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Title:

Does the Ebro basin connect to the Mediterranean before the Messinian Salinity Crisis?

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Abstract

The connection of the Ebro river to the Mediterranean is supposed to have played a major role in the relief rejuvenation of northern Spain and especially of the South-Pyrenees by lowering the initial base level of the Ebro internal drainage area down to the sea level. However, the timing and causes of this connection are still debated. A fundamental question is: was the Ebro river connected to the Mediterranean before or after the Messinian Salinity Crisis? Morphologic analysis and landscape evolution numerical modelling show that this connection did not exist before the Messinian Salinity Crisis but is effective from the Pliocene onward due to progressive regressive erosion.

Keywords: Ebro basin opening, Messinian Salinity Crisis, Sea level fall, Surface process model.

The Ebro Basin in NE Spain corresponds to the southern foreland basin of the Pyrenees with a Tertiary sedimentary fill. Until the end of the Eocene, the basin was open towards the Atlantic Ocean. Further tectonic shortening along the Pyrenees and the Iberian Range closed this western marine connection, resulting in internal drainage and lacustrine sedimentation during the Oligocene and the Miocene (Biro 1937, Reille 1971, Riba et al. 1983). At present the Ebro Basin is drained through the Ebro river toward the Mediterranean Sea and both the Ebro basin and the Pyrenees are deeply dissected by the current drainage network.

When the opening of the interior Miocene Ebro basin started is still the subject of debate. This is a key point in the understanding of both continental erosion dynamics and submarine sedimentation in NE Spain and NW Mediterranean respectively.

According to Roca (2001), and Evans and Arche (2002), the presence of a thick succession of deposits in the adjacent offshore Valencia Trough of Middle to Late Miocene age indicates a considerable flux presumably supplied by a proto Ebro river of a considerable size. For Riba et al (1983) and Serrat (1992) the opening of the interior basin started during the Miocene and was a combined result of lake capture by a Mediterranean stream and sediment overflowing of the basin. Quantitative validation of this mechanism by numerical modelling (Garcia-Castellanos et al. 2003) provides ages between 13 Ma and 8.5 Ma for the basin opening toward the Mediterranean. Field and Gardner (1990) observe a change of the sedimentary record from clays to prograding sandstones in the Valencia Trough, which they attribute to the capture of the Ebro basin during the Quaternary. Coney et al. (1996) state that the capture could result from either the Miocene rifting in the Valencia Trough or regressive erosion during the Messinian Salinity Crisis, or a combination of these two processes that would have led the Ebro river to erode across the Catalan Coastal Ranges.

From the analysis of erosion dynamics in the western Mediterranean and sedimentation pattern along the eastern Spanish margin from Miocene to Quaternary times, we argue hereafter that the Ebro basin was not connected to the Mediterranean Sea before the Pliocene.

The Messinian fluvial incisions

During the Late Messinian, the sea-level of the Mediterranean dropped dramatically (about 1500 m) consecutive to its isolation from the Atlantic waters and its subsequent desiccation (Hsü et al. 1973, Ryan 1976). This base-level fall induced the rejuvenation of the continental Mediterranean landscape, and especially the strong incision of the pre-Messinian

drainage network. Deep canyons developed along most of the present day valleys around the Mediterranean. This event, which lasted from 5.96 Ma to 5.32 Ma (Krijgsman et al. 1999), is called the Messinian Salinity Crisis (MSC) because of the concomitant deposit of a thick layer of evaporites. These incisions have been largely preserved due to the sudden reflooding of the Mediterranean during the Early Pliocene (Denizot 1952, Chumakov 1973, Clauzon 1982). A remarkable feature is the relation that exists at first order between the length of the Messinian incisions and the present-day drainage areas, so that the larger the drainage area, the longer the incision length (Fig. 1).

As a general rule, following the base-level fall of a drainage network, the length of river incision is related by a power law to the upstream drainage area (e. g. Schumm et al. 1987, Rosenbloom & Anderson 1994, Bishop et al. 2005). According to Loget et al (2005), in most of the Mediterranean region, the regional slopes and the size of the pre-Messinian drainage areas were similar to the present-day ones, so that the relation between the present-day drainage areas and the Messinian incisions reflects fluvial erosion dynamics during the MSC. A notable exception to this relation concerns the Ebro drainage area, the dimensions of which are of the same order (10^5 km²) of the Rhone ones (Fig. 1). Indeed in the Rhone valley, fluvial incision propagated more than 300 km inland and the canyon depth reached more than 1000 m in the downstream part (Gennesaux & Lefebvre 1980, Clauzon 1982). Therefore, if the Ebro basin was connected to the Mediterranean before the onset of the MSC, then a similar canyon would have incised far inland within the basin.

In fact offshore deep Messinian canyons do exist along the Spanish Mediterranean shelf, but their depth does not exceed 400 m (Farran & Maldonado 1990, Nelson & Maldonado 1990, Estcutia & Maldonado 1992, Frey-Martinez et al. 2004). To our knowledge, no Messinian canyon has been positively documented onshore. Some studies (Agustí et al. 1983, Martinell 1988, Arasa Tuliesa 1990, Maillard 1993) have reported an Early Pliocene,

marine to continental lithological succession that is identical to that observed in the infilling of inland Messinian canyons elsewhere around the Mediterranean. These series are separated from the underlying basement by a Late Messinian irregular erosional surface. This suggests that the offshore canyons could have propagated inland, but only a short distance from the present-day coastline. For example, a paleotopography is buried by Early Pliocene marine to continental sediments in the downstream Ebro valley, suggesting that incision had propagated only a few kilometers distance, from the coastline to near Tortosa (Agustí et al. 1983, Martinell 1988, Arasa Tuliesa 1990, Maestro et al. 2002).

Mass balance between eroded volume in the Ebro basin and coeval deposits in the Valencia Trough since the Pliocene.

According to Nelson (1990), most of the sediments transported by the Ebro river are deposited in the Valencia Trough and the deep-sea Valencia fan (Fig. 2). Therefore the volume of sediments in these areas must be correlated to the upstream eroded volume in the Ebro drainage basin, whatever the age of the connection (Miocene or later) to the Mediterranean Sea, via the Ebro River.

We estimate a maximum eroded volume in the Ebro basin by restoring the Miocene paleotopography (Fig. 3). This paleotopography is computed by fitting a smooth surface between all the summits of the surrounding mountains (Pyrenees, Iberian Range, Catalan Coastal Range) and the top of the Miocene sediment remnants within the Ebro basin. The present-day maximum elevation of these lacustrine deposits is 860 m (Arenas 1993), providing a minimum elevation for the Miocene basin paleotopography. On the margins of the basin, Miocene sediments reach a minimum elevation of about 1000m (e.g. Babault et al.

2005). For the Iberian Range and the Coastal Range, where current mean elevation is in the order of 1300 m respectively, the surface is directly fitted between the summits and the basins. Concerning the northern margin of the basin, i.e. along the southern flank of the Pyrenees, Oligocene sediments reach up to an elevation of 2000 m. According to Babault et al. (2005) these sediments attest for a highly-elevated piedmont with a paleoslope of order $1.25^\circ \pm 0.25$ (Fig. 3 and Fig. 4), a value compatible with that of chains surrounded by internal basins (e.g. Smith 2000). This highly-elevated piedmont that developed from the Oligocene was responsible for the inhibition of upstream erosion resulting in a highly elevated Pyrenean peneplain. The presence of relics of this peneplain at high elevation (up to 2500 m) strongly suggests that summit erosion since the Miocene was rather weak. Fitting the surface between the surrounding ranges and the basin implies that no Miocene valley existed, an unlikely statement, but one that provides a maximum estimate of $37800 \pm 800 \text{ km}^3$ of eroded material (Fig. 4).

We estimate the volume of sediments that were deposited during the Pliocene-Quaternary within the Valencia trough to be $25\,700 \text{ km}^3$, from the difference between the Messinian top-surface (Maillard 1993) and the current bathymetry (Fig. 2). On the other hand Nelson (1990) has estimated the volume of post-Messinian detrital sediments that are discharged by the Ebro river in the Valencia fan to be 6300 km^3 . This provides a total amount of post-Messinian sediments of $32\,000 \text{ km}^3$. Keeping in mind that (1) we probably overestimated the eroded volume by neglecting the likely occurrence of Miocene valleys and (2) we probably underestimate the deposited offshore volume, because the whole extent of the offshore sedimentation area is uncertain, we conclude that both estimates are similar, precluding the pre-Messinian connection of the Ebro basin to the Mediterranean.

Numerical modelling

Principles

The principle of the modelling has been described elsewhere (Davy & Crave 2000, Crave & Davy 2001, Loget et al., 2005). It assumes that erosion laws in the past were similar to that deduced from the analysis of current topography. It also considers that erosion on a regional scale is almost entirely achieved by rivers so that hillslope erosion can be minimized (Loget et al. 2005). The numerical simulator EROS incorporates a generic stream power law such as:

$$e = kQ^m S^n - e_c ,$$

where e is the erosional flux, Q is the water flow, S is the local slope, k and e_c are two constants depending on material strength properties, and m and n two exponents related to the time-length scaling (Howard et al. 1994, Whipple & Tucker 1999). Deposition flux is proportional by $1/Lt$ to the sediment concentration in the stream, where Lt is the characteristic transport length of sediments (Beaumont et al. 1992, Crave & Davy 2001). The elevation of the channel bed corresponds to the balance between these two fluxes. Therefore when Lt is small, the model comes to the transport-limited case and the elevation of the channel bed varies proportionally to the gradient of the sediment flux. By contrast, when Lt is large, rivers carry all the eroded sediment out of the system and the elevation is only controlled by the detachment flux (detachment-limited model).

In the present modelling, the values of the different parameters ($m = 1.5$, $n = 1$, $Lt = 0.2$ km) are deduced from previous modelling of the Messinian Rhone valley (Loget et al. 2005). The parameters k and e_c are considered homogeneous and negligible, respectively, on a

regional scale (Loget et al. 2005). Numerical times that correspond to the duration of the Messinian Salinity Crisis range from 20 to 40. All the rivers around the Mediterranean flowed on very different terranes during the sea-level drop, but were all incised by deep canyons. Therefore, the threshold e_c is considered as negligible at the regional scale and the bedrock erodibility k is set as unity and spatially homogeneous.

Pre-Messinian topography.

We test four scenarios with regard to the morphology of the eastern edge of the Ebro basin. Except for this eastern edge, the slope of the basin margins has been deduced from the present-day morphology by smoothing the contour lines derived from the current DEM GTOPO 30 (Fig. 5). Indeed, since the late Miocene the stress field and resulting regional deformation did not vary significantly in the area (Bergerat 1987, Herraiz et al. 2000) and therefore regional slopes were dipping as the present ones.

The first case considers that the Ebro River was already connected to the Mediterranean Sea before the onset of the MSC. The second configuration assumes that the eastern edge of the Ebro basin corresponded to a high elevated, flat topography, due to the overfilling of the internal basin up to 1000 m (Coney et al. 1996). In the third case, the Ebro basin is separated from the Mediterranean Sea by a topographic barrier that would correspond to the Catalan Coastal Ranges. The fourth experiment involves the same basin configuration as in the second experiment, but without a sea-level drop, that is, the base level is considered to be similar to the present one.

Results

In all the experiments represented on figure 5, when topographic profiles lie below initial profiles it means that streams incise, and conversely if topographic profiles lie above, streams deposit sediment.

Experiment 1 shows that a deep canyon (up to 750 m) develops after $t = 40$ and rapidly propagates inland (about 300 km with regard to the present coast line) in a similar way as canyons did in many pre-Messinian valleys around the Mediterranean, in particular in the Rhone valley (Clauzon 1982, Loget et al. 2005).

In experiment 2, a stream starts to incise the eastern edge, but it propagates on a distance that is much shorter than in experiment 1 after the same time (about 150 km for $t=40$). The maximum incision is about 500 m. The period required for incision to propagate as far as in experiment 1 is $t = 100$, i.e. 2.5 times the period needed with the configuration of experiment 1, that represents the real duration of the MSC.

Experiment 3 shows that if a relief existed between the basin and the Mediterranean Sea, no stream could have cut through it and entered the basin.

As mentioned before, the configuration of experiment 4 is similar to experiment 2, but it does not involve a sea-level drop. The results of experiment 4 show that even in this case, the stream eventually enters the basin.

Discussion

No fluvial incision has been identified within the Ebro basin. All rivers that were flowing to the Mediterranean incised their basement, whatever the lithology and the Mediterranean climatic environment after the Messinian sea-level fall (Loget et al. 2005). Except for experiment 3, all the experiments show more or less deep incisions of the Ebro basin. Following experiment 1, if the Ebro basin was already connected to the Mediterranean Sea before the MSC, a deep canyon would have deeply incised onshore and entered within the Ebro basin, up to a distance near Zaragoza. Experiment 3 suggests that if any relief was overhanging the eastern edge of the Ebro basin, no stream flowing toward the Mediterranean could have entered the basin. However, the present modelling only addresses fluvial erosion and does not take into account hillslope surface processes, such as landslide, or groundwater-sapping effects as well. Therefore, we cannot exclude that this would have induced the breaking of a possible topographic barrier, but to our knowledge, there is to date no evidence of such processes in the sediment record. There is also no evidence for tectonic processes such as NW-SE directed normal faulting that could explain the breaking of a topographic barrier at the onset of the MSC.

On the other hand the experiments 2 and 4 show that regressive erosion could result in Ebro basin capture if this latter was overfilled “to the brim”, that is, the western flank of the Catalan Coastal Ranges were buried under sediments. These experiments suggest that the sea-level during the MSC was not a *sine qua non* condition to induce the capture of the Ebro basin although this could have favoured it (see also Garcia-Castellanos et al. 2003).

The only explanation to the lack of Messinian fluvial incision in the Ebro basin is to consider that it was not connected to the Mediterranean. The current Ebro drainage area is comparable to that of the current Rhone. There is no reason for post-Messinian erosion to

have completely erased any remnant of such incision in the Ebro basin. Strong erosion would require tectonic uplift and/or climate change. This would result also in the re-incision of the Pliocene rias. It would be very unlikely that Pliocene terraces did not develop as Quaternary terraces did in uplifting active mountain belts such the Himalayas or the Alps. Moreover, large remnants of the Var Pliocene ria are found at an elevation up to 1000 m in the southern French Alps (Clauzon 1978).

Yet, our results are contrary to recent interpretations suggesting that the Ebro basin was already connected via the Ebro river to the Mediterranean Sea before the Messinian. Such interpretations rely on (1) mass balance between eroded materials coming from the Ebro basin and the surrounding ranges, and coeval sediments within the Valencia trough and (2) the presence of pre-Messinian, prograding detrital sediments in the Ebro delta and the significance of the Castellon group.

(1) Mass balance

Using a similar type of calculation to us, Garcia-Castellanos et al. (2003) reach a different conclusion, considering, as we do, that the Ebro basin incision was triggered by its opening toward the Mediterranean. They conclude that the post-Messinian delta estimated by Nelson (1990) (27000 km³) does not account for this post-opening complete incision.

Firstly, our estimate of sediment budget in the Ebro delta, from recent offshore seismic data on the top-Messinian surface (Maillard 1993), is larger than that provided by Nelson's work who used borehole interpolation, leading to a total budget of 32 000 km³ of sediments for the Ebro delta and Valencia trough.

Secondly, our estimate of the eroded volume in the Axial zone since the Late Miocene is only 4000 km³, compared with the 10000 km³ suggested by Garcia-Castellanos et al. (2003). Their calculation is based on local denudation rate estimates that are deduced from a thermochronology study, implying up to 2-3 km of denudation within this area since the

Miocene (Fitzgerald et al. 1999). It is beyond the scope of the present paper to discuss in detail such an estimate, but we would like to stress that it has long been recognized that a major morphological characteristic of the Pyrenean Axial Zone, is the occurrence of a high elevated (more than 2000 m), low relief, Miocene erosional surface, now dissected by the recent drainage network (Birot 1937, de Sitter 1952). This suggests that erosion since the Miocene within the Axial Zone mainly corresponds to the present dissection of this erosional palaeosurface (see figure 4) and that local denudation rates deduced from thermochronology are far overestimated when applied at regional scale in the present case.

Although we agree with Garcia-Castellanos (2003) that such type of calculations remains rough, our estimate of volume balance challenges theirs and shows that the assumption of a post-Messinian dissection of the Ebro basin and the surrounding reliefs is likely.

(2) Significance of the Castellon group

Evans and Arche (2002) have suggested that the presence of a pre-Messinian succession of prograding detrital deposits, the Castellon group, in the Valencia Trough, as observed by Bartrina et al. (1992), was presumably indicative of the connection of the Ebro basin to the Mediterranean. These authors consider that a river with a catchment limited to the Catalan Coastal Ranges can hardly provide such an amount of sediment, but they did not provide any quantification. They acknowledge that conclusive confirmation of an origin from the Ebro basin requires additional studies. For Bartrina et al. (1992) the Castellon group may result from the reworking of pre-Serravallian terrigenous deposits initially trapped in the onshore active half-grabens, when the older paleohighs were overlain under high sea-level conditions. Post-Langhian prograding terrigenous systems, with basal unconformity, also developed just before the MSC in the Gulf of Lion (Gorini et al., Gorini 1993), whereas no major change in the drainage basin pattern is observed (Loget et al. 2005). Therefore the

Castellon group in the Valancia trough does not appear as a specific sedimentary event that would be related to the opening of the Ebro basin.

Conclusion

The sea-level fall of the Mediterranean during the Messinian was responsible for the strong fluvial incision of the pre-Messinian drainage networks. Incision propagation was directly controlled by the pre-existing drainage areas. These incisions were later sealed by Early Pliocene sedimentation all around the Mediterranean region. If the Ebro basin, as observed today, was connected to the Mediterranean, similar strong incision would have developed and would have been preserved as in the case of the present Rhone drainage area. Therefore, the lack of Messinian incision within the Ebro basin shows that it was not connected to the Mediterranean before the Messinian Salinity Crisis.

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Figure captions

Figure 1: Distance of headwater position from the present outlet (river length) vs. current drainage area for some Mediterranean rivers.

Grey circles: present headwater position; black circles: Messinian headwater incision. N-Nil; R-Rhone; E-Ebro; H-Herault; O-Orb; TT-Têt; TC-Tech; m and c: index for Messinian and current respectively (Database compiled after (Chumakov 1973, Clauzon 1978, 1982, Clauzon et al. 1987, Ambert et al. 1998).

The length of current rivers is a function of drainage area, such as $L=2.5A^{0.5}$, which corresponds to Hack's law (Hack 1957, Montgomery & Dietrich 1992). When plotted against current drainage areas, lengths of Messinian canyons follow a similar law such as $L=1.3A^{0.45}$, except for the Ebro. This strongly suggests that (1) the pre-Messinian drainage areas were similar to the present ones, (2) the duration of the Messinian sea-level drop was not long enough for fluvial incision to propagate up to pre-Messinian headwaters, and (3) the pre-Messinian drainage area of the "proto-Ebro" river was much less extensive than the present one or (4) the Ebro basin was not yet connected to the Mediterranean. (see text for further discussion).

Figure 2: Estimate of the deposited volume in the Valencia Trough since the Pliocene.

Topography of NE Spain (SRTM90). Black line onshore: location of the topographic profile (Figure 4). Black lines offshore: isobaths of Pliocene and Quaternary deposits. The Catchment of the Ebro river is also shown. The volume of post-Messinian detrital sediments within the Valencia trough has been determined to be 25700 km³ from the difference between the Messinian top-surface and the current bathymetry (Accurate reconstruction of the top-Messinian surface is from Maillard (1993)). Nelson (1990) estimated the volume of post-

Messinian detrital sediments that are discharged by the Ebro river in the Valencia fan as 6300 km³. This provides a total amount of post-Messinian sediment of 32 000 km³.

Figure 3: Miocene paleotopography.

A: Current topography of the Ebro drainage basin. B and C: The two palaeotopographies are computed by drawing a surface between the Pyrenean, Iberian and Catalan summits to the centre of the Ebro basin that corresponds to a trough, the maximum elevation of which is 860 m (Arenas 1993). Elevation of the basin edges reaches 1000 m. From the southern limit of the Axial Zone to the limit of the South-Pyrenean zone, the palaeosurface elevation decreases from 2000 m to 1000 m. The palaeotopographies B and C are calculated with maximum slope values of the Pyrenean piedmont of 1.5° and 1°, respectively (Contour lines equidistance is 500 m).

Figure 4: Estimate of the eroded volume in the Ebro catchment since the Miocene.

Dark grey: NS topographic profile across the Ebro drainage basin. Light grey: Eroded material (*E*). Mean slope value of the Miocene Pyrenean paleopiedmont $\langle s \rangle$ is $1.25^\circ \pm 0.25$. The two eroded volumes are computed from the difference between two surfaces: the paleotopographies (B and C) and the current topography. The minimum (37000 km³) and maximum (38600 km³) estimates of eroded volume are obtained for slope values of 1.5° and 1° respectively. The eroded volume ($37\,800 \pm 800$ km³) is comparable to that of post-Messinian deposits in the Valencia trough and Valencia fan.

Figure 5: Numerical modelling of the western Mediterranean drainage system after a 1500 m sea-level drop (vertical dilatation x 32).

CCR-Catalan Coast Ranges; MSL-Messinian Sea-Level; $t=40$: numerical time that corresponds to the duration of the MSC (Loget et al.).

Three configurations (A, B, C) of the eastern edge of the Ebro basin at the onset of the MSC have been tested:

- A. The Ebro river was already connected to the Mediterranean Sea (experiment 1);
- B. The eastern edge of the Ebro basin corresponded to a high elevated, flat topography, resulting from the overfilling of the endorheic basin up to 1000 m a.s.l. (experiment 2);
- C. The Ebro basin is separated from the Mediterranean Sea by a topographic barrier that would correspond to the CCR (experiment 3);
- D. In this experiment the configuration is similar to that in B, but no sea-level drop occurred, that is, the base level is considered to be similar to the present one. This experiment has been designed to test the real influence of the MSC sea-level drop on the incision propagation (experiment 4).

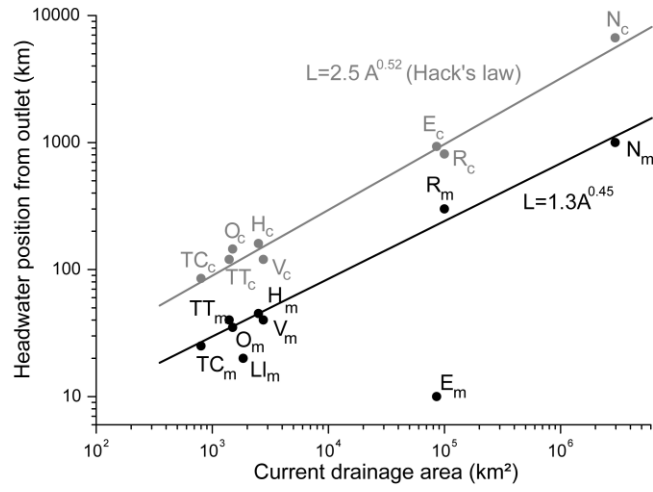


Figure 1

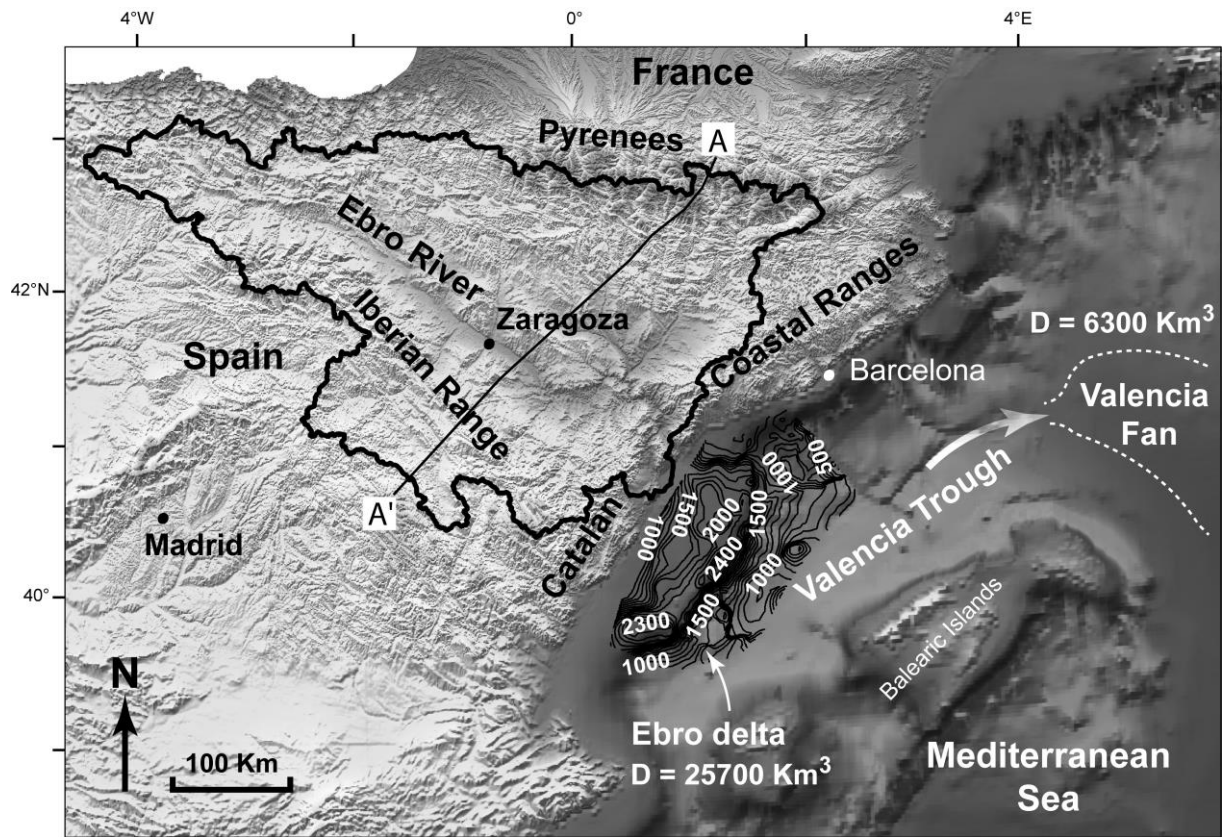


Figure 2

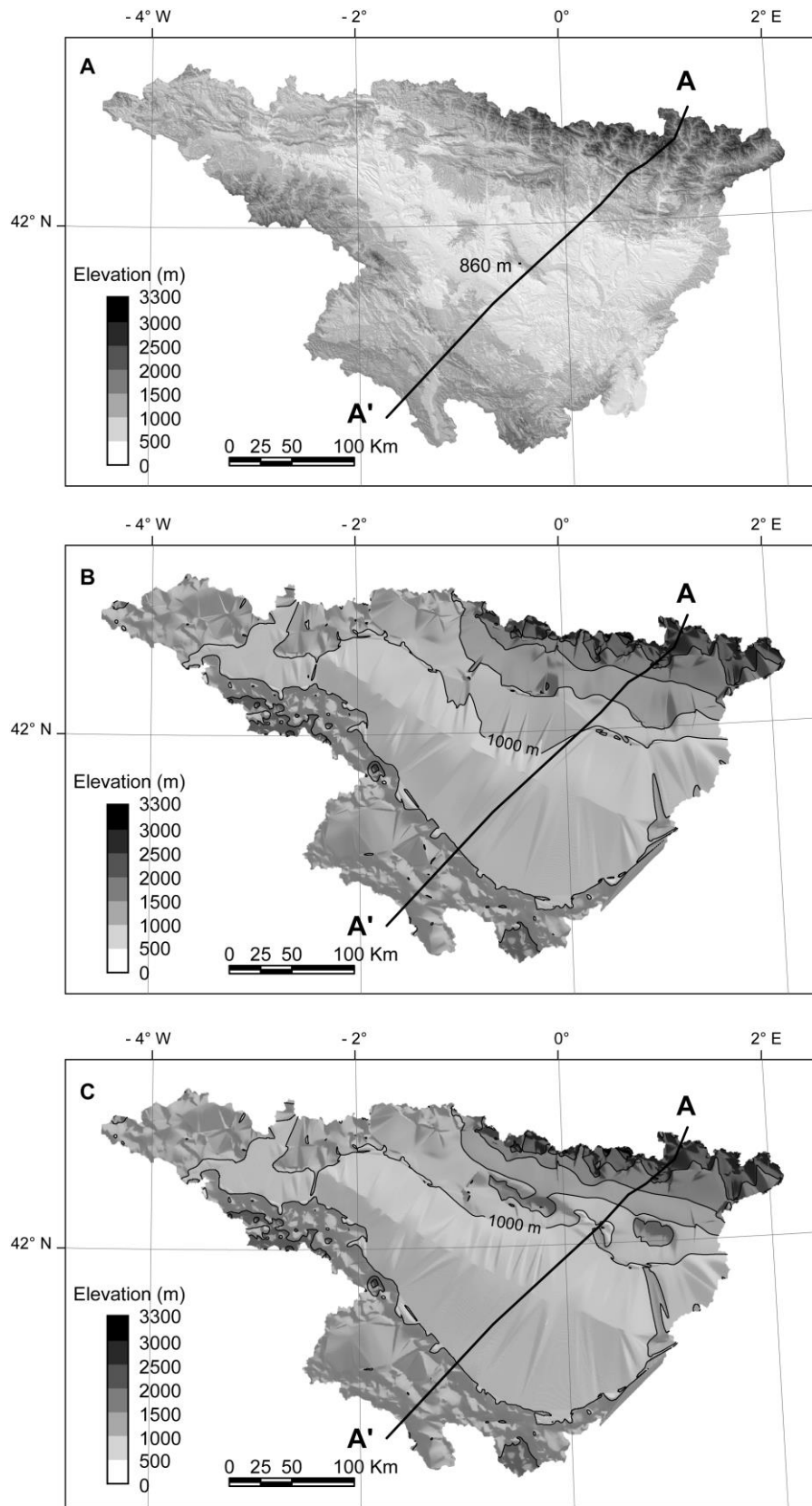


Figure 3

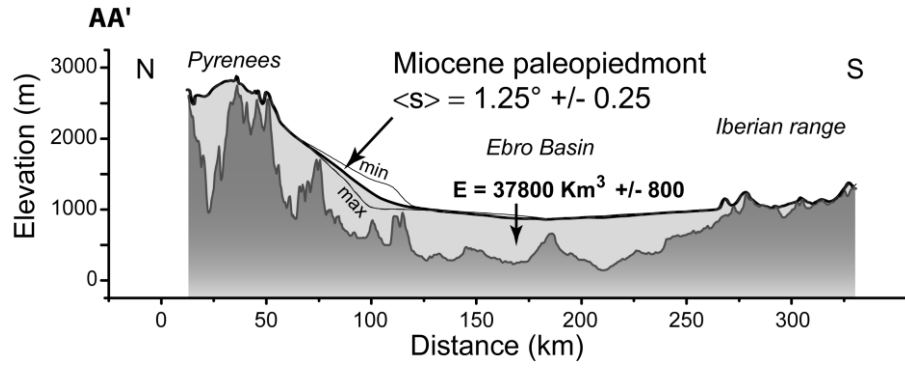


Figure 4

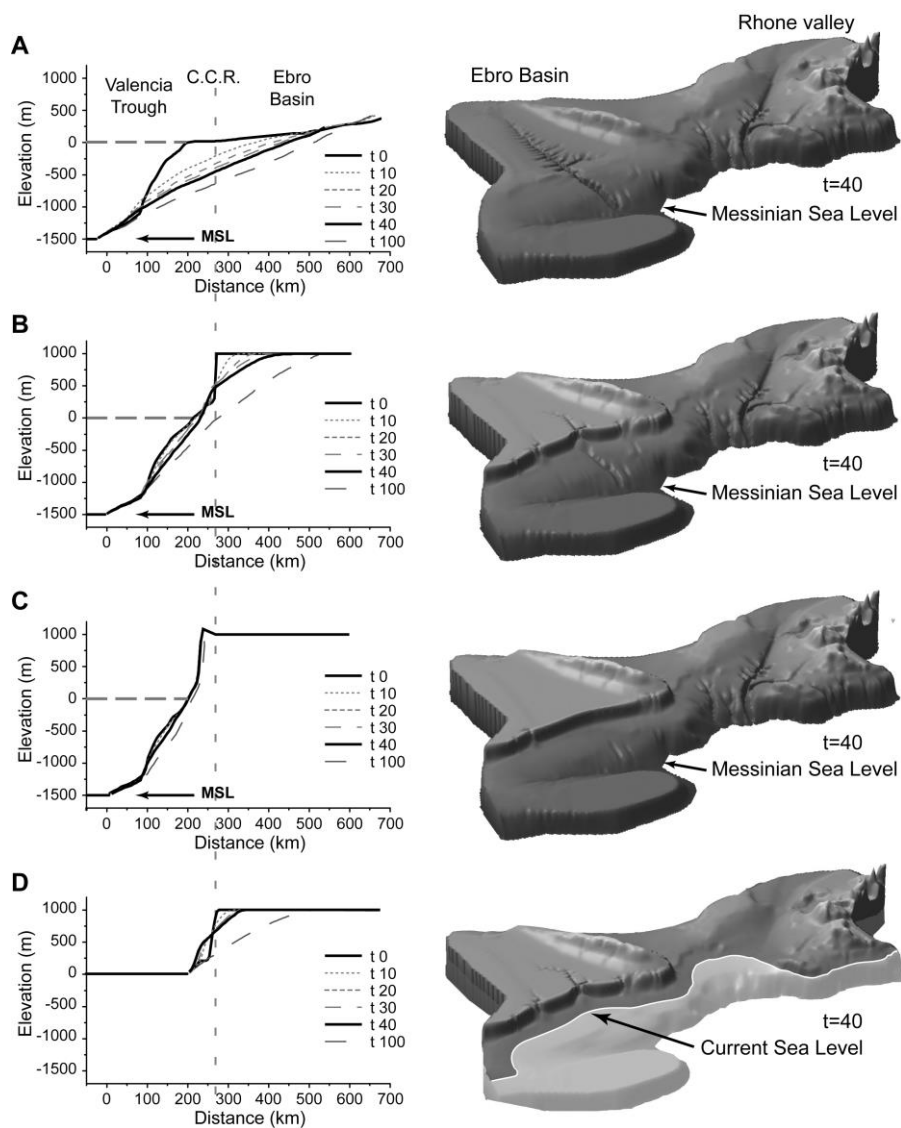


Figure 5