicated by shading. Western limit of region is poorly documented; erosion may continue into western Alps. Region of late Messinian deposition is indicated as conformable. B: Cross section of Alps showing major tectonic units. Modified from Pfiffner et al. (2002); erosion estimates in Molasse Basin are from Cederbom et al. (2004).

sional flux. The other important event that occurred in the late Messinian is reflected in the Lago Mare conditions of the Mediterranean that we argue represent a climate change that included higher precipitation. If the Lago Mare conditions in the Mediterranean reflect a shift in climate throughout Europe, we expect a higher sediment yield on both sides of the Alps, and potentially, a destructive state of the orogen, that would have persisted into the Pliocene.

There is a clear global driver to European climate change at this time. Based on the oxygen isotope record of benthic foraminifera in the Atlantic, Hodell et al. (2001) and Vidal et al. (2002) demonstrated that the period of expanded global ice volume that characterized the late Miocene ended at precisely 5.55 Ma, predating the end of the MSC, but coincident with the onset of Lago Mare conditions. The end of this period of expanded ice volume includes a warming of the Atlantic, and we infer that there was consequently higher precipitation in Europe, leading to the change in water budget for the Mediterranean. The warm, wet, postglacial climate produced the conditions that are characteristic of the Lago Mare phase of the MSC and the early to middle Pliocene of Europe (Fauquette et al., 1999; Fortelius et al., 2002).

CONCLUSIONS

The coincidence in timing between the MSC, the deactivation of the Lombardic thrust belt, the inversion and erosion of the North Alpine (Molasse) foreland basin, the termination of deformation in the Jura Mountains, and an increase in sediment yield both north and south of the Alps provides strong circumstantial evidence that these events are causally related, and are diagnostic of an increase in erosional flux from the Alps. This increase may have initiated with the base-level fall associated with the MSC, but the persistence of high sediment yield into the Pliocene suggests a wetter, more erosive climate that initiated with the end of the late Miocene glacial period and is marked by the Lago Mare conditions in the Mediterranean.

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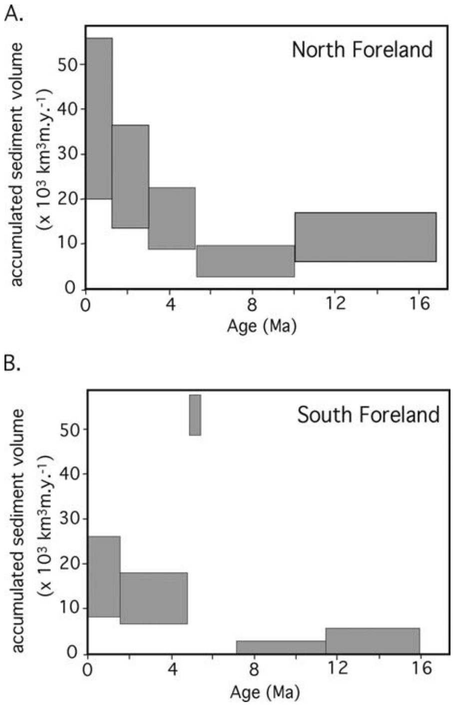

Figure 3. A: Sediment yield from northern Alpine drainages. Data are from Kuhlemann (2000), with modified range to reflect our estimate of uncertainty. B: Sediment yield from southern Alpine drainages (for methodology and data, see footnote 1).

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