# PLEISTOCENE CHANGE FROM CONVERGENCE TO EXTENSION IN THE APENNINES AS A CONSEQUENCE OF ADRIA MICROPLATE MOTION

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*"Deciphering the sequence of tectonic events in this region can be likened to attempting to reconstruct the pictures in a stack of jigsaw puzzles when 90% of the pieces are missing and the remaining 10% are no longer in their original shape."*

Morris and Tarling, 1996

## ABSTRACT

Discussions about the Adria microplate offer differing views depending on the timescale and data considered. Neotectonic studies using earthquake mechanisms and GPS site velocities find Adria moving northeastward away from Italy, and bounded by an extensional boundary in the Apennines and convergent boundaries in the Dinarides and Venetian Alps. However, geologic data show that Adria was subducting southwestward beneath Italy during Mio-Pliocene time. We suggest that these views are consistent and reflect the recent spatio-temporal evolution of a multiplate system. We assume that during Mio-Pliocene time Adria was no longer part of Africa and had become an independent microplate. Convergence occurred as Adria moved northeastward with respect to Eurasia as at present, because the faster back arc spreading in the Tyrrhenian Sea caused Adria to move southwestward with respect to Italy. The transition from convergence to extension in the Apennines in the past 2 Ma resulted from the cessation of subduction in the Apennines accompanied by breakoff of the subducting Adria slab, and the associated cessation of back arc spreading in the Tyrrhenian Sea. As a result, western Italy became part of Eurasia, and Adria's northeastward motion produced a new extensional boundary along the Apennines.

## INTRODUCTION

Considerable attention, illustrated by the papers in this volume, has been directed over the years to assess the present and past tectonics of the circum-Adriatic region (Figure 1). Essentially the question is how crustal blocks in the area have moved during the complex and ongoing collision of the African and Eurasian plates, which is thought to have begun in Cretaceous time and has built the present Alpine mountain belt (Dewey et al., 1989). The boundary zone between the two major plates appears to have involved a number of distinct blocks that have moved - and still do - as coherent entities distinct from the two major plates. One important question is whether the Adria region behaves at present and in the past as part of Eurasia, a distinct microplate, or a promontory of Africa. At present the latter possibility is posed in terms of Adria being distinct from Nubia (Africa west of the East African Rift, along which Africa began splitting 15-35 Ma). Views on this issue depend on the assumed extent of the region defined as Adria, and the time and data types considered.

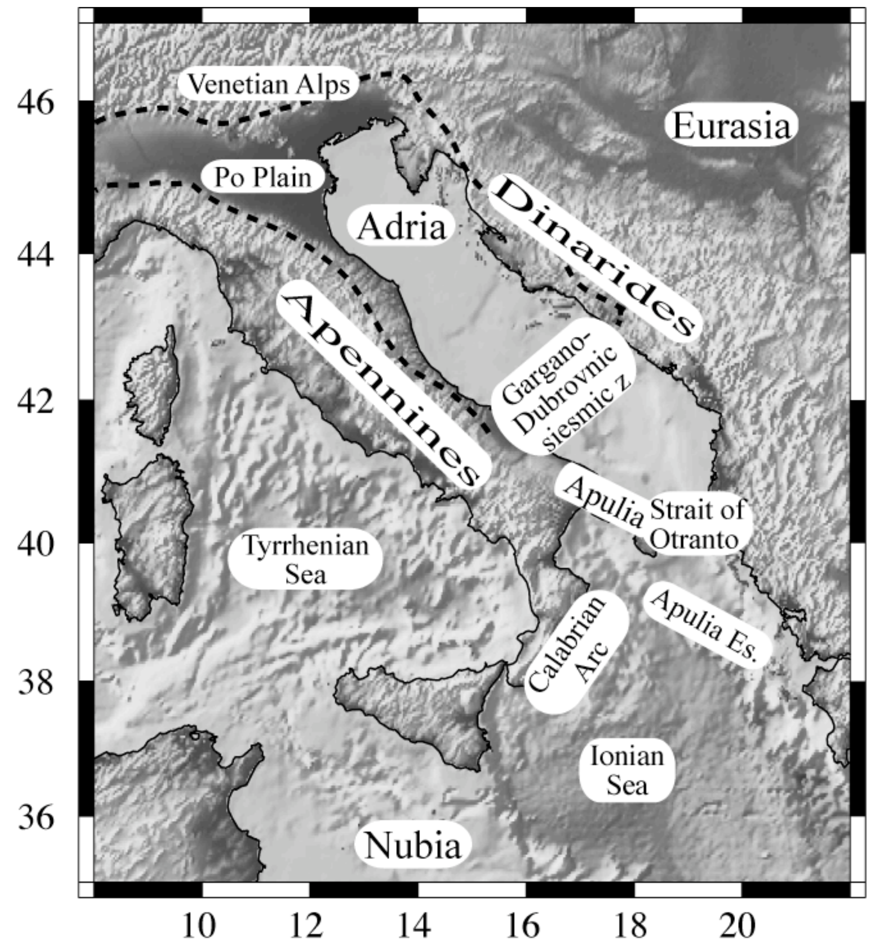


Figure 1: Geography of the circum-Adriatic region. Dashed line denotes approximate boundary of present Adria microplate.

## NEOTECTONIC VIEW

Not surprisingly, the issue is most directly addressed for the present, where crustal motions are directly observed (Figure 2). Anderson and Jackson (1987a) and Anderson (1987) noted lower levels of seismicity in the Adriatic Sea and eastern Italy relative to their surroundings, and proposed that this region acted as an Adria microplate. In their model Adria rotates with respect to Eurasia about a pole in the northern Po plain. Hence earthquakes in the Apennines, which show dominantly but not exclusively normal faulting, reflect extension between western Italy south of the Po plain (presently considered to be part of Eurasia) and Adria, whereas the thrust faulting mechanisms in the Dinarides and Venetian Alps reflect Adria-Eurasia convergence. The pole's proximity to the microplate illustrates a common pattern for microplates in the boundary zone between major plates, in which the pole for the relative motion between the major plates is far away, so motion between them varies slowly along the boundary, whereas those for the microplate's motion with respect to the major plates are nearby and so describe rapidly varying motion (Engeln et al., 1988).

This basic picture has been confirmed by GPS data (Calais et al., 2002; Battaglia et al., 2004; Weber et al., this volume). Continuous GPS (CGPS) sites MATE and MEDI show eastern Italy moving northeast relative to stable Eurasia. This motion is essentially perpendicular to the direction of Nubia's motion with respect to Eurasia shown by global plate motion models (DeMets et al., 1994) or space geodetic data (Sella et al., 2002; Grenerczy and Kenyeres, this volume; Kahle, this volume), as illustrated by the motion of site LAMP. Interestingly, the space geodetic data show slower motion than predicted by the NUVEL-1A model. Although the difference may reflect weaknesses in NUVEL-1A, which averages motion over the past 3 Ma, it may also represent real slowing.

Statistical tests (Battaglia et al., 2004) show that the improved fit to the GPS data resulting from the assumption of an Adria microplate distinct from Nubia exceeds that expected purely by chance due to the introduction of the three additional parameters associated with an additional Euler vector (Stein and Gordon, 1984), so the microplate and its general motion are kinematically resolved. However, its boundary geometry remains under investigation. Due to the presence of extensional earthquakes in the southern Apennines, Anderson (1987) and Ward (1994) draw the southern boundary with Nubia at the Strait of Otranto, although there is little seismicity along this presumed boundary. In contrast, Calais et al. (2002) favor a similar geometry but suggest that the southern boundary is further north and extends seaward from the Gargano peninsula to Dubrovnik, as implied by a zone of seismicity (Console et al., 1993). Battaglia et al. (2004) favor a similar geometry but add a second microplate to the south separated from Nubia along the Apulia escarpment and Kefallinia fault. In contrast, Oldow et al.

(2002) favor two Adria microplates, with northern and central Italy and the Tyrrhenian Sea on the northern one, such that the northern Apennines are not a plate boundary.

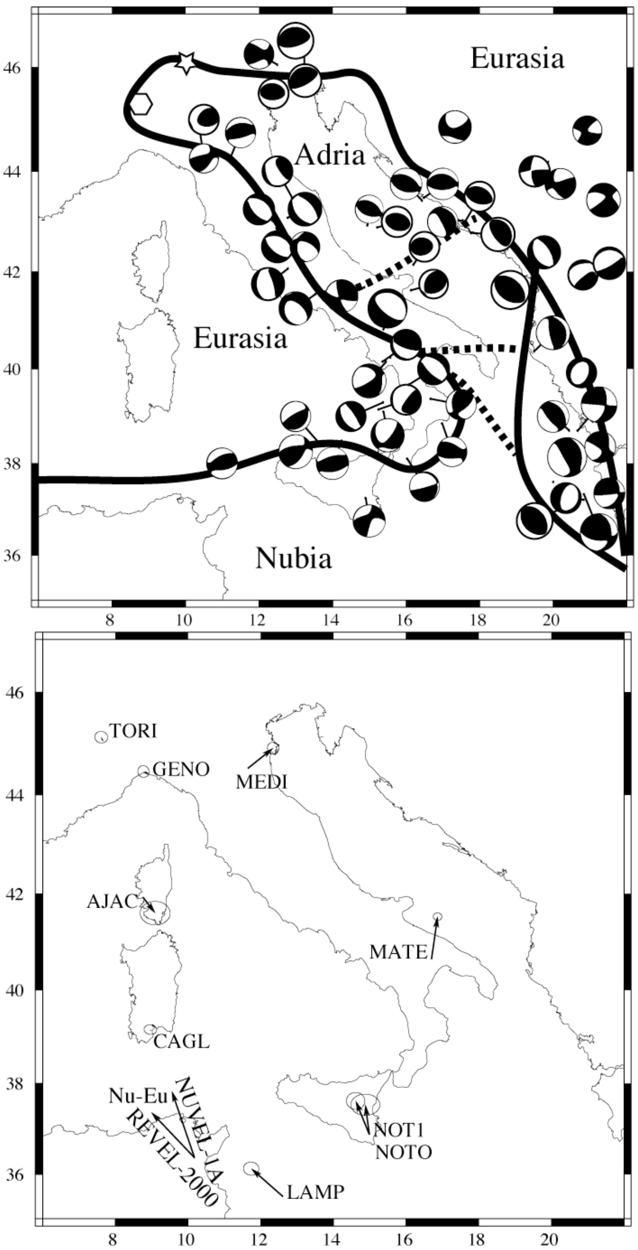


Figure 2: Neotectonics of the circum-Adriatic region. Top: selected earthquake mechanisms from Harvard CMT catalog. Plate boundaries are illustrative, because the precise geometry remains unresolved. Dashed lines indicate some of the proposed southern boundaries of the Adria microplate. Star and hexagon are Adria-Eurasia pole locations from Anderson and Jackson (1987a) and Calais et al. (2002). Bottom: motion of CGPS sites with respect to Eurasia. Error ellipses are 2 σ.

As the papers in this volume illustrate, the steady accumulation of GPS data at more sites spanning longer time series (and hence yielding more precise velocities) is likely to significantly advance understanding of the motion and boundary geometry of Adria. For example, the fact that sites TORI, GENO, AJAC, CAGL have no significant motion with respect to Eurasia suggests that they are not part of a distinct Adria. The discrepancy between NOTO/NOT1 and LAMP suggests that Sicily may not be part of Nubia.

## GEOLOGIC VIEW

Geologic studies offer a seemingly different view (Figures 3, 4). Beginning in Miocene time, Adria subducted westward beneath Italy, forming the Apennines as the northwestern-trending segment of an arcute thrust belt that extends through Calabria to Sicily (Royden et al., 1987). The arc evolved in association with the opening of the Tyrrhenian sea beginning about 15 Ma, which is interpreted as back arc spreading associated with retrograde (rollback) motion of the Adria slab (Malinverno and Ryan, 1986; Rosenbaum and Lister, 2004). As subduction migrated eastward, Italy rotated counterclockwise with respect to Eurasia, as shown by paleomagnetic data. Hence during this time, a western Italy microplate moved independently from Eurasia.

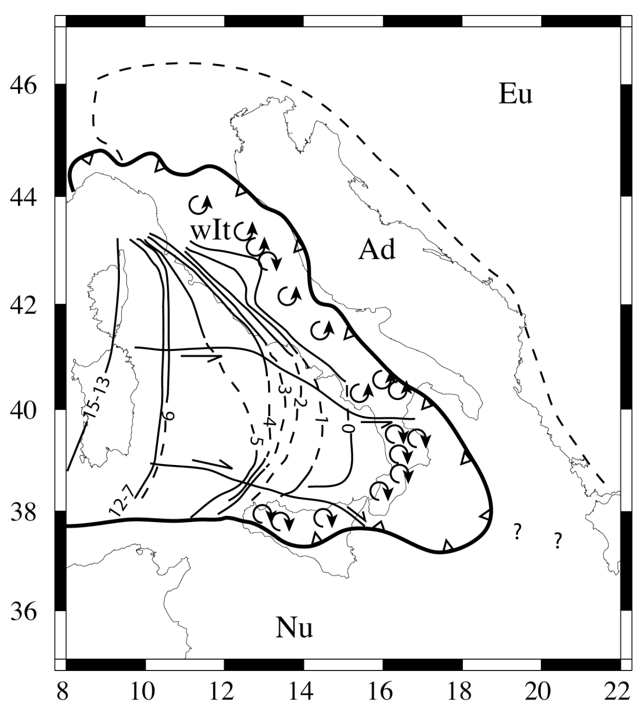


Figure 3: Inferred post 15-Ma evolution of the magmatic arc, shown by isochrones in Ma, associated with opening of the Tyrrhenian Sea and rollback motion of the Adria slab. As subduction migrated eastward, western Italy (wIt) rotated counterclockwise with respect to Eurasia, as shown by paleomagnetic data north of the 41 parallel strike-slip fault zone. (After Rosenbaum and Lister, 2004)

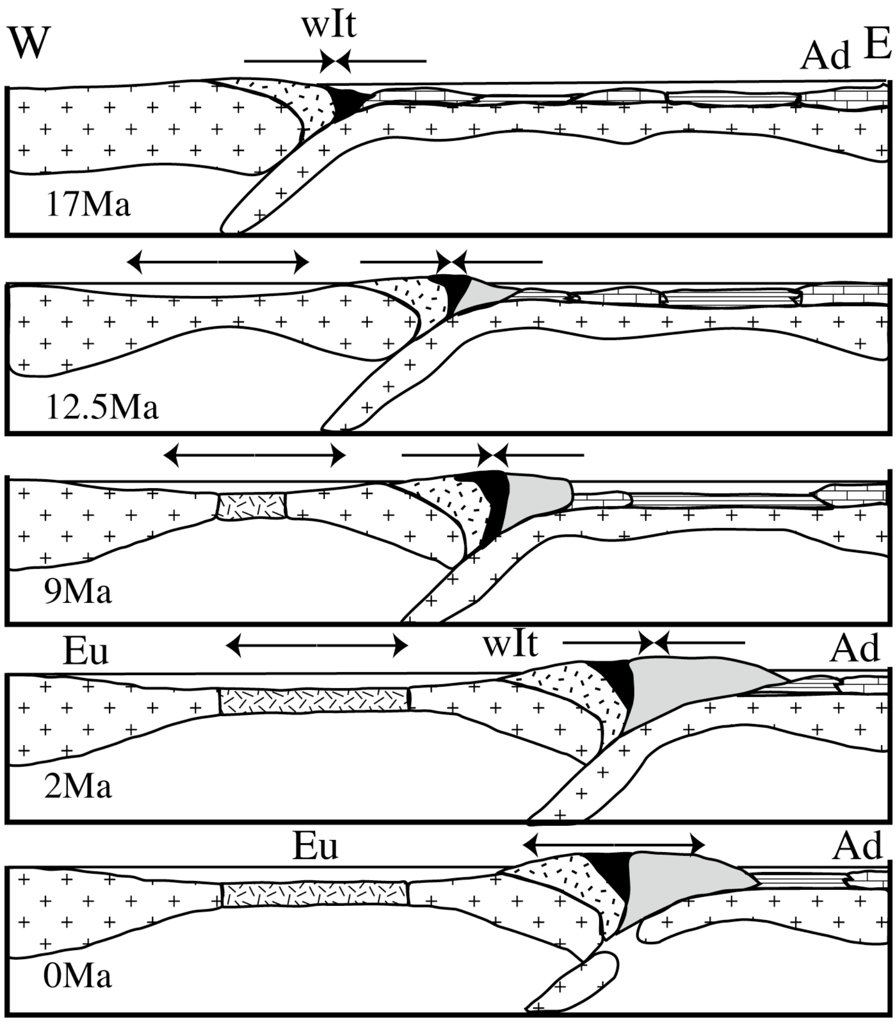


Figure 4: Schematic evolution of the Tyrrhenian Sea and Apennine arc. In this modification of Malinverno and Ryan (1986)'s scenario, subduction and back arc spreading ceased within the past 2 Ma, making Italy west of the Apennines part of Eurasia (Eu). Adria (Ad) motion then caused a shift from convergence to extension in the Apennines.

This subduction, however, has been slowing since Pliocene time. At present, earthquakes deeper than about 200 km below the Tyrrhenian Sea occur only in the Sicily-Calabria portion of the arc, suggesting that active subduction beneath the Apennines has ceased (Anderson and Jackson, 1987b). Convergence is indicated by the thrust fault mechanisms north of Sicily, and by GPS data (Figure 2) showing Sicily moving northwestward with respect to Eurasia (Grenerczy and Kenyeres, this volume; Kahle, this volume). A similar view emerges from seismic tomography that shows a high-velocity slab extending to the surface only below Calabria (Wortel and Spakman, 2000).

Wortel and Spakman (2000) interpret the slab geometry as a consequence of progressive slab detachment, beginning about 8 Ma in the northern Apennines, which has by now detached the slab except in Calabria (Figure 5). The slab detachment hypothesis remains under discussion, largely owing to differences between the results of tomographic studies (Lucente et al., 1999). However, there is general agreement that subduction along the Apennines has either stopped or is near its end, whether because of slab detachment or because oceanic crust in the Adriatic has been subducted, leaving only unsubductable continental crust (Lucente et al., 1999). Similarly, the extension in the northern Tyrrhenian Sea is thought to have stopped, although it may continue in the south (Rosenbaum and Lister, 2004).

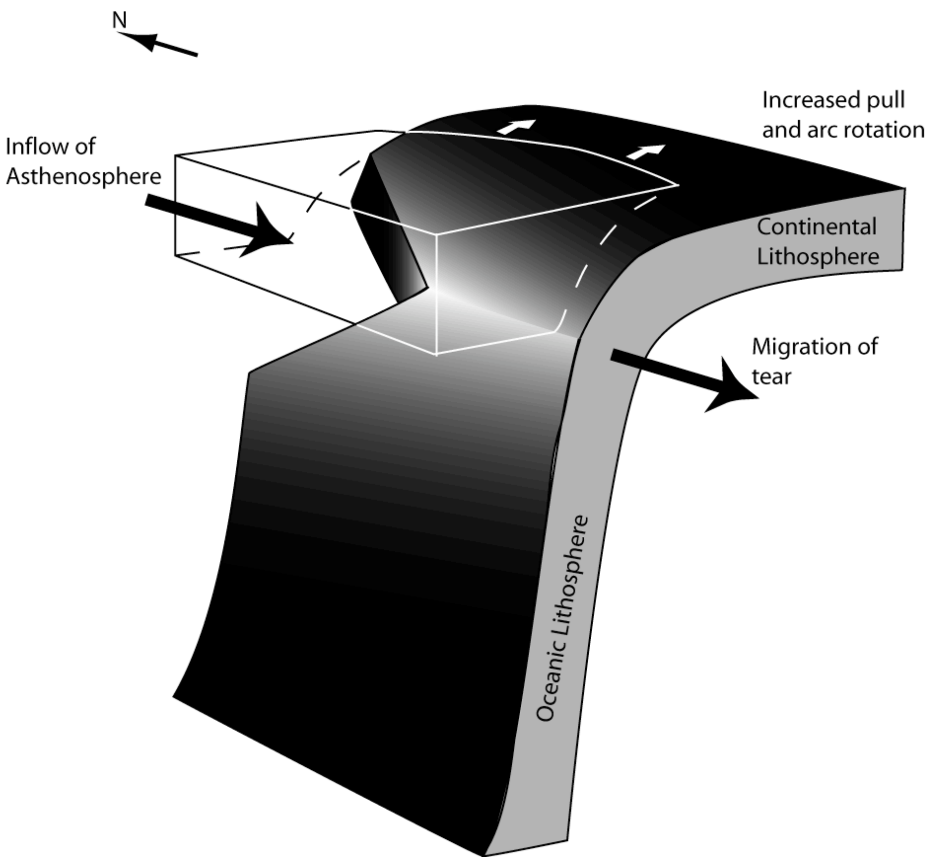


Figure 5: Slab detachment model of Wortel and Spakman (2000), shown for the case where detachment of the Adria slab begins in the north and propagates southward.

## TRANSITION IN PLATE MOTIONS

We suggest that the ending of subduction, slab detachment, and spreading in the northern Tyrrhenian sea gave rise to a change in regional plate motions that explains the Pleistocene shift from convergence to extension in the Apennines. This scenario is summarized in Figure 4, which modifies the sequence proposed by Malinverno and Ryan (1986). We regard their "present" geometry as somewhat older, perhaps 2 Ma, and assume that at present subduction and back arc spreading have ceased. Hence Italy west of the Apennines now moves as part of Eurasia rather than as a distinct block. Adria now moves northeastward with respect to Eurasia, making the Apennines an extensional boundary between Adria and western Italy, now Eurasia. Initiation of this boundary is indicated by the 0.8 Ma change from compression to extension in the Apennines (Bertotti et al., 1997; Piccardi et al., 1999), and its present nature is indicated by active faulting and extensional earthquake mechanisms. (Although our interpretation is that the extensional events illustrate a divergent plate boundary, they can also be interpreted as back arc extension above still-ongoing subduction (Frepoli and Amato, 1997).)

How this transition might have taken place depends on the relative plate motions at the time, which are essentially unknown. Figure 6 illustrates considering hypothetical linear velocities with respect to Eurasia at a point in the Apennines at 43°N, 13°E. Africa-Eurasia motion (7.5 mm/yr at N27°W) is illustrated by that predicted by NUVEL-1A (DeMets et al., 1994), which gives an average over the past 3 Ma. Adria-Eurasia motion (3.5 mm/yr at N36°E) is illustrated by the present motion derived from GPS site velocities by Calais et al. (2002). Absent magnetic anomaly data in the Tyrrhenian Sea, we crudely estimate a western Italy-Eurasia motion of 13 mm/yr at N40°E from the motion of the northern Apennine magmatic arc over the past 3 Ma (Rosenbaum and Lister, 2004).

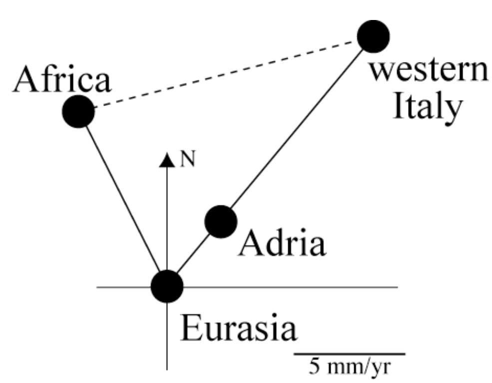


Figure 6: Linear velocity vectors for possible Adria, western Italy, and Africa plate motions with respect to Eurasia prior to the change in plate motions within the past 2 Ma.

Comparing these velocities is at best schematic, given both their individual uncertainties and the fact that they span different time periods. Even so, the velocities allow us to explore how the transition in plate motion may have occurred.

For simplicity, we assume that Adria already existed as an independent microplate, whose motion with respect to Eurasia was similar to that at present. In this case, as a result of the difference in northeastward motion rates, Adria moved southwestward at about 10 mm/yr with respect to western Italy, causing convergence beneath the Apennines. Once subduction and back arc opening ceased, western Italy moved as part of Eurasia, and the Apennines became an extensional Adria-Eurasia boundary.

## DISCUSSION

The transition in plate geometry we suggest is a simple approach to reconciling two different views of Adria's behavior each emerging from different data over different times. This transition is a plausible consequence of a widely assumed change in the geometry of subduction and back arc spreading. How the transition occurred depends on the nature of Adria and its surroundings before the transition.

For this issue, the past plate geometry on Ardia's eastern boundary is crucial. The Dinarides are thought to have formed by eastward subduction of Adria prior to the Late Eocene (Pamic et al., 2002ab), after which convergence slowed as a consequence of slab breakoff. Possible evidence for slab breakoff comes from the absence of deep or intermediate depth earthquakes beneath the Dinarides, which argues against a continuous subducting Adriatic slab. Resolving the presence or absence of a high-velocity slab has been a challenge for tomographic studies. Initial studies showed a high-velocity anomaly ringing the Adriatic on both sides at about 250 km depth that did not extend to the surface, as shown in de Boorder et al. (1998). Subsequent studies find this anomaly smaller, as shown in Carminati et al. (1998) or absent (Marone et al., 2004). Post-Eocene deformation included right-lateral motion (Picha, 2002).

Figure 7 shows a schematic scenario for how Adria and its surroundings may have evolved over the past 30 Ma. Initially, we assume that Adria was part of Africa (soon to be Nubia), consistent with paleomagnetic (Channell, 1996) and paleontologic (Bosellini, 2002) data that are interpreted as showing that in the Cretaceous Adria was not distinct from Africa, whereas it clearly is today. (A contrary view is that Adria has been independent since the Cretaceous (Platt et al., 1989).) Hence at some point during the complex history of Africa-Eurasia convergence Adria began to move independently. In the Miocene, subduction began beneath the Apennines, causing back arc extension in the Tyrrhenian sea. A combination of the effects of the new western boundary and slab detachment in the east (beginning at the southern end) slowed Adria-Eurasia convergence and

Adria (perhaps part of Africa/Nubia) subducting beneath the Dinarides. Slab begins tearing. Open triangles indicate detached slab. Velocities (thick arrows) are shown with respect to Eurasia.

Subduction of Adria beneath western Italy (wIt) begins, forming the Apennines. Extension results from back arc spreading in the Tyrrhenian sea. Slab beneath the Dinarides keeps tearing.

Nubia changes direction to NNW. Adria moves NE yielding a zone of deformation on its southern boundary. Extension in the Tyrrhenian sea increases in the south, wIT rotates CCW, and the subducting slab beneath the Apennines begins to tear.

Slab beneath Apennines torn all the way to Calabria. Extension in the Tyrrhenian sea slows.

Tyrrhenian sea extension stopped, making western Italy part of Eurasia. Adria moves as a rigid plate north of the Gargano-Dubrovnic seismic zone (GDSZ). Extension occurs along the Apennines and slow convergence continues on the eastern boundary

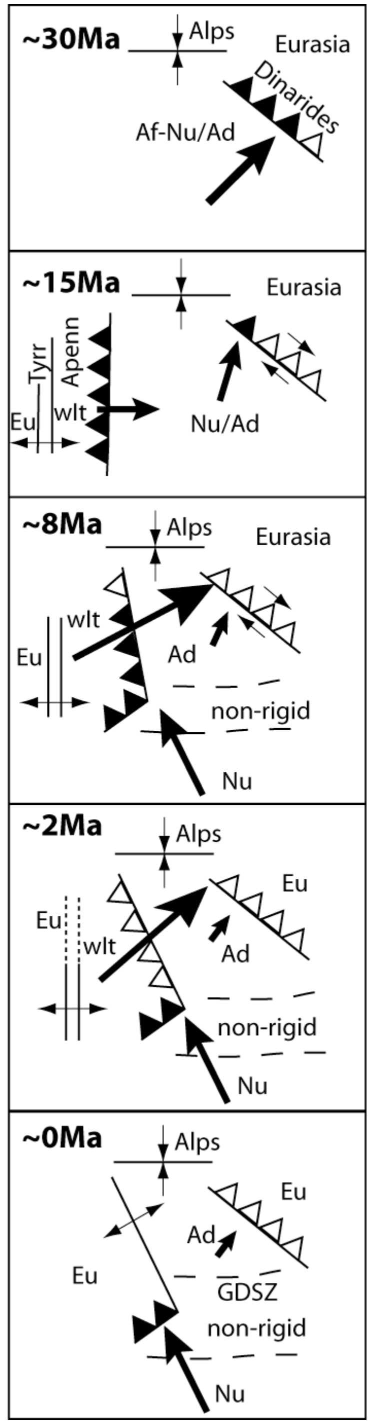


Figure 7: schematic scenario for how Adria and its surroundings may have evolved over the past 30 Ma.

changed its direction, causing strike-slip motion along Adria's eastern boundary. Although Adria may have become distinct from Nubia at this time, we suspect that it occurred later. At about 8 Ma, Adria separated as a consequence of Nubia's change to its present NW motion with respect to Eurasia (Dewey et al., 1989). Hence Adria preserved NE motion even though Africa's motion changed. A broad deformation zone coinciding with the already-thinned crust of the Ionian Sea (Catalano et al., 2001) marked the new Nubia-Adria boundary zone, which remains ill-defined today. At about the same time, progressive slab detachment began in the northern Apennines. Eventually, detachment extended south to Calabria, ending back arc spreading in the Tyrrhenian sea and making western Italy part of Eurasia.

This scenario is, of course, speculative. However, we think it offers useful insights into the evolution of Adria and its eastern and western boundaries, which need to be considered simultaneously. Testing these ideas and moving beyond them involves several possible lines of research. First, it is crucial to understand how motion varied around Adria as a function of time. At present, because of the nearby Adria-Eurasia pole, these motions change rapidly along strike. Hence it would be important to understand these motions at least for the past 15 Ma. For example, the focal mechanisms show present convergence in the Dinarides, and the pole position implies strike slip further to the north. Geologic evidence could help test whether the past motions were similar. There has also been extensive discussion in the paleomagnetic literature about rotations in the circum-Adriatic area, including both regions considered to be part of present Adria and regions surrounding it (Channell, 1996; Marton et al., 2002). As noted by the paper's epigram, these data can help establish at what point Adria became an independent entity, and how its motion both before and after this time affected its surroundings.

A particularly crucial issue is to understand the geometry of Adria's boundaries and the relation of Adria both at present and in the past to the African (now Nubian) plate. At present, as noted earlier, it is unclear where Adria ends to the south and Nubia begins. For example, the motions of MEDI and MATE are discordant. It seems likely that Calabria, Apulia, and eastern Sicily are not part of Adria, but instead are blocks distinct from both Adria and Nubia. Although present convergence is often assumed to occur south of Sicily, the thrust fault mechanisms north of Sicily imply that some convergence occurs there at present. However, GPS data show that the motion of site NOTO in southern Sicily is somewhat discrepant from that of LAMP, on the Nubian plate. How and when this geometry developed is a crucial question, and presumably reflects the complex history of both the subduction geometry and the larger-scale complex history of Africa-Eurasia motion. Understanding these kinematic issues would give important insight into the complex dynamics of this multiplate system's evolution.

In summary, Adria and surroundings illustrate that although Africa-Eurasia convergence has been going for a very long time, the boundary zone between these two major plates remains complex and rapidly evolving.

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