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► **To cite this version:**

Joseph Martinod, Ayend-Christ Daou, Laurent Métral, Christian Sue. Did subduction in the western Mediterranean drive Neogene alpine dynamics? Insights from analogue modeling. Bulletin de la Société Géologique de France, 2024, 195, pp.5. 10.1051/bsgf/2024001 . hal-04942558

HAL Id: hal-04942558

<https://hal.science/hal-04942558v1>

Submitted on 12 Feb 2025

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Did subduction in the western Mediterranean drive Neogene alpine dynamics? Insights from analogue modeling

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Received: 21 April 2023 / Accepted: 10 January 2024 / Publishing online: 19 April 2024

Abstract – In the Western Alps, a first Late Cretaceous to Eocene “Pyrenean-Provençal” compressive phase accommodating N-S shortening resulting from the convergence between Africa and Eurasia is classically described. It is followed by the Neogene “Alpine phase” accommodating E-W shortening. Since this major tectonic change is not explained by a modification of the global Africa-Eurasia convergence, it should be explained instead by more local causes, possibly by the subduction of the Ligurian Ocean that initiated in the Oligocene beneath the European and Iberian plates. In this paper, we present analogue models simulating the Neogene evolution of this subduction zone, in order to understand how it impacted the regional tectonics. Although models do not include the lithospheric plate overriding the subduction zone, their surface deformations share many similarities with the Neogene tectonics of Western Europe and Iberia. We observe that the tectonic evolution is largely controlled by the roll-back of the slab, that occurred much faster than the Africa-Eurasia convergence. Models reproduce the opening of the Western Mediterranean Basins and the dispersion of the AlKaPeCa continental fragments (Alboran, Kabylia, Peloritani and Calabrian blocks). They also show that the subduction of the Ligurian Ocean favors the counterclockwise rotation of Adria. In more elaborated models, we introduced a pre-existing weakness along the Africa and Adria margins, to reproduce the break-off of the oceanic slab that followed the beginning of continental subduction both in Northern Africa and Adria. Slab break-off is followed by the exhumation of the subducted continent. We observe that the influence of subduction on the kinematics of Adria largely decreases following slab break-off. In the models, the total counterclockwise rotation of Adria varies between 7° and more than 30°, depending on the timing of slab break-off. Since the process of subduction modifies the displacement of Adria, it also impacts the tectonic evolution of surrounding regions, especially in the Alpine belt: Our models show that during slab-roll back and before the Ligurian slab break-off, the azimuth of convergence between Adria and Europe shifts from ~N-S to ~ENE-WSW. Hence, they suggest that the oceanic subduction in the Western Mediterranean may contribute to the “Oligocene revolution” described by Dumont *et al.* (2011), leading to E-W shortening in the Western Alps and to the activation of the Periadriatic right-lateral shear zones in the Central Alps. We conclude that the western Mediterranean region is a spectacular example showing how the tectonics of mountain ranges and plate boundaries may be controlled by distant subduction processes.

Keywords: Subduction / Analogue models / West Mediterranean / Adria / Alps / Neogene

Résumé – La subduction en Méditerranée occidentale est-elle à l’origine de la dynamique néogène de la chaîne alpine ? Apports de la modélisation analogique. Dans les Alpes occidentales, on décrit classiquement une phase tectonique “pyréno-provençale” ancienne, du Crétacé supérieur à l’Éocène, accommodant un raccourcissement N-S résultant de la convergence entre l’Afrique et l’Eurasie. Elle est suivie par la “phase alpine” Néogène, qui correspond à un raccourcissement E-W. Comme ce changement tectonique majeur ne résulte pas d’un changement de convergence entre l’Afrique et l’Eurasie, il doit être expliqué par des causes plus locales, en particulier par la subduction de l’Océan Ligure qui s’est produite à partir de l’Oligocène sous les plaques européenne et ibérique. Nous présentons des modèles analogiques simulant l’évolution de cette zone de subduction, afin de déterminer dans quelle mesure elle a modifié la tectonique régionale. Bien que ces modèles ne comportent pas de plaque lithosphérique chevauchant la zone

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de subduction, nous observons que leurs déformations de surface présentent de nombreuses similitudes avec la tectonique néogène de l'Europe occidentale et de l'Ibérie, qui est largement contrôlée par le recul du plan de subduction. En effet, celui-ci a été beaucoup plus rapide que la convergence Afrique-Eurasie. Les modèles reproduisent l'ouverture des bassins de Méditerranée occidentale et la dispersion des fragments continentaux AlKaPeCa (Alboran, Kabylie, bloc péloritain et Calabre). Ils montrent également que la subduction de l'Océan Ligure a favorisé la rotation antihoraire de la plaque Adria. Dans certains modèles, nous avons introduit une faiblesse préexistante au niveau des marges africaine et adriatique, afin de reproduire le détachement de la plaque océanique qui s'est produit suite à la subduction continentale, sous l'Afrique du Nord et Adria. Le détachement de la plaque océanique entraîne l'exhumation du continent subduit. L'influence de la subduction sur la cinématique de la plaque Adria diminue fortement après que le détachement se soit produit. Dans les modèles, la rotation antihoraire totale d'Adria varie entre 7° et plus de 30°, en fonction de la chronologie du détachement de la plaque plongeante. Puisque le processus de subduction modifie le déplacement d'Adria, il impacte aussi l'évolution tectonique des régions qui bordent cette plaque, en particulier dans les Alpes: Nos modèles montrent que pendant le recul de la plaque plongeante, et avant le détachement océanique, l'azimut de convergence Adria-Europe tourne de ~N-S à ~ENE-WSW. Ils suggèrent donc que la subduction océanique de Méditerranée occidentale a contribué à "révolution oligocène" décrite par Dumont *et al.* (2011), conduisant à un raccourcissement E-W dans les Alpes occidentales et à l'activation des zones de cisaillement dextres péri-adriatiques dans les Alpes centrales. Il apparaît que la région méditerranéenne occidentale est un exemple remarquable montrant comment la tectonique des chaînes de montagnes et des frontières de plaques peut être contrôlée par des processus de subduction lointains.

Mots clés : Subduction / Modèles analogiques / Méditerranée occidentale / Adria / Alpes / Néogène

1 Introduction

At the end of the Lower Cretaceous, Africa definitely separated from South America and initiated its northward drift towards the Eurasian plate (*e.g.*, Dewey *et al.*, 1973, 1989; Savostin *et al.*, 1986; Handy *et al.*, 2010). The convergence between Africa and Europe has controlled the overall geodynamic context that has prevailed in southern Europe since then. It resulted in the subduction of most of the Alpine Tethys and other oceanic basins that had formed following the break-up of Pangea and its separation into two major continental domains (*e.g.*, Ricou, 1994). The tectonic evolution of Southern Europe, however, underwent significant changes during this period of overall N-S convergence, and was marked by several episodes of intense crustal stretching (*e.g.*, Jolivet and Brun, 2010; Royden & Faccenna, 2018). Indeed, the convergence rate between Africa and Europe always remained slow (~1 cm/yr, *e.g.*, Rosenbaum *et al.*, 2002a), significantly slower than the subduction velocity of the old oceanic lithospheres that separated the two main continents, likely because the subducting plates were too small to accelerate the northward motion of Africa. As a result, subductions in the Mediterranean domain generally resulted in back-arc extension accommodating trench retreat. This process is ongoing in a spectacular way in the Aegean Sea today (*e.g.*, Gautier *et al.*, 1999; Nocquet, 2012) where geodetic, seismological and tectonic data evidence the stretching of the continental plate overriding the Hellenic subduction zone at velocities several times higher than the present-day Africa-Eurasia convergence rate.

A similar process occurred in the Western Mediterranean region from the Oligocene onwards, where trench retreat accommodating the subduction of the old Mesozoic oceanic sea-floor that separated Adria and Africa from Europe and Iberia (Ligurian Ocean) triggered back-arc extension. It resulted in the opening of the Liguro-Provençal, Algerian and Tyrrhenian Basins, and in the dispersion of the AlKaPeCa

(Alboran, Kabylia, Peloritan, Calabrian) continental fragments (*e.g.*, Bouillin *et al.*, 1986; Faccenna *et al.*, 2001a; Rosenbaum *et al.*, 2002b; Michard *et al.*, 2002, 2006; Romagny *et al.*, 2020). Several authors described the tectonic evolution of the European/Iberian plates accommodating the retreat of the oceanic slab (*e.g.*, Séranne, 1999; Faccenna *et al.*, 2004; van Hinsbergen *et al.*, 2014a, Romagny *et al.*, 2020). Slab retreat first resulted in continental thinning followed by oceanic spreading in the Liguro-Provençal Basin, accommodated by the rotation of Corsica and Sardinia (Montigny *et al.*, 1981; Gattacecca & Speranza, 2002). In the Late Miocene-Pliocene, slab retreat continued to the SE accommodated by the lithospheric thinning of the Tyrrhenian Sea resulting in the opening of the Vavilov and Marsili basins (Faccenna, 2001b; Guillaume *et al.*, 2010), meanwhile another slab segment was retreating to the West beneath the Alboran Sea.

If the extension of the overriding plate resulting from the retreat of the Western Mediterranean slab has been largely described, in particular thanks to the geophysical data available in region (*e.g.*, Séranne, 1999; Jolivet *et al.*, 2015), less attention has been given to the consequences of this subduction on the kinematics of Adria and hence on the Alpine belt itself, as resulting from the collision between Adria and Europe. Often, reconstructions describing the post-Oligocene evolution of the Western Mediterranean region do not consider the relative motion of Adria and Apulia with respect to the African plate (*e.g.*, Séranne, 1999) because, indeed, related velocities are small compared to the slab roll-back motion (Handy *et al.*, 2019; van Hinsbergen *et al.*, 2020). However, oceanic subductions exert forces both on the overriding and subducting plates (*e.g.*, Funicello *et al.*, 2003a; Cerpa *et al.*, 2018) and may affect the kinematics of plates situated on both sides of the subduction zone. The maximum trench-parallel length of the oceanic slab in the Western Mediterranean region (~1000 km) remained small compared to Africa, so that this subduction did not generate forces that could have had a major effect on this huge and

rigid tectonic Plate. Adria in contrast is a much smaller plate, and its kinematics may have been impacted by the subduction that initiated ~35 Ma ago (Séranne, 1999; Jolivet *et al.*, 2015). Hence, this subduction may have had repercussions on the tectonic evolution of all the regions that bound Adria, especially in the Alpine belt.

In this paper, we present analogue models simulating the oceanic subduction that occurred in the Western-Central Mediterranean region from the Oligocene. We consider the possible effects of oceanic slab detachment on plates kinematics and tectonics. Models suggest that the Western Mediterranean subduction, by modifying the kinematics of Adria, could explain part of the major tectonic changes that occurred in the Alpine arc during the Oligocene and that led Handy *et al.* (2010) and Dumont *et al.* (2011) to speak of the “Alpine Oligocene revolution”.

2 Experimental set-up

The experimental set-up adopted in these experiments is similar to that used in Funicello *et al.* (2004), Martinod *et al.* (2005) or Guillaume *et al.* (2013). We use Newtonian viscous materials within a Plexiglas tank (60 x 40 x 15 cm³) to reproduce the subduction of a lithospheric plate in the upper mantle (Fig. 1). The bottom of the tank simulates the upper mantle–lower mantle discontinuity as an impermeable barrier, meaning that the reference frame corresponding to the tank may be considered in experiments as the analogue of the lower mantle reference frame in nature.

Lithospheric plates are modeled using silicone. They initially float above glucose syrup that models the sub-lithospheric upper mantle. Silicone is mixed with iron powder to tune its buoyancy. Plates modelling continental lithosphere are buoyant, while plates modelling oceanic lithosphere are denser than the glucose syrup. The buoyancy and thickness of oceanic lithosphere simulates a 65 Ma-old oceanic plate (see Tab. 1 for the scaling of experiments): According to Cloos (1993), the plate is 80 km-thick and its negative buoyancy close to -70 kg/m³ if the thickness of the oceanic crust is small, which is often observed in oceanic sea floors that formed in slow spreading ridges. The buoyancy of silicone plates modelling continents is positive and corresponds to the average buoyancy of a lithosphere in which the continental crust thickness varies between 20 and 25 km (Tab. 1).

The plate overriding the subduction zone is not modelled. We monitor deformation at the surface of the glucose syrup considering that deformation of the overriding plate is largely controlled by the mantle flow resulting from the process of subduction (*e.g.*, Jolivet *et al.*, 2009; Sternai *et al.*, 2014). This monitoring is achieved using passive markers (small plastic beads) that float above the syrup. We added a thin layer (<1 mm) of silicone oil above the silicone plate modeling oceanic lithosphere to better simulate the low coupling between the subducting and overriding plates at trench. Indeed, Duarte *et al.* (2015) show that subduction interfaces are weak with shear stresses smaller than 30 MPa. We observed that in the absence of this low-viscosity interface, the plastic beads quickly reach the trench and subduct with the sinking plate, which would correspond in nature to huge amounts of erosion of the upper plate by the subduction process. In models that do

not include a lubricated subduction interface between the plates, a huge and unrealistic amount of overriding plate erosion is indeed observed (see for instance the models presented in Regard *et al.*, 2003). This upper plate erosion is very limited using the silicone oil that may represent in nature the superficial layers of the oceanic plate such as sediment, or serpentinized mantle whose strength is much smaller than that of peridotite (*e.g.*, Reynard, 2013). Although adding this low-viscosity modifies the superficial velocity field above the subduction zone, we note that it does not change significantly the overall evolution of subduction in experiments.

Using uniform silicone plates to model the oceanic and continental lithospheres is clearly a simplification of their complex rheological and density layering. The justification of this experimental approach that has been extensively used both in analogue and numerical models is that the lithosphere in first approximation behaves like a viscous fluid in a process characterized by large temporal and spatial scales, such as subduction (*e.g.*, Funicello *et al.*, 2004). The viscosity of silicone putty is Newtonian, whereas laboratory data indicate that creeping lithospheric rocks obey power-law type behavior (*e.g.*, Carter & Tsenn, 1987). A consequence of this approximation is that slab break-off is generally not observed in analogue experiments because Newtonian rheology, favoring homogeneous deformations, inhibits any possible rupture of the plate, at least at time scales comparable to those of the process of subduction. Few studies investigated slab break-off in this kind of analogue models (Regard *et al.*, 2008; Fernandez-Garcia *et al.*, 2019). To obtain slab break-off, we introduced in some experiments a pre-existing fault at the passive margin separating the oceanic lithosphere from the continent, and we lubricated the fault using silicone oil. Break-off in these experiments does not always occur at the same time: it is highly sensitive to the thickness of the silicone oil layer present in the cut simulating the pre-existing fault, that we could not constrain precisely. In fact, in nature break-off probably also occurs along inherited weaker structures. But actually, the objectives of this procedure are not to study the process of slab break-off, but rather to look at the consequences of this phenomenon on the surface dynamics by comparing experiments with and without break-off. In this experimental set, we observe when slab break-off occurs in experiments and we study how it subsequently modifies the superficial tectonic regime.

Experiments are monitored using top and lateral views (photos taken from the side of the transparent Plexiglas tank). The initial geometry of the models roughly approximates the geometry of NW Africa (Maghreb), Adria/Apulia, and of the oceanic sea floor (Ligurian Ocean) 35 Ma ago, before its subduction beneath Europe/Iberia, as proposed by Romagny *et al.* (2020) (Fig. 1). We consider that Africa, the Ligurian sea floor, Apulia and Adria correspond to the same lithospheric plate and we do not model any fault within this plate except, in some experiments, pre-existing faults along the passive margins bordering the Ligurian Ocean to obtain slab break-off. Some Neogene deformations may have occurred between Apulia and Africa. For instance, the reconstructions by Handy *et al.* (2010) imply the subduction of part of the Ionian oceanic sea-floor beneath Apulia, but these authors recognize that the evolution they propose for the Ionian domain is highly speculative. Furthermore, the amount of subduction would

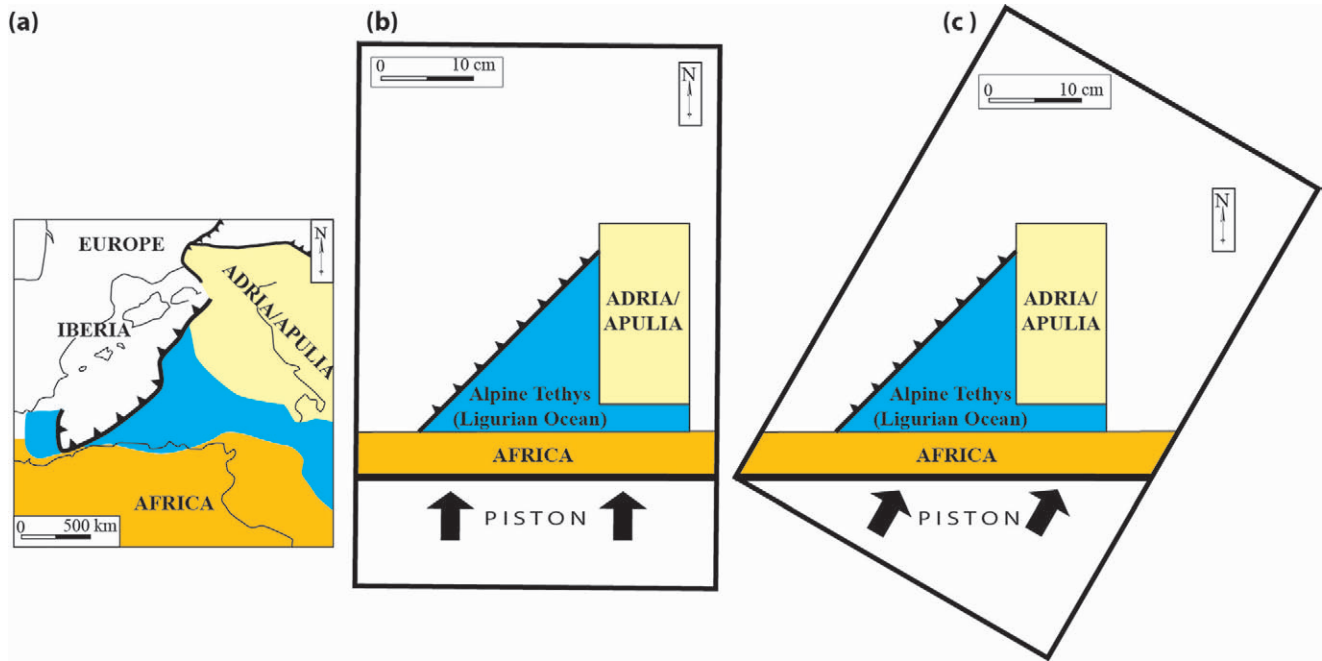


Fig. 1. (a) the Western Mediterranean region 35 Ma ago, after Romagny *et al.* (2020); (b) and (c) the analogue models at the beginning of experiment. Plates geometry is similar in (b) and (c) and reproduce the Oligocene situation. Silicone plates modelling the Adria/Africa plates are deposited above glucose syrup modelling the upper mantle. Continents (yellow and orange colors) are modelled using buoyant silicone and oceanic lithosphere (blue color) is modelled using silicone whose density is larger than that of the glucose syrup. The glucose syrup is not covered by any silicone sheet in the white-colored areas and passive floating plastic beads show its surface deformations. (b) configuration with northward motion of Africa in case the piston moves (Models 5, 7 and 8, see Tab. 2). (c) configuration facilitates the side view of the slab, and results in NE motion of Africa if the piston advances (Models 6 and 9).

remain small, and in fact the 35 Ma-old plate configurations proposed by Romagny *et al.* (2020) does not differ significantly from that proposed by Handy *et al.* (2010). Geological and geodetic data also show deformations along the Gargano-Dubrovnik line (*e.g.*, Oldow *et al.*, 2002; Nocquet, 2012; Handy *et al.*, 2019). In fact, the relative motion between these plates is small compared to displacements that occurred in the Western Mediterranean during the Neogene. That's why in the following, we denominate “Adria” the continental domain corresponding to the present-day “Adriatic” and “Apulian” plates located north and south of the Gargano-Dubrovnik line, respectively.

Since the aim of this experimental set is to consider the possible effects of oceanic subduction on the kinematics of Adria and its consequences on the Alpine belt, we do not model the small slab segment retreating westward in the Alboran Sea region, considering that this small and remote subduction should not impact significantly the Alps. The plate initially floats above the mantle and oceanic subduction is initiated manually by sinking the edge of the oceanic lithosphere at a depth of ~ 15 mm inside the glucose syrup. This initial geometry of the models and the procedure to initiate subduction is quite similar to the set-up adopted by Lo Bue *et al.* (2021) in their numerical models simulating subduction in the Central Mediterranean Region. A difference, however, is that boundary conditions inhibit any possible relative displacement of Adria with respect to stable Africa in the set-up adopted by Lo Bue *et al.* (2021). In fact, these

authors do not consider the effect of subduction on the motion of Adria. In contrast, their paper details the process of slab break-off depending, both on the characteristics of the continental plate and on resulting deep mantle flow, which our analogue models cannot do properly.

In three experiments, we simulate the Northern motion of Africa towards Europe using a piston pushing Africa at constant speed towards the North (Fig. 1b). We set the piston velocity so that the ratio between Africa/Europe convergence (~ 8 mm/yr) and the maximum slab-retreat velocity that occurred in the Western Mediterranean (~ 50 mm/yr) region is respected. In two other experiments, we push the African plate towards the NE (Fig. 1c) to take into account its motion in the hot spot reference frame. Finally, in four simpler reference experiments, the piston does not move, in order to isolate the effect of subduction and slab-retreat on the surface deformations. Experiments in which the piston advances show possible effects of slab stagnation above the lower mantle when the subducting plate moves in the hot spot reference frame. Indeed, we observe that the silicon plate deposited at the bottom of the box does not slide horizontally as the subduction process continues. However, these experiments do not model possible effects of background mantle flow that may result from other regional subduction zones or from global circulations in the upper mantle.

Experiments were performed in the analogue model laboratory of Université de Savoie-Mont Blanc (Le Bourget

Table 1. Scaling of parameters for the reference experiment (Model 1).

Parameters		Model	Nature
g (m/s ²)		9.81	9.81
Thicknesses (m)			
$H_o = H_c$	Lithospheric plates	0.012	80 000
H_{um}	Upper mantle	0.1	670 000
		Length (thickness) scale factor $H_{Model} / H_{Nature} = 1.5 \times 10^{-7}$	
Buoyancies (kg/m ³)			
$\Delta\rho_o$	Oceanic lithosphere	-243	-69
$\Delta\rho_c$	Continental lithosphere (21 km-thick crust)	+221	+61
		Buoyancy scale factor $\Delta\rho_{Model} / \Delta\rho_{Nature} \sim 3.5$	
Viscosities (Pa.s)			
η_o	Oceanic lithosphere	64 000	$\sim 3 \times 10^{23}$
η_{um}	Upper mantle	210	$\sim 10^{21}$
		Viscosity scale factor $\eta_{Model} / \eta_{Nature} \sim 2.1 \times 10^{-19}$	
Characteristic time (s)			
$t_{Model} / t_{Nature} = (\Delta\rho \cdot g \cdot H)_{Nature} / (\Delta\rho \cdot g \cdot H)_{Model} \times \eta_{Model} / \eta_{Nature}$ $\sim 4 \times 10^{-13}$		13	3.16×10^{13} (1 Ma)
Characteristic velocity (m/s)			
$U_{Model} / U_{Nature} = t_{Nature} / t_{Model} \times H_{Model} / H_{Nature}$ $= 3.8 \times 10^5$		1.2×10^{-4} (0.12 mm/s)	3.2×10^{-10} (1 cm/a)

Table 2. Experimental parameters. U_{Model} is the piston velocity; $\Delta\rho_c$ and $\Delta\rho_o$ are the continental and oceanic plate buoyancy, respectively; η_{syrup} is the glucose syrup viscosity that varies with temperature according to the following equation: $\eta_{syrup} = 3740 \cdot e^{(-0.16 \cdot T)}$, where T is the syrup temperature in °C; All the other experimental parameters remain the same between experiments: the density of the glucose syrup is 1444 kg/m³, the viscosity of the silicone plates modeling the continental and oceanic plate are 6.4×10^4 and 4.1×10^4 Pa.s, respectively, and their thickness is 12 mm; The thickness of the glucose syrup layer is 100 mm; The viscosity of the thin silicone oil layer deposited above the subducting plate is 2 Pa.s. The horizontal dimensions of the box and of silicone plates are indicated in Figure 1. U_{Nature} is the scaled piston velocity (in mm/yr), and we report the average counterclockwise rotation of Adria at the end of experiment. > 35 for Models 5 and 6 indicates that the microplate was still rapidly rotating when we stopped the experiment.

Experiment	1	2	3	4	5	6	7	8	9
azimuth long box axis	N30°E	North	N30°E	North	North	N30°E	North	North	N30°E
U_{Model} (mm/s)	0	0	0	0	0,13	0,27	0,13	0,13	0,27
$\Delta\rho_c$ (kg/m ³)	221	231	211	221	220	221	189	195	217
$\Delta\rho_o$ (kg/m ³)	-243	-283	-197	-254	-179	-231	-290	-188	-197
Temperature	18	16	19,7	15,4	20	17,3	16,5	16,8	20,7
η_{syrup} (Pa.s)	210	289	160	318	152	235	267	254	136
slab break-off	no	no	yes	yes	no	no	yes	partial	yes
U_{Nature} (mm/a)	0	0	0	0	11	26	12	17	18
Adria Rotation (°)	25	22	14	7	> 35	> 35	10	30	35

du Lac, France). Table 1 summarizes the scaling of models, Table 2 presents the physical parameters of the experimental set, and the dimensions and experimental conditions adopted in the different models are presented in Figure 1.

3 Results: effects of subduction on the kinematics of Adria

We performed 9 models with the same plates geometry (Tab. 2). They essentially differ between them by the presence

or not of a heterogeneity favoring the detachment of the oceanic slab, and by the advance of the piston which simulates in some experiments the motion of Africa. The orientation differs between experiments: in some experiments, the North is oriented parallel to the long axis of the Plexiglas tank, which allows to simulate the northward advance of Africa towards Europe if the piston moves. In other experiments, the long axis of the tank corresponds to an azimuth oriented N30° (Fig. 1). This configuration allows to simulate the movement of Africa towards the NE, in a reference frame linked to the lower

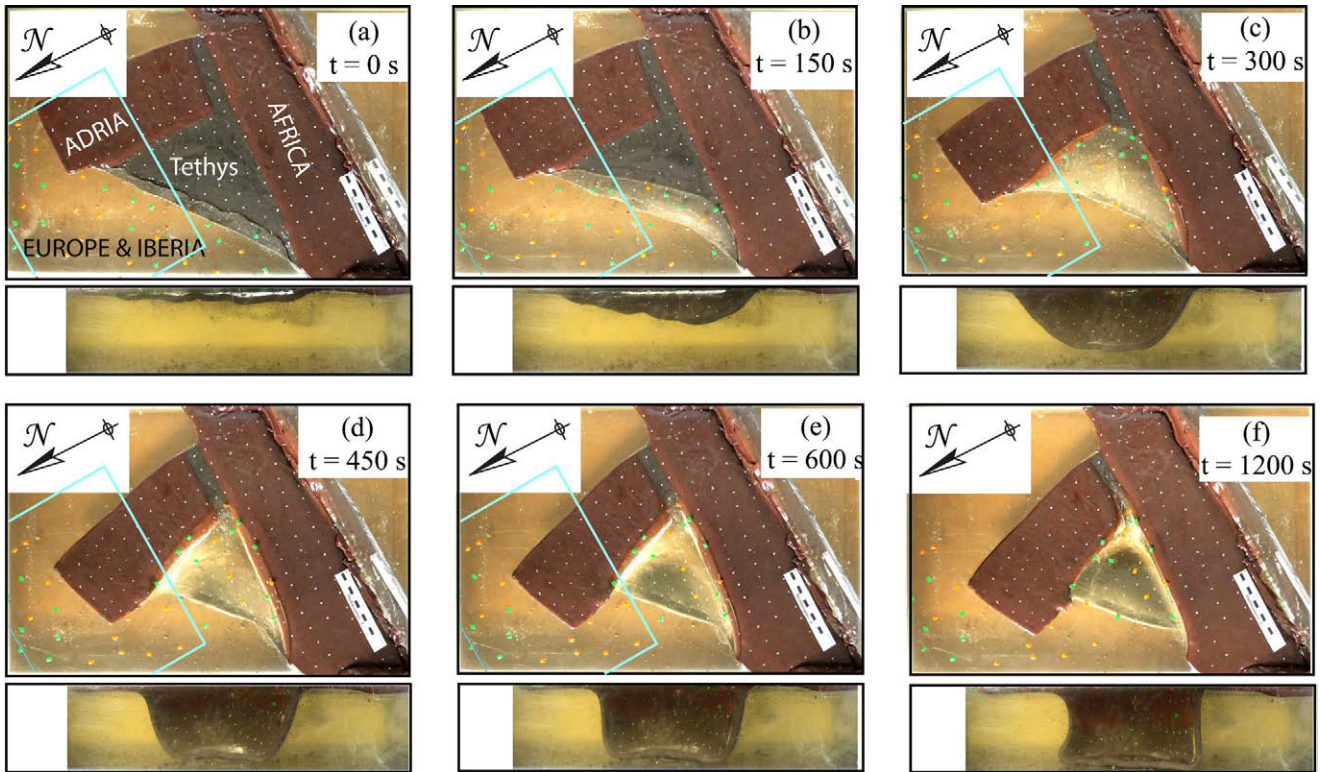


Fig. 2. Top and lateral views of Model 1. The red silicone is buoyant and models continental lithosphere. In contrast, the buoyancy of the black silicone modeling oceanic lithosphere is negative. (a) beginning of experiment, the oceanic plate has just been forced downward in the upper mantle to initiate subduction; (b) and (c) after 150 and 300 s of experiment, respectively: the process of subduction is accelerating and Adria initiates counterclockwise rotation; (d), (e) and (f) after 450, 600 and 1200 s, respectively: the oceanic plate deposits above in the lower mantle (bottom of the box), and the dip of the slab increases, further increasing the rotation of Adria. Floating colored plastic beads show surface flow in the glucose syrup. Blue rectangles show the domain for which the principal axes of the strain tensor is presented in Figure 4.

mantle. This configuration also permits to observe more clearly the evolution of the slab using a camera placed along the lateral (NW) side of the box. We checked that experiments which differ only in the orientation of the model with respect to the walls of the box, for instance models 1 and 2, evolve in the same way. Table 2 summarizes the main experimental conditions of the 9 experiments. For each experiment, we measured the superficial velocity field, and especially the velocity of subduction, rotation of Adria and the strain regime at its northern and NW boundaries (*i.e.*, the area corresponding to the Alpine arc).

3.1 Models 1 and 2: reference experiments

The thickness of oceanic and continental plates is constant in these simple experiments, and there is no fault favoring slab detachment. The evolution of model 1 is detailed in this section. In fact, the evolution and the final geometry of the plates is very similar in model 2 (Tab. 2). The piston does not move, and the deformation of the models only results from the negative buoyancy of the oceanic plate that sinks naturally in the glucose syrup. Figure 2 presents successive top and lateral views of model 1. A video showing the evolution of Model 1 is available in the [supplementary data](#) of this paper.

Subduction begins slowly and progressively accelerates as the length of the slab increases (Fig. 3). This velocity increase resulting from the growth of the slab and the associated increase in slab-pull force (Becker *et al.*, 1999) has already been observed in many analogue experiments modeling oceanic subduction (*e.g.*, Funicello *et al.*, 2003b; Martinod *et al.*, 2005). The increase in subduction velocity stops when the slab interacts with the bottom of the tank simulating the lower mantle. In the simple experiments presented for instance in Martinod *et al.* (2005), in which the trench-parallel width of the subducting plate is constant, subduction pursues at constant speed following slab stagnation above the lower mantle (steady-state regime of subduction). In Model 1, following slab anchoring after 330 s, the subduction velocity decreases sharply since most of the oceanic plate already subducted (see Fig. 2c) and the length of the oceanic trench is restricted to the narrow oceanic domain that separates Adria from Africa. Because both the Adriatic and African continents are highly coupled with the subducting oceanic plate in model 1, continental margins are dragged down, diminish the negative buoyancy of the slab, slowing down subduction. Slab break-off is not observed in this experiment.

Subduction in this experiment is achieved through slab roll-back, since the subducting plate is maintained fixed by

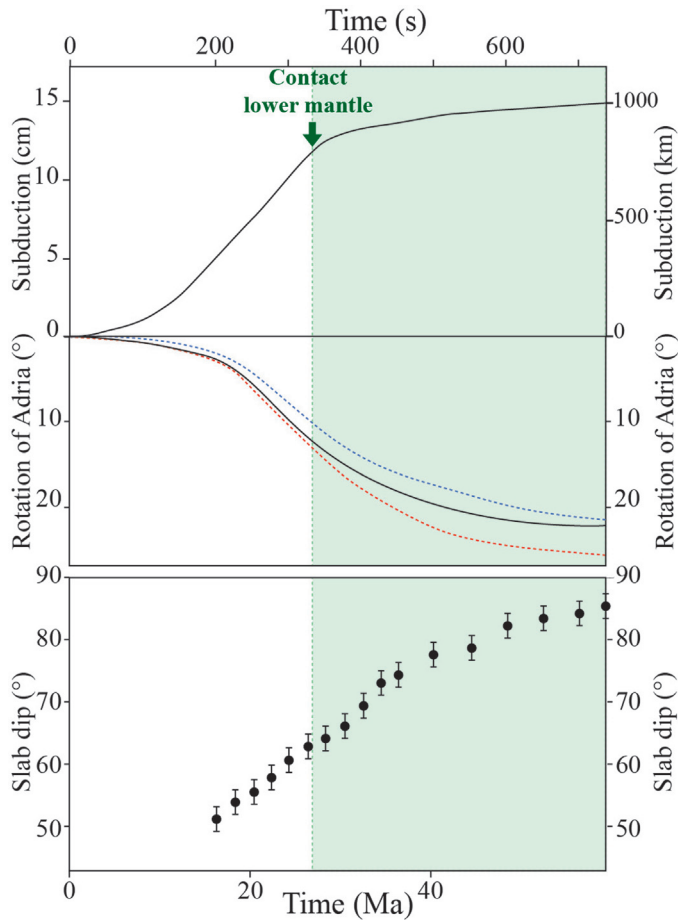


Fig. 3. Amount of subduction, counterclockwise rotation of Adria and dip of the slab, vs. time, in Model 1. Blue and red dotted curves indicate rotations of northern and southern Adria, respectively, and the black curve the average rotation of the plate. Slab dip is measured beneath the African margin.

lateral boundary conditions. It generates displacements in the upper mantle (glucose syrup), necessary to accommodate the retreat of the slab. The observed surface velocity field is a proxy of the deformations that would occur in potential overriding plates in response to the process of subduction: slab roll-back generates trench perpendicular extension in the overriding plates above the subduction zone and suction forces explain the transport of continental fragments moving towards the retreating trench (*e.g.*, Hassani *et al.*, 1997; Funicello *et al.*, 2003b, 2006).

Surface displacements are also significantly affected by the motion of Adria, because this small plate is easily pulled towards the subduction zone. The southern boundary of Adria is coupled to the African plate, considered fixed in this experiment. It cannot move freely towards the West, and the force that pulls Adria westward causes the plate to rotate counterclockwise (Figs. 2 and 3). Figure 3 shows that rotation initiates during oceanic subduction. It pursues after slab

stagnation above the lower mantle (330 s), despite all the oceanic plate (except the narrow oceanic domain located south of Apulia) has already sunk in the upper mantle. Indeed, although continental subduction rapidly stops the retreat of the trench, the dip of the slab increases. Slab dip increase following the beginning of continental subduction is generally observed because the lower dense part of the slab pursues its descent in the upper mantle, while the buoyant upper slab segment does not (Martinod *et al.*, 2005). This increase of the dip of the slab is only possible if Adria further moves trenchward, *i.e.*, if the Adria's rotation continues.

The strain-tensor observed at the surface of the model, above the subduction zone and around Adria, is affected by the westward motion of the plate. Figure 4 focuses on the surface strain on the NW side of Adria (roughly corresponding to the Western and Central Alps). Subduction initiation triggers back-arc extension (Fig. 4a), but as soon as the rotation of Adria starts, it results in strike-slip deformations on the northern boundary, and in E-W shortening combined with some N-S extension west of the plate.

3.2 Effect of slab break-off on the dynamics of Adria: models 3 and 4

Models 3 and 4 are comparable to models 1 and 2, the only difference being the presence of a pre-existing fault at the boundary between the buoyant (continental) and dense (oceanic) silicone plates, favoring slab break-off. Figure 5 presents successive top and lateral views of Model 3. A video of this model is also available in the supplementary data. As explained in the section describing the experimental set-up, we do not constrain precisely the properties of the pre-existing fault, that are highly dependent on the thickness of the silicone-oil present in the initial cut modelling the fault. Then, slab break-off happens more or less rapidly in experiments, and our experimental procedures do not permit to determine when it will occur. In fact, the objective of these experiments is not to predict the timing of slab break-off, but rather to study how the rupture of the slab alters the deformations in the model. In Model 3 for instance, slab break-off initiated rapidly (~ 160 s) in the northern sector of Adria, then migrated southward to reach the southern part of the continent (~ 220 s). It occurred later in the African margin, between 260 s and 300 s from East to West. Following slab-break-off, the dense plate rapidly sinks and deposits at the bottom of the box, and the continental margin that had been pulled downwards in subduction comes back to the surface (Fig. 6a). Figure 5f shows that the maximum amount of continent that subducted reached ~ 25 mm (corresponding to ~ 170 km in nature).

As in Model 1, subduction is accommodated by slab roll-back and triggers extension in the overriding compartment. It also exerts a westward oriented force resulting in the counterclockwise rotation of Adria (Fig. 6). But as soon as break-off occurs beneath Adria, the rotation rate decreases, and the final total rotation (14°) is significantly smaller than in models 1 and 2 without any break-off (Tab. 2). Model 4 in which slab break-off occurred earlier than in Model 3 is characterized by an even lower rotation of Adria (7°).

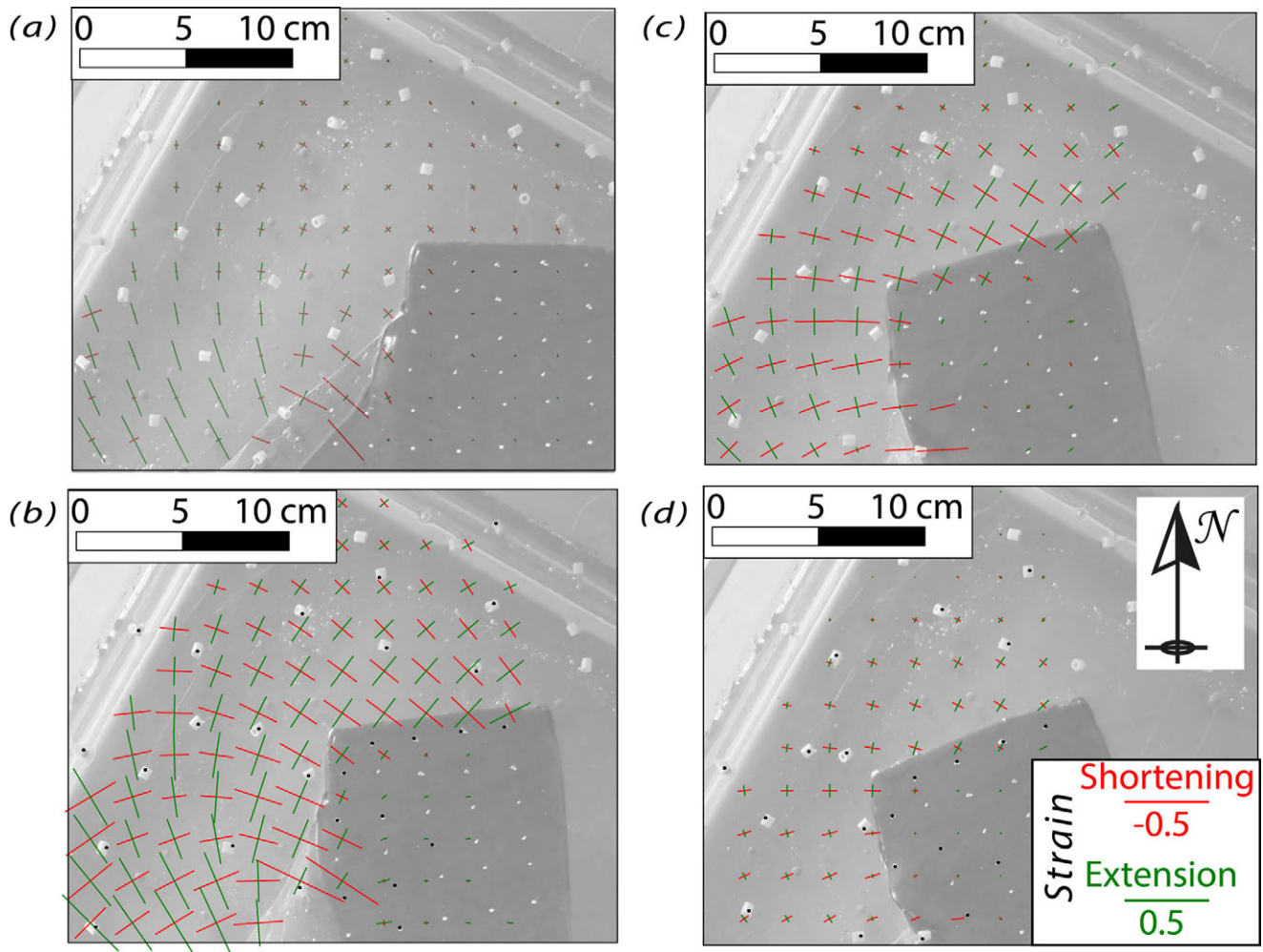


Fig. 4. Deformations of the surface of Model 1: the principal axes of the strain tensor are reported. Green and red lines indicate extension and shortening, respectively. Strain tensors have calculated between (a) 50 and 150 s; (b) 200 and 300 s; (c) 350 and 450 s; (d) 500 and 600 s of experiment. After 600 s, slabs are almost vertical and deformation is very slow.

3.3 Effect of the northward motion of Africa, with and without slab break-off: models 5 to 9

In Models 5 to 9, a piston is advancing parallel to the long-axis of the box, to evaluate the influence of the motion of Africa and Adria on the dynamics of subduction. In models 5, 7 and 8, the long-axis of the box is oriented towards the North (Fig. 1b, Tab. 2). The piston motion then imposes a northward motion of Africa. The piston velocity is 0.13 mm/s, which would correspond to ~ 11 mm/a in nature (Tab. 2). This motion is close to the relative motion of Northern Africa with respect to Europe (~ 8 mm/a, along a N334°E azimuth at the longitude of Tunisia).

Model 5 did not contain any pre-existing fault, so that slab break-off did not occur. Its evolution is close to that of Models 1 and 2 (Fig. 7). Subduction results in back-arc extension, because the northward motion of the African plate is much slower than slab roll-back. The dip of the slab progressively increases. At the end of experiment, the slab beneath the African margin is overturned (dip larger than 90° in Fig. 7c)

because the lower part of the subducted plate is anchored on the bottom of the plexiglas tank meanwhile Africa and the upper part of the slab still move northward. As in Models 1 and 2, subduction triggers the counterclockwise rotation of Adria. But the final amount of rotation is larger in Model 5, and rotation is still increasing at the end of experiment although the subduction of the oceanic plate is achieved. The rotation keeps going on after the end of the subduction for two reasons: (1) the lower part of the slab being anchored; it pulls back Adria and slows down its advance towards the north; (2) fluxes in the upper mantle move southward with respect to Adria.

In Model 7, slab break-off occurs rapidly beneath northern Adria (after ~ 130 s of experiment), before propagating to southern Adria. Before break-off, deformation is comparable to that observed in Model 5, with slab roll-back triggering trench-perpendicular extension above the retreating slab (Fig. 8). Break-off is achieved beneath Southern Adria at 300 s. It occurs later beneath the African margin, first at ~ 240 s in the western segment, and the break-off of the oceanic slab is complete after 380 s of experiment (Fig. 9). Again, this

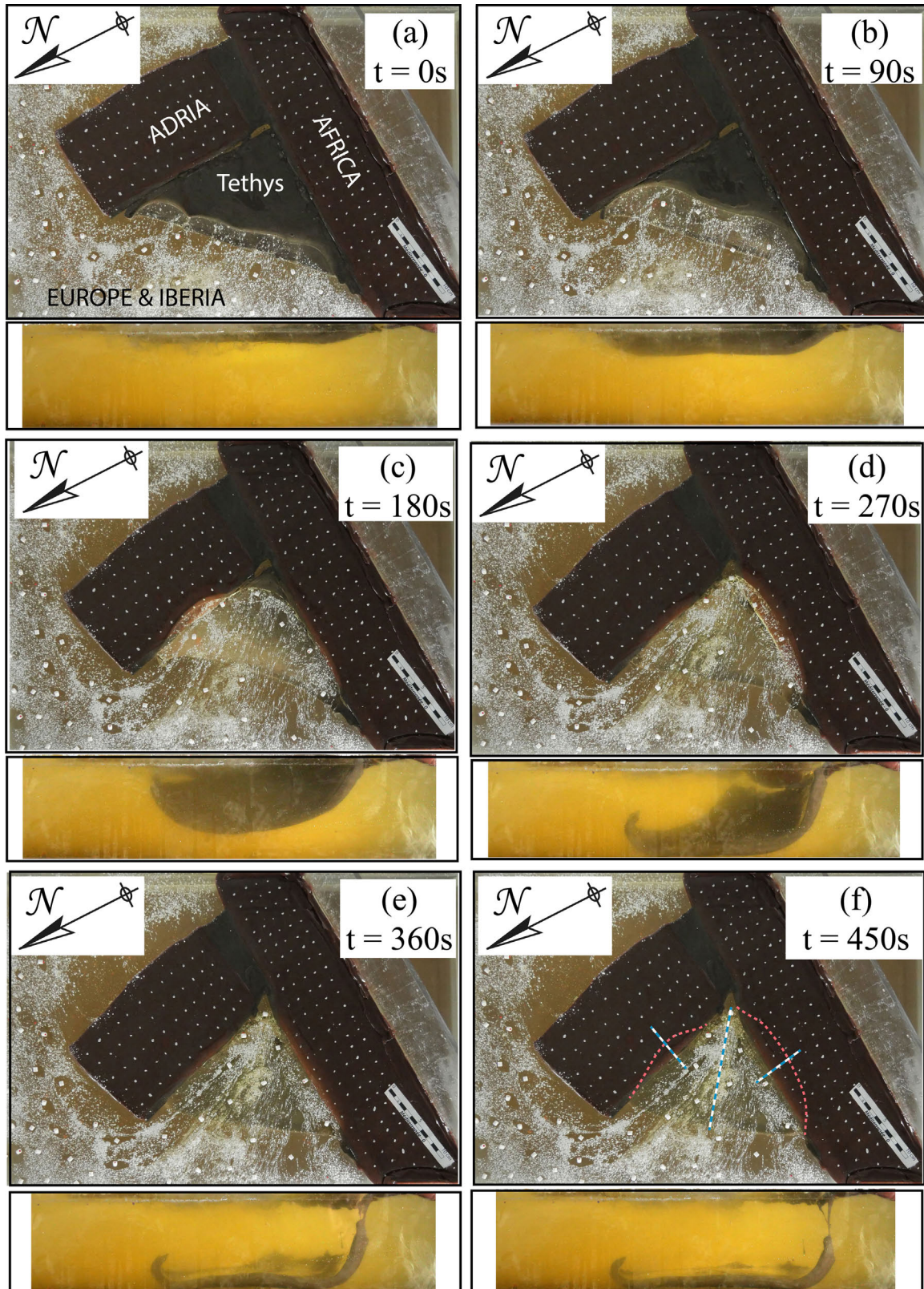


Fig. 5. Top and lateral views of Model 3. Slab break-off occurs between 160 s (margin of northern Adria) and 300 s (margin of western Africa). The red dotted-line in (f) shows the boundary of the continental domain that first subducted and then came back to the surface following break-off, and the white-blue dotted lines show the position of the cross-sections along which subduction lengths presented in [Figure 6a](#) are measured.

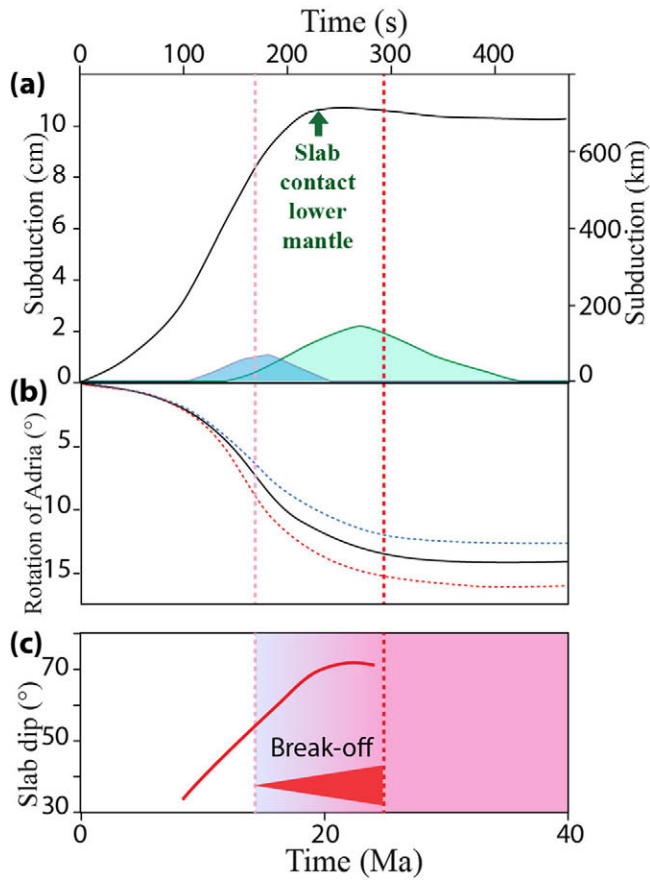


Fig. 6. (a) length of subduction (black curve), and length of subducted continent in Adria (blue curve) and Africa (green curve) vs. time, in Model 3. The position of the three sections along which lengths of subduction are measured are visible in Figure 5. In this model, subduction of the continental part of Adria starts earlier than that of Africa. Slab break-off also occurs sooner explaining why the subducted continental plate comes back earlier to the surface. (b) counterclockwise rotation of Adria (black curve = average rotation of the plate; blue and red dotted curves = rotation of northern and southern Adria, respectively). (c) dip of the slab beneath the African margin, and propagation of slab break-off from Adria to Africa, vs. time.

different chronology is largely explained by the initial heterogeneities of the pre-existing fault we introduced in the model, that we do not precisely constrain. However, since the length of the subducting oceanic plate is greater offshore southern Adria than northern Adria, continental subduction initiates first in the north favoring an earlier slab break-off in this sector. The same is true for the African margin, slab break-off generally occurs first in the western sector.

The total amount of rotation of Adria is much smaller in Model 7 including break-off, than in Model 5. Rotation in Southern Adria is larger than in the north. This difference partly results from the later break-off in the South, with the plate pulling the southern Adria westward for a longer time. Rotation rate largely drops when the break-off is complete beneath the plate, but the northward motion imposed by the piston maintains a slow rotation of Adria.

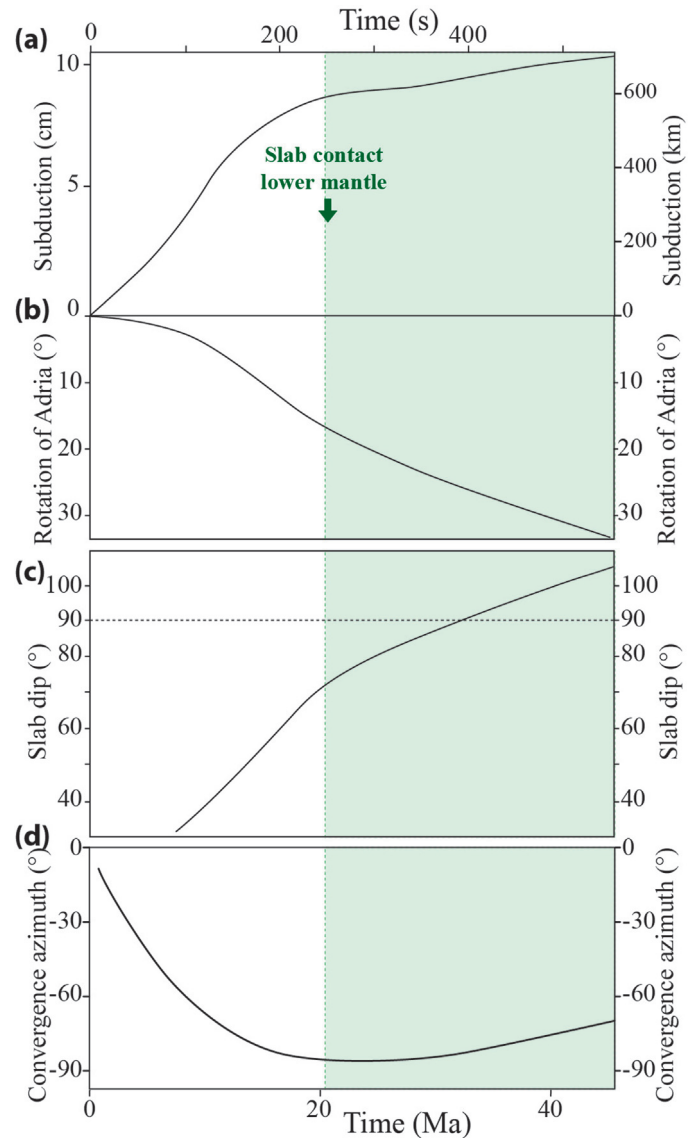


Fig. 7. (a) Length of subduction, (b) rotation of Adria, (c) dip of the slab and (d) azimuth of the motion of northern Adria, vs. time, in Model 5. Slab dip is measured beneath the African margin. Values larger than 90° mean that the slab is overturned (dipping southward) as a result of the northward motion of Africa.

Models 6 and 9 correspond to experiments in which the long-axis of the box is oriented $N30^\circ E$. This azimuth corresponds to the motion of northern Africa in the Atlantic-Indian hot spot reference frame since 30 Ma (Romagny *et al.*, 2020). Then, the advance of the piston simulates the motion of Africa in this reference frame. As in all other experiments, subduction results in slab roll-back, trench-parallel extension above the slab, and rotation of Adria triggers dextral strike-slip north of the plate and E-W shortening West of Northern Adria. Rotation is amplified if slab break-off does not occur (Tab. 2). The rotation rate of Adria following slab break-off is also larger than in models with N-S convergence, the SW mantle flow beneath Adria making the plate turn more efficiently.

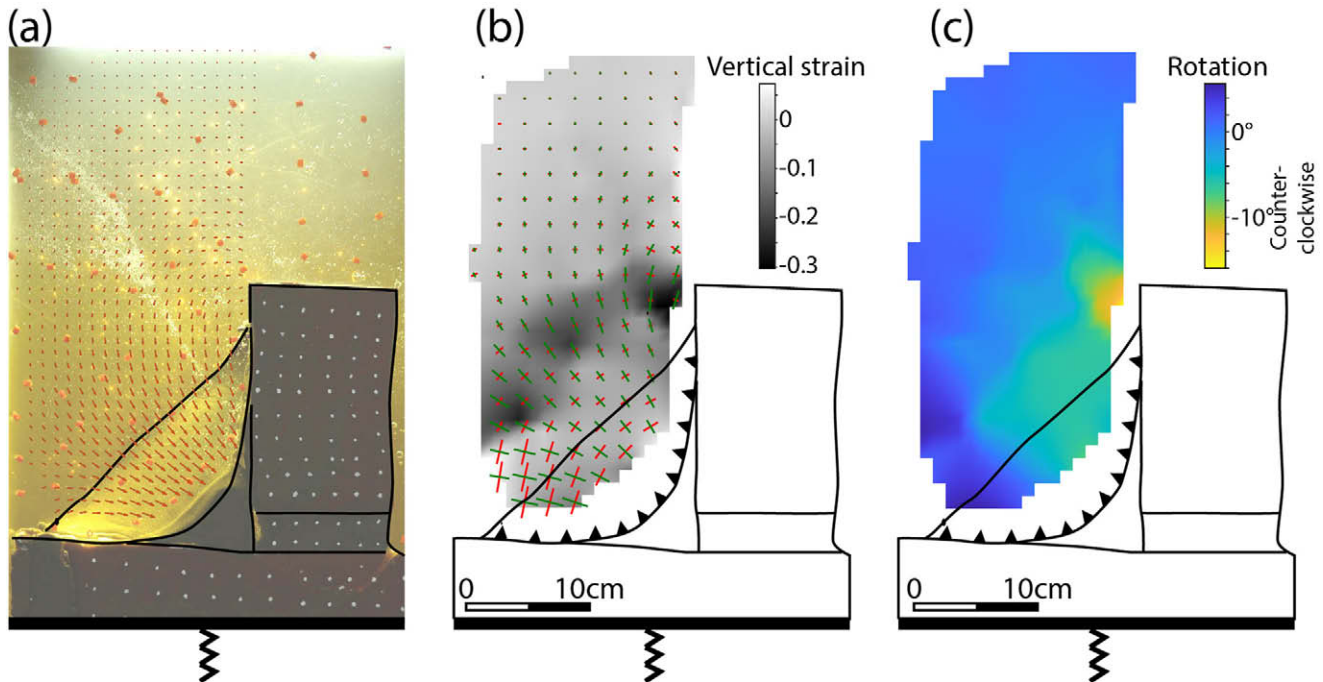


Fig. 8. (a) Top view of Model 7 after 210 s. Red arrows indicate the superficial velocity field in the glucose syrup. (b) Vertical strain at the surface of the glucose syrup between 110 and 210 s. The vertical strain was calculated from the horizontal surface strains, assuming that glucose syrup is an incompressible material. Negative values correspond to thinning. The principal axes of the strain-tensor are reported (extension in green, shortening in red). Superficial thinning is larger in a SW-NE oriented domain. SE of this sector, trench-parallel shortening compensates the trench-perpendicular extension, reducing superficial thinning. (c) Superficial rotations between 110 and 210s.

4 Discussion: Consequences of subduction in the Western Mediterranean on the dynamics of Adria and on the deformations of the European plate

4.1 Limitations of models

We describe hereafter how these experiments may help in understanding the effects of the Neogene subduction that occurred in the Western Mediterranean area, on the regional tectonic evolution. Although the models presented above largely simplify the complex geodynamics of the study area, they allow to better understand and constrain the effects of oceanic subduction on the geological evolution of the Western Mediterranean region, and more specifically of the Alpine belt.

A major limitation of these models is the absence of any lithospheric plate overriding the subduction zone. We observe deformations at the surface of the model, here at the surface of the glucose syrup modelling the upper mantle, and we suppose that crustal deformations within the overriding European and Iberian plates are largely controlled by this mantle flow. Then, we do not consider the possible effect of inherited structures, such as those resulting from the possible previous subduction of an oceanic domain separating a Meso-Mediterranean domain from Iberia and Europe (Richard *et al.*, 2002; Guerrero *et al.*, 2021). We notice, however, that the surface deformations in models share many similarities with the Neogene evolution of Western Europe, although they do not permit to individualize tectonic blocks and to simulate faults.

A second limitation arises from the fact that these models do not take into account other distant subduction zones which may also affect the dynamics of Western Europe: no attempt has been made to simulate the Gibraltar slab. This slab being very narrow and far away from the Alps and Adria, it probably did not influence significantly the dynamics of the Alpine and Adriatic realm. The Neogene subduction of the European plate beneath the Carpathians has not been modeled either, although this subduction resulted in the eastward motion and thinning of the lithosphere, forming the Pannonian Basin (Ustaszewski *et al.*, 2008) which, in turn, favored eastward lateral escape in the Eastern Alps (*e.g.*, Ratschbacher *et al.*, 1991; Frisch *et al.*, 2000). Finally, the kinematics of Adria may also have been impacted by the Dinarides/Hellenides subduction zone (Le Breton *et al.*, 2017; Handy *et al.*, 2019). The small length of the slab beneath the Dinarides (Piromallo & Morelli, 2003), however, suggests moderate amounts of Neogene subduction compared to that occurring in the Hellenides. This may result from the smaller density of the Adria plate beneath the Dinarides, therefore indicating that the force pulling downwards this segment of the Adria slab is small. In contrast, slab-pull forces beneath the Hellenides resulted in a larger amount of slab roll-back from the Lower Miocene onwards (*e.g.*, Jolivet & Brun, 2010) and may, in turn, exert forces on the southern part of the Adria plate, which is not modelled here. Then, models presented above do not attempt to reproduce the tectonic evolution of the eastern boundary of Adria, and only constrain the possible effect of the West-Mediterranean subduction on the dynamics of Adria, acknowledging that

many other forces may have contributed to the regional tectonic evolution.

Finally, our models do not consider possible fault zones within the Adriatic/Apulian plate. In fact, geodetic data show different present-day kinematics for the Apulian and Adriatic plates, south and north of the Gargano-Dubrovnik line, respectively, but the deformation seems to be diffuse rather than localized on a single fault (d'Agostino *et al.*, 2008; Nocquet, 2012; Handy *et al.*, 2019). Some deformation also occurs between Africa (Nubia) and Apulia, suggesting the possible influence of faults separating the Hyblean Plateau from stable Africa (d'Agostino *et al.*, 2008).

4.2 Consequences of slab roll-back on the dynamics of the overriding plate

In all the models we presented, oceanic subduction resulted in slab roll-back. The subduction velocity in models is, indeed, largely faster than the advance of the piston that simulates the northward motion of Africa. Actually, this correctly mimics the Western Mediterranean context, where the velocity of slab roll-back approached 50 mm/yr while the Africa/Europe convergence rate was less than 10 mm/yr (*e.g.*, Romagny *et al.*, 2020). In the models, subduction velocity peaks between 0.5 and 0.8 mm/s, which scales between 40 and 60 mm/yr. Slab roll-back results in superficial extension above the subduction zone. Extension is E-W oriented close to the African margin, roughly trench perpendicular above the central part of the subduction zone, and N-S close to the Adriatic margin (Fig. 8b). Areas of maximum thinning are located far from the trench (~15 cm in model, which corresponds to ~1000 km in nature, see Fig. 8b) because close to the trench, trench-parallel extension is compensated by trench perpendicular shortening. This shortening results from the mantle flow converging toward the central part of the subduction zone where slab retreat is active, meanwhile continental subduction in Western Africa and Northern Adria largely slows down the retreat of the lateral edges of the slab (Fig. 8a). Mantle flow converging towards the central part of the subduction zone is also observed in the numerical models presented by Lo Bue *et al.* (2021). This pattern of deformation in which trench-parallel shortening combines with trench-perpendicular extension differs from that observed in the absence of lateral continents, as for example in the case of the Hellenic arc where stretching is observed both parallel and perpendicular to the trench, in models as well as in nature (*e.g.*, Hatzfeld *et al.*, 1997; Gautier *et al.*, 1999).

The passive plastic beads lying above the glucose syrup that were located close to the trench moved towards the trench during slab roll-back, and they come to rest against Adria and Africa at the end of the experiment. This kinematic evolution reproduces the Neogene tectonic deformations of the European and Iberian continents above the Western Mediterranean subduction, with the separation from stable Europe of the AlKaPeCa blocks and their migration above the retreating subduction zone (Bouillin *et al.*, 1986).

4.3 Slab break-off following the end of oceanic subduction

Accretion of continental fragments along Africa and Adria was followed by slab break-off, which is actually imaged by

seismic tomography (*e.g.*, Wortel & Spakman, 2000; van der Meer *et al.*, 2018) and can also be dated considering the tectonic and magmatic evolution of the region, both along the African margin (*e.g.*, Maury *et al.*, 2000; Michard *et al.*, 2006; Booth-Rea *et al.*, 2018; Azizi & Chihi, 2021) and along the Adriatic margin (*e.g.*, Hippolyte *et al.*, 1994; Chiarabba *et al.*, 2008). In Northern Africa, slab break-off initiated in central Algeria 16 Ma ago (Maury *et al.*, 2000), and afterwards progressively propagated eastward towards the still active Calabrian subduction zone (Faccenna *et al.*, 2001a; Argnani, 2009). Beneath Adria, slab break-off has been proposed to migrate southward from the Central Apennines during the Late Miocene and Pliocene (Chiarabba *et al.*, 2008; Guillaume *et al.*, 2010). Beneath the Northern Apennines, tomographic data image a fast anomaly (van der Meer *et al.*, 2018) that may correspond to a deep and almost vertical slab, suggesting that the slab may still be continuous, although Spakman and Wortel (2004) suggest that the North Apennines slab reaches a depth of only ~300 km and is separated from a deeper anomaly corresponding to an Alpine slab. The slab beneath Calabria imaged by tomography is clearly continuous and highlighted by the Wadati-Benioff plane dipping towards the NW, showing that the subduction that initiated 35 Ma ago is still going on (*e.g.*, Faccenna *et al.*, 2001a; Neri *et al.*, 2009; Jolivet *et al.*, 2015). However, the post 2 Ma rapid uplift of Calabria at rates approaching 2 mm/yr (Antonoli *et al.*, 2006) suggests that the break-off process may be initiating here also, announcing the forthcoming tear-off of the subducting plate, and hence the end of this subduction.

Models without any preexisting fault do not result in any break-off, although models last an equivalent of 60 Ma after the onset of subduction and 30 Ma after the end of oceanic subduction (Fig. 3). It confirms that silicone is not a suitable material to reproduce faulting in lithospheric plates and that models in which the silicone plates do not contain any heterogeneity fail to reproduce the break-off that is generally observed following oceanic closure and the beginning of continental subduction (Fernandez-Garcia *et al.*, 2019). Our models in which a fault separates the dense oceanic plate from the buoyant continental plate reproduce slab break-off following the beginning of continental subduction, and the order of magnitude of the delay between oceanic closure and break-off (5-15 Myrs) corresponds to that observed in nature and in the numerical models of Lo Bue *et al.* (2021). Break-off is followed by the exhumation of the subducted buoyant plate (Fig. 5f). Slab break-off modifies mantle flows and the surface kinematics of both the overriding domain and the Adriatic plate, as further detailed in the next section.

4.4 Consequences of slab roll-back on the rotation of Adria

Oceanic subduction results in forces that stretch the overriding plate and cause back-arc extension, as explained above and largely described in the literature (*e.g.*, Faccenna *et al.*, 2001a; Rosenbaum *et al.*, 2002b). But tension forces also pull the subducting plates towards the trench, and consequences have been less discussed. In simpler 2D experiments modeling the subduction of a homogeneous oceanic plate followed by continental subduction, Martinod *et al.* (2005)

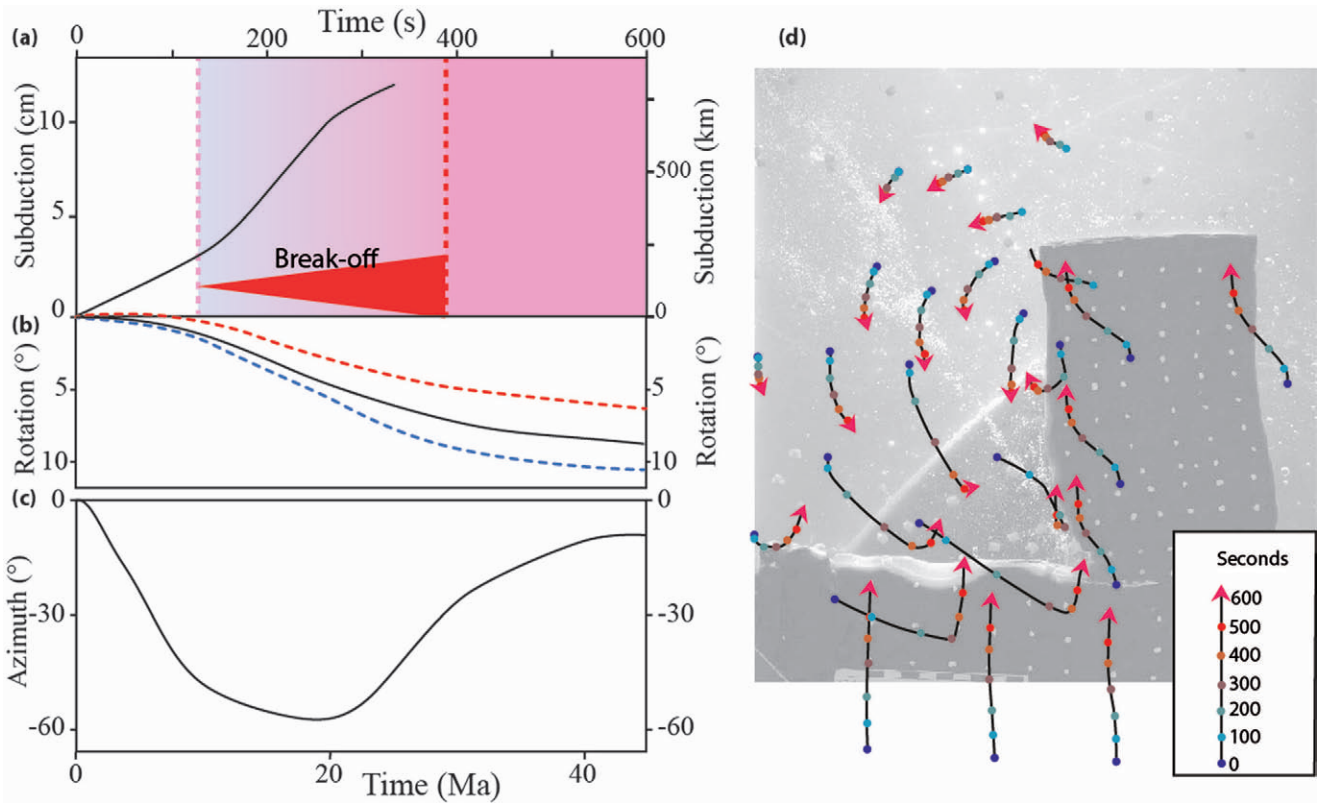


Fig. 9. (a) Length of subduction vs. time, in Model 7. Slab break-off initiates after 130 s beneath northern Adria and is complete after 380 s. (b) rotation of Adria vs. time (black curve = average rotation of the plate; blue and red dotted curves = rotation of northern and southern Adria, respectively). (c) azimuth of the motion of northern Adria vs. time. (d) superficial motion path superimposed above the top view at the end of experiment (600s). Note that the motion of Adria shifts to the NW when the subduction is active, before slab break-off.

note a rapid trenchward motion of the subducting plate (1) during the initiation of oceanic subduction before slab anchoring and (2) when the continental part of the plate initiates subduction, increasing the dip of the slab. In the Western Mediterranean subduction zone, the subducting ocean is narrow and continental subduction starts before the slab interacts with the lower mantle, explaining why the subducting plate is pulled towards the trench during the whole process of subduction before slab break-off. The African plate being a huge and rigid tectonic plate, the pull force arising from the small West-Mediterranean subduction zone cannot impact significantly its motion. In contrast, Adria is a small plate and its Neogene kinematics was probably largely affected by subduction, as suggested by the models presented here. If the southward boundary of Adria is coupled with Africa, the westward force that applies on the plate must favor counterclockwise rotation (Fig. 10).

Le Breton *et al.* (2017) discuss the factors that resulted in the post-Eocene counterclockwise rotation of Adria. They exclude the possibility that the subduction of the Ligurian Ocean and the pull of the slab beneath the Apennines may have favored this rotation, because they consider that the NW boundary of the Adriatic plate is blocked against the European plate in the Western Alps, and hence that forces arising from the West Mediterranean subduction zone should have instead favored clockwise rotations of the plate. Then, they propose

that the observed counterclockwise rotations result (1) from the northward motion of Africa and (2) from the forces that pull the southern part of Adria towards the Hellenic trench. Their model requires large amounts of divergence between Africa and the Southern Adria. Pliocene deformations in the Sicily channel evidence that some displacements occurred between the Hyblean Plateau and stable Africa. But it is difficult to estimate precisely the amount of displacement that occurred between the two plates (Le Breton *et al.* (2017)), and in fact, deformations observed in the Sicily channel would only initiate in the Pliocene (Civile *et al.*, 2010), *i.e.*, at the end of slab retreat in the West-Mediterranean area. Argnani (2009) considers that these deformations result from the last steps of slab retreat, when slab break-off was propagating eastward from Northern Tunisia to Sicilia, and when the Vavilov basin was opening. Indeed, in Tunisia, older ENE-WSW extension occurred in the Late Miocene, before a Plio-Quaternary inversion that Booth-Rea *et al.* (2018) also relate to the tearing of the slab beneath Northern Africa. In fact, divergence between Apulia and Africa resulting from the Hellenic slab pull, that may have accommodated the rotation of Apulia, although possible, is not clearly evidenced in the geological record. On the other hand, post-Oligocene E-W shortening in the Western Alps is clear, meaning that the wedging of NW Adria against Europe was not complete and that the northern part of Adria moved to the West, pulled by the West

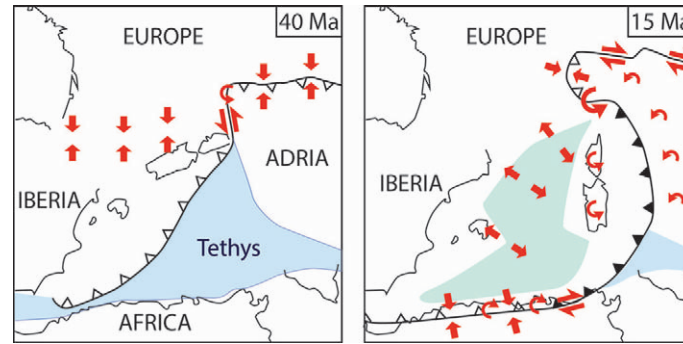


Fig. 10. Illustration of the modifications of the tectonic activity resulting from slab roll-back in the Western Mediterranean. Oceanic subduction favors the rotation of Adria which, in turn, modifies the azimuth of convergence in the Alpine belt.

Mediterranean subduction. We conclude that although slab pull forces arising from the Hellenic slab may explain part of the observed rotations, the Western Mediterranean subduction zone must have contributed significantly to the rotation of Adria.

Our models show that the amount of rotation of Adria resulting from the Western Mediterranean subduction largely depends on the occurrence and timing of slab break-off. The earlier it occurs, the smaller the rotation. In our models, the total counterclockwise rotation of Adria varies between 7° and more than 35° . These values may be compared with data obtained from paleomagnetism around the bend of the alpine realm and in Adria. Marton *et al.* (2007; 2011), analyzing samples coming from the stable part of northern Adria estimates 20° of counterclockwise rotation since the late Eocene, but data do not precisely indicate the timing of these rotations. Van Hinsbergen *et al.* (2014b; 2020) compiled data collected in stable sectors of Adria and Apulia, and consider that they are compatible with a post 20 Ma $10\pm 10^\circ$ counterclockwise rotation. Collombet *et al.* (2002) revised the paleomagnetic data available in the Western Alpine arc evidencing the rotations around a vertical axis since 40 Ma. They show that all the internal zones of the Western Alps indicate consistent large counterclockwise rotations varying between 20 and 60° . Data presented by Thöny *et al.* (2003) also indicate 30° counterclockwise rotations of the intra-Alpine part of the Adriatic Plate, in the Eastern Alps, that occurred between Oligocene and Middle Miocene, *i.e.*, before slab break-off beneath Adria. Collombet *et al.* (2002) propose that the rotation of the Adriatic plate may account for 25° of the rotations observed in the Western Alpine arc, the additional rotations being related to tectonic deformations resulting from left-lateral shear at the NW boundary of Adria (Figs. 8c and 10). A symmetrical process may explain the Neogene clockwise rotations accommodating right-lateral deformations accompanying slab retreat along the Algerian coasts (Derder *et al.*, 2013).

Plate kinematics reconstructions proposed by Le Breton *et al.* (2017) favor smaller rotations ($5\pm 3^\circ$) than those suggested by paleomagnetism. Then, despite rotation of Adria is poorly constrained, all available data suggest that counterclockwise rotations occurred during the Neogene, and models presented here support the idea that part of these rotations resulted from the western Mediterranean subduction. Although models do not indicate the exact amount of rotation that depends

on the timing of slab break-off, models with slab break-off, that are closer from the natural example, suggest that the rotation of Adria resulting from the West-Mediterranean subduction should not exceed 15° (Tab. 2). They also suggest that the rate of rotation should decrease following slab break-off beneath Adria, despite some slower rotations may persist as a consequence of northward motion of Africa (Fig. 9b). Models finally confirm that left-lateral shear between Adria and Europe may explain the larger counterclockwise rotations registered in the internal zones of the Western Alps (see Fig. 8c).

To conclude, although we acknowledge that boundary conditions that apply in the Dinarides and Hellenides on the Eastern side of Adria contributed to the kinematics of this plate (Le Breton *et al.*, 2017), our models that evaluate the effects of the West Mediterranean subduction show that it triggered part of the observed counterclockwise rotation of Adria. Models taking into account the northward motion of Africa result in larger rotations, suggesting that part of the rotation may also result from the Africa/Europe convergence.

4.5 Consequences on the Alpine tectonics

If the subduction of the Western Mediterranean slab modified the overall kinematics of Adria, it also impacted tectonics at the boundaries of the plate, in particular in the Alps to the North, and more specifically in the Western Alpine arc. In fact, rotation of the Adriatic Plate has been proposed for a long time to explain part of the deformations observed in the Alps (Vialon *et al.*, 1989; Laubscher, 1988; 1991). Our set of analogue models shows that the rotation of Adria largely modifies the azimuth of convergence in the Alps: the initial azimuth of convergence shifts from N-S to $N120^\circ$ and $N100^\circ$ in Model 7 and 5, respectively (Figs. 7d and 9c). Many geological observations confirm that the overall N-S azimuth of convergence that prevailed before the Oligocene shifted to NW-SE (Goguel, 1963; Ricou and Siddans, 1986; Choukroune *et al.*, 1986; Schmid and Kissling, 2000). Dumont *et al.* (2011) describe in detail all the tectonic changes that occurred during the Oligocene in the core of the Western Alpine arc. They propose that before the Oligocene, the Western Alps corresponded essentially to a major sinistral transform zone accommodating the northward motion of Adria, before the onset of the E-W shortening (see also Ford *et al.*, 2006; Schmid *et al.*, 2017) (Fig. 10). E-W shortening in the Western Alps is coeval with the onset of dextral shear along the Periadriatic line

segments (Ricou and Siddans, 1986; Schmid and Kissling, 2000), meaning that the tectonic regime north of the Adriatic “indenter” also changed, and that the onset of E-W shortening in the Western Alps did not simply result from lateral extrusion responding to the ongoing northward motion of Adria as proposed by Tapponnier (1977).

In the Eastern and Central Alps, parts of the dextral strike-slip displacements have been attributed to the southern boundary of an extruding system resulting from the lateral escape of the Eastern Alps toward the East (Ratschbacher *et al.*, 1989; 1991; van Gelder *et al.*, 2017). Indeed, conjugate sinistral strike-slip faults accommodating the eastward motion of the Eastern Alps are observed east of the Lepontine Dome (e.g., Salzachtal-Ennstal-Mariazell-Puchberg faults system, Engadin Line) (Frisch *et al.*, 2000; Ciancaleoni & Marquer, 2008; Schmid *et al.*, 2013; Favaro *et al.*, 2017). This lateral escape has been favored by another slab retreat occurring at that time in the Carpathians, opening the Pannonian Basin (Ratschbacher *et al.*, 1991; van Gelder *et al.*, 2017). The two explanations are not exclusive in the Central/Eastern Alps, and we propose that part of the right-lateral motion accommodated along the Tonale Line marks the westward motion of Adria with respect to stable Europe which, in turn, resulted from the Western Mediterranean subduction.

In the Western Alps, an older Late Cretaceous to Eocene “Pyrenean-Provençal” tectonic phase accommodating N-S shortening is classically described. It is followed by the Neogene “Alpine phase” accommodating E-W shortening (e.g., Gratier *et al.*, 1989; Agard & Lemoine, 2003; Graciansky *et al.*, 2011). Since this major tectonic change is not explained by a modification of the global Africa-Eurasia convergence, it should be explained instead by more local causes. The evolution of subduction zones located between Africa and Europe is a good candidate to explain this change, since forces arising from subduction are known to exert a major control on plate kinematics and tectonics (e.g., Deparis *et al.*, 1995; Faccenna *et al.*, 2006; Jolivet *et al.*, 2009). They can lead to major changes far away from the subduction itself, with forces being transmitted through the rigid plates to deformable zones at plate boundaries, such as the Alpine orogeny for the Adria-Europe system. The change from N-S to E-W shortening enhanced left-lateral motions in the Southern border of the Western Alps (Collombet *et al.*, 2002) and may account for the development of radial strain around the bend of the arc (Gidon, 1974; Vialon *et al.*, 1989; Laubscher, 1991).

Then, we propose that the drastic modification of the tectonic regime that occurred in the Oligocene in the Western Alps with the shortening azimuth of the belt shifting from N-S to E-W, resulting in the present-day orogen arc, was largely favored by the onset of subduction in the Western Mediterranean region. The Anatolian-Aegean domain is another example of remote subduction-controlled tectonics in a partially comparable setting, in which the westward movement of Anatolia is largely the result of traction forces arising from the Hellenic subduction zone (Gautier *et al.*, 1999; Martinod *et al.*, 2000; Faccenna *et al.*, 2006).

Since the Late Miocene, E-W shortening has stopped in the Western Alpine Arc (Vigny *et al.*, 2002; Nocquet, 2012; Walpersdorf *et al.*, 2015; Bilau *et al.*, 2023). Our models suggest that end of the westward motion of northern Adria has been favored by slab detachment beneath Italia. Nevertheless,

geological and geodetic data indicate the ongoing slow counterclockwise rotation of Northern Adria with respect to stable Europe, the relative pole of rotation being located in Northern Italy (Ménard, 1988; d’Agostino *et al.*, 2008). This rotation is accommodated along the arc by generalized right-lateral orogen-parallel strike-slip faults (Bertrand and Sue, 2017) as for instance the dextral Rhone Simplon Fault (Hubbard and Mancktelow, 1992), the dextral Belledonne Border Fault (Thouvenot *et al.*, 2003), or the normal to transtensive High Durance – Bersezio Fault (Sue and Tricart, 2003). This slow counterclockwise rotation ($\sim 0.3^\circ/\text{Ma}$) is coeval with the clockwise rotation of Apulia, south of the Gargano-Dubrovnik line, evidencing that Adria and Apulia now correspond to two rigid blocks with different kinematics. Their present-day motion may be governed by the Africa-Eurasia convergence, as proposed by d’Agostino *et al.* (2008), without any major control exerted by the Western Mediterranean subducting slab that almost entirely detached from the superficial plates.

5 Conclusion

We modelled the Neogene subduction of the Tethys sea-floor beneath Western Europe. Although the simple experiments presented above do not include any overriding plate, we observe that surface mantle flows reproduce the regional Neogene kinematics: Subduction being much faster than the convergence between Africa and Eurasia, it triggers back-arc extension, resulting in surface displacements that mimic the rotation of Corsica and Sardinia, and the Alkapeca dispersal. Models also show that subduction favors the counterclockwise rotation of Adria which, in turn, impacts the Alpine realm. From the Oligocene, the start of oceanic subduction in the Western Mediterranean leads to E-W shortening in the Western Alps and to the activation of the Periadriatic right-lateral shear zones in the Central Alps. The influence of subduction on the kinematics of Adria largely decreases following slab break-off. We conclude that the western Mediterranean region is another spectacular example showing how the dynamics of mountain ranges and plate boundaries may be controlled by distant subduction processes.

Acknowledgments

We thank Laurent Jolivet, editor in chief of the journal, Olivier Vanderhaeghe, associate editor, and the two reviewers of this paper, Nicolas Riel and Mark Handy, for their detailed analyses and criticisms of the first version of this article, which have enabled us to make significant improvements. This work has been financed by the Syster Program of INSU (Institut National des Sciences de l’Univers) and by the BQR program of the ISTerre lab. Analogue models were realized in the Laboratory of Analogue modelling, ISTerre, Université de Savoie-Mont Blanc. Many thanks to the pre-graduate students that performed the first models for their enthusiasm : Evan Hérin, Céline Leblanc, Juliette Crépel, Kim Junique.

Supplementary Material

Video 1: Top and lateral view, experiment 1.

Video 2: Top and lateral view, experiment 3.

The Supplementary Material is available at <https://www.bsgf.fr/10.1051/bsgf/2024001/olm>.

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Cite this article as: Martinod J, Daou AC, Métral L, Sue C. 2024. Did subduction in the western Mediterranean drive Neogene alpine dynamics? Insights from analogue modeling. *BSGF - Earth Sciences Bulletin* 195: 5.